This is to certify that the

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AUTOMATIC CONTROL OF COMMERCIAL CROSSFLOW GRAIN DRYERS

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AUTOMATIC CONTROL OF COMMERCIAL CROSSFLOW GRAIN DRYERS

By

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ABSTRACT

AUTOMATIC CONTROL OF COMMERCIAL CROSSFLOW GRAIN DRYERS

By

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Automatic control of continuous-flow grain dryers has been commercially available for a decade. These feedback control systems are temperature-activated and relatively inexpensive, but are not able to control the outlet moisture content of the grain in dryers adequately when the inlet moisture varies by more than two percentage points. The goal of this study was to develop a feedforward grain-moisture activated controller, and test the system commercially on crossflow grain dryers. The design objective was to control the exit moisture content to within ±1.0% from the set point at inlet moisture variations up to 10 percent.

First, an unsteady state model of crossflow grain drying was developed consisting of four differential equations. Solution of the model requires excessive computer power and time, and thus several empirical models were tested as the process model in the feedforward dryer control system. The simplified empirical drying models predict the exit grain moisture from a crossflow dryer well compared to that predicted by the unsteady-state dryer simulation model and to that measured experimentally.

Subsequently, the control system consisting of an empirical drying model, an on-line moisture meter, a tachometer, a data acquisition software, a microcomputer, and the feedforward/feedback control

software was implemented, and tested during two drying seasons, on two commercial crossflow maize(corn) dryers. The inlet grain moisture content varied between 16.1% to 34.3% (w.b.). The new control system controlled the outlet grain moisture content to ±0.6% of the set point.

The automatic control system can be adopted to different dryer types and different cereal types. Advantages of the feedforward control system include: (1) improved dryer control, (2) improved grain quality, (3) improved energy efficiency, (4) improved drying records, and (5) improved dryer economics.

Approved F. W. Bakker-Arkema
Major Professor 8/19/87

Approved Donald M. Edwards
Department Chairman 8/10/87

Dedicated

To the Memory of My Mother, Mariam,

My Sister, Madeena,

and

To Mahasin and Hiba

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LIST of SYMBOLS

A_o constant

A_1 constant

A_i constant

B_o constant

B_1 constant

C specific heat, kJ/kg-^{o}c

D diffusion coefficient, m^2/hr

G flow rate, kg/hr-m^2

h convective heat transfer coefficient, kJ/hr-m^2-^{o}c

h_{fg} latent heat of vaporization for water in the grain, kJ/kg

M moisture content, decimal, d.b.

T air temperature, ^{o}c

t time, second, minute or hour

V velocity, m/hr

W absolute humidity of air, lb water/lb dry air

x coordinate direction along the width of the dryer, m

y coordinate direction along the length of the dryer, m

Subscripts

a air
p product
v water vapor
w water liquid

Greek Symbols

θ grain temperature, ^{o}c
ϵ bed porosity
ρ density, kg/m^3

1. INTRODUCTION

Grain dryers normally operate by forcing hot air through a static or moving layer of grain. The drying process is an energy intensive process when weather conditions do not allow for low-temperature drying systems. In such cases, a high-temperature drying system is a suitable alternative to a low-temperature drying system.

A high-temperature drying system is energy efficient when the dryer operates at a high inlet air temperature and a low airflow rate. Grain quality is one of the limiting factors in the use of high inlet air temperatures.

The main objective of a drying process is to decrease the grain moisture content from one level of moisture content to a desired lower level of moisture content(set point). As the inlet moisture content of the grain entering the dryer changes, the above objective becomes difficult to achieve. Underdrying and overdrying usually take place due to the moisture variation in the grain entering the dryer. Overdrying and underdrying are not only caused by the variation in the inlet moisture content of the grain, but may also be a result of changing weather conditions and internal factors related to the dryer or grain.

Underdrying is most serious, since wet spots and spoilage of the grain may occur. Overdrying is expensive due to the unnecessary costs in fuel, labor, maintenance, and investment.

With a wide range of inlet moisture contents, grain dryer operators have a difficult task to control the grain outlet moisture content. The usual approach taken to ensure that all grain is dried to or below a set point, is to overdry. Thus, the necessity exists for a system with the capability to control a dryer automatically. It should be noted that even an experienced dryer operator is not able to adjust the dryer parameters (such as the inlet air temperature or grain flow rate) properly to obtain exactly the desired average outlet moisture content.

The unavailability of an inexpensive and yet accurate on-line moisture meter has had a negative effect on the development of an automatic dryer controller. This situation has lead some researchers to correlate the outlet grain temperature with the grain outlet moisture content, since grain temperature can be measured relatively easily. The use of such controllers for commercial grain dryers has not been successful, since many factors in addition to a change in the inlet grain MC can change the air exhaust temperature. The recent development of an on-line moisture meter, and the need for a dryer control system, constitute the inspiration for this work on a MC-based grain dryer control system.

CHAPTER 2

2. OBJECTIVES

The objectives of this dissertation are:

1. To develop a mathematical unsteady state grain-drying model for use in an automatic dryer control algorithm for crossflow grain dryers.
2. To develop a control algorithm for the control of commercial crossflow grain dryers.
3. To combine an on-line moisture meter, the grain-drying model, the control algorithm, and a motor controller into an automatic control system for crossflow grain dryers.
4. To test the control system on several commercial crossflow grain dryers.
5. To evaluate the newly-developed automatic dryer control system, and recommend alternative dryer models and control algorithms.

CHAPTER 3

3. LITERATURE REVIEW

3.1 Types of Dryers

Various types of dryers are used in drying grains to the desired moisture content. The most common types of grain dryers make use of passing air through the grain. Heat and moisture are transferred between the passing air and the grain kernels by convection, and thus such grain dryers are named convective grain dryers.

Grain dryers fall into two categories, namely batch dryers and continuous-flow dryers. Batch dryers are characterised by the fact that grain is dried either with heated air or with near-ambient air in stationary bed depths up to several meters. In near-ambient, or low-temperature drying, the drying process takes place over many hours, days, or even months. Batch dryers will not be discussed here, a detailed discussion of the subject is given by Brooker et al.(1974).

Continuous-flow dryers are classified by the relative direction of air and grain movement through the dryer. Several types are shown in Figure 3.1. In crossflow dryers, the flow of air is perpendicular to the flow of grain. The air and the grain move in the same direction in concurrent-flow dryers; in counter-flow dryers, the air and grain flow in opposite directions.In mixed-flow dryers, the air flows partially in the grain direction and partially opposite to the grain direction.

3.1.1 Crossflow Dryers

Crossflow dryers are simple in construction. They generally have a lower initial cost than other continuous-flow dryer types. Commercial crossflow dryers are usually non mixing type dryers.

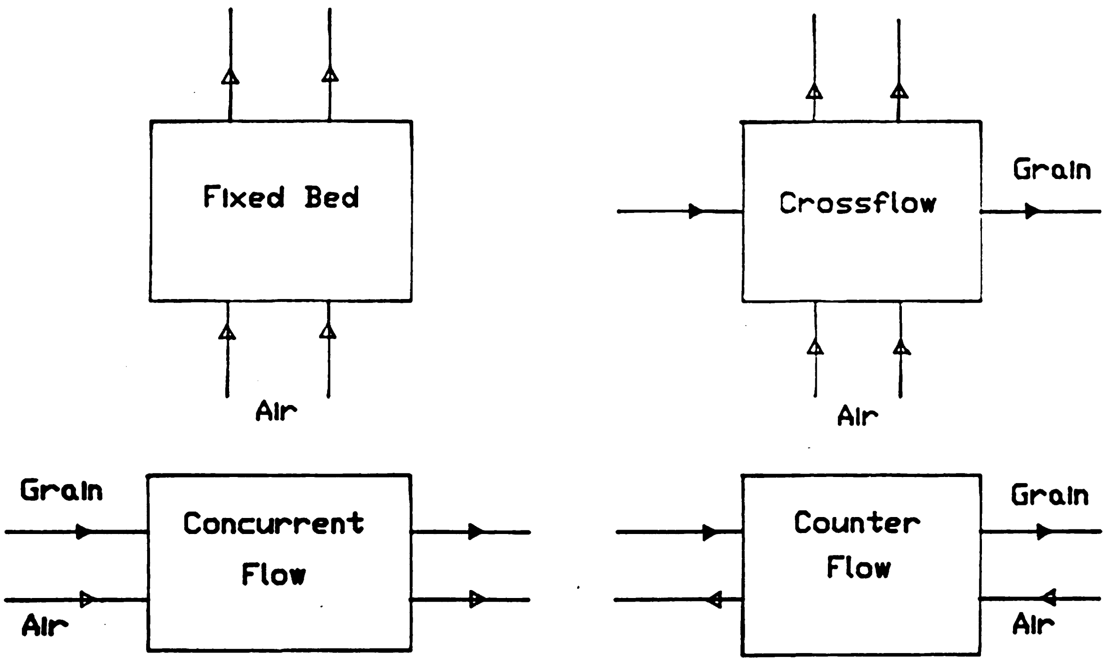


Figure 3.1 Schematic of Four Types of Convective Grain Dryers.

The drying process in a crossflow dryer is achieved by allowing wet grain to flow from the holding bin down the drying columns. Hot air is forced across the columns to heat the grain and to remove the evaporated moisture from the grain. The dried grain is cooled and unloaded at the bottom of the dryer (Fig 3.2). The grainflow rate is regulated by the grain discharge augers at the bottom of the dryer columns.

One of the major disadvantages of a crossflow dryer is the moisture gradient which develops across the drying column as the grain flows through the columns. Over-heating, over-drying, and over-cooling are characteristics of kernels at the air inlet side, whereas under-drying and under-cooling of kernels occur at the air outlet (Gygax et al., 1974).

Gustafson and Morey(1981) investigated experimentally the moisture gradient and grain quality across the drying column of a crossflow dryer. They found large differences in moisture content, grain temperature, breakage susceptibility, and germination across the drying column. Raising the drying temperature, and/or removing more moisture, reduced the overall quality of the grain.

Grain turning midway through the drying section or reversing the airflow are the methods used to reduce the temperature and moisture gradients occurring across the drying columns. Air-recycling results in an improvement of the energy efficiency of crossflow dryers.

The energy consumption of conventional crossflow dryers without air recycling is 7000-9000 kJ/kg(3017-3878 Btu/lb) of water removed (Nellist, 1982).

Pierce and Thompson (1981) investigated the influence of various dryer operating parameters on the performance of several crossflow

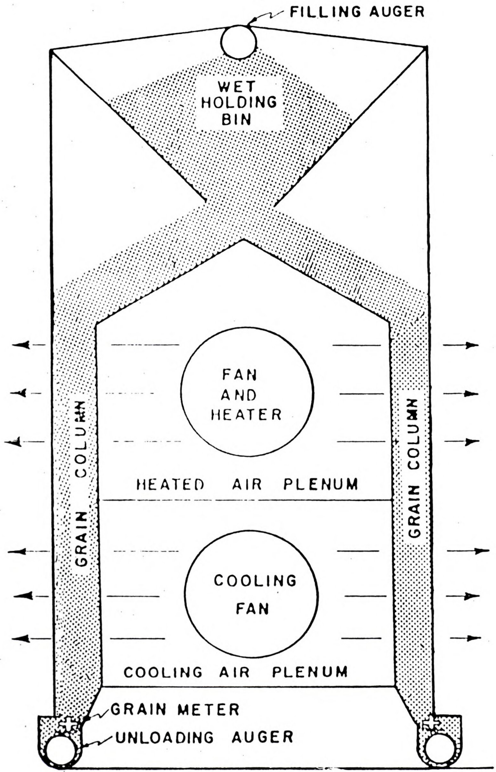


Figure 3.2 Schematic of a Conventional Continuous-Flow Crossflow Grain Dryer (Brooker et al., 1974).

grain dryers: (a) a conventional crossflow dryer, (b) a reversed airflow model, (c) a reversed airflow dryer with air recirculation of the cooling air and 50% of the heating air (Hart-Carter), and (d) a recirculating model which re-uses the cooling air and the drying air from the second stage. The comparison of these units, drying corn at the same capacity from 25% to 15% moisture content (w.b.) under ambient conditions of 10 degrees C and 50% relative humidity, is shown in Table 3.1. It is clear that modification of the conventional crossflow dryer can decrease the energy requirements and improve the grain quality without affecting the dryer capacity.

Differential grain-speed and tempering are two recent features added to the basic crossflow dryer design. Differential grain-speed refers to the movement of grain close to the air inlet side at a faster speed through the column than grain at the air outlet side (Bakker-Arkema et al., 1982). The variation in grain speed is accomplished through dual discharge rolls rotating at different speeds. The optimum speed ratio depends on the grain type and the initial moisture content. Differential grain-speed improves grain quality, increases dryer energy efficiency and dryer capacity (Bakker-Arkema et al., 1982).

Tempering between subsequent drying passes or stages in multi-stage drying systems is practiced with rice. During tempering the temperature and moisture gradients within the individual rice kernels diminish (Steffe et al.; 1979, Ezeike and Otten; 1981), resulting in less subsequent fissuring and breakage.

Bakker-Arkema et al. (1982) tested a commercial crossflow corn dryer which with differential grain-speed, tempering and air recycling features. The energy efficiency of the dryer was found to be 3700 kJ/kg (1600 Btu/lb) of water removed.

Table 3.1: Calculated energy requirements for dryer types operating under conditions which maintain grain quality and allow a grainflow rate of 48.5 kg of grain per hour per meter square of dryer area.

Dryer Type	Total Energy kJ/kg H_2O	Drying Air Tem. (°C)	Airflow Rate, (m^3/mi m^2)	Maximum Grain Tem. (°C)	Moisture Differential (%, w.b.)
Conven. Crossflow	6940	68	42	60	5.0
Reversed Crossflow	7020	68	41	60	1.9
Hart-Carter	4890	65	58	60	1.3
Recicul. Air Dryer	4380	66	51	60	1.1

Source: Pierce and Thompson(1981)

3.1.2 Concurrent-Flow Dryers

A concurrent-flow dryer consists of one or more concurrent-flow drying beds coupled to a counter-flow cooling bed (see Fig 3.3). In multi-stage units, a tempering zone separates two adjacent drying beds. The air and grain flow in the same direction with the hottest air encountering the wettest grain. Concurrent-flow dryers have only recently become available commercially.

The drying temperature in concurrent-flow dryers is not limited by the type or moisture content of the product since grain velocity is the governing factor. Air temperatures up to 500 ^{o}C are used in drying corn without affecting product quality (Hall and Anderson, 1980). The high rate of evaporation cools the air rapidly and prevents excessive grain-kernel temperatures. As the grain moves downward, its temperature increases rapidly, and then decreases slowly along with the drying air temperature. The high drying-air temperatures result in a high energy efficiency and a low airflow requirement for the concurrent-flow dryer.

Moisture and temperature gradients among the dried kernels are small in concurrent-flow dryers since each kernel undergoes the same drying, tempering, and cooling treatment, in contrast to grain dried in crossflow dryers. The grain temperature is better controlled in concurrent-flow dryers and the maximum air temperature is maintained for a much shorter period of time in the drying section than in other dryers types.

In the counterflow cooling section, hot grain is cooled gently due to the small difference (5-10 ^{o}C) in temperature between the warm grain kernels and the cooling air. Due to the beneficial effects in the

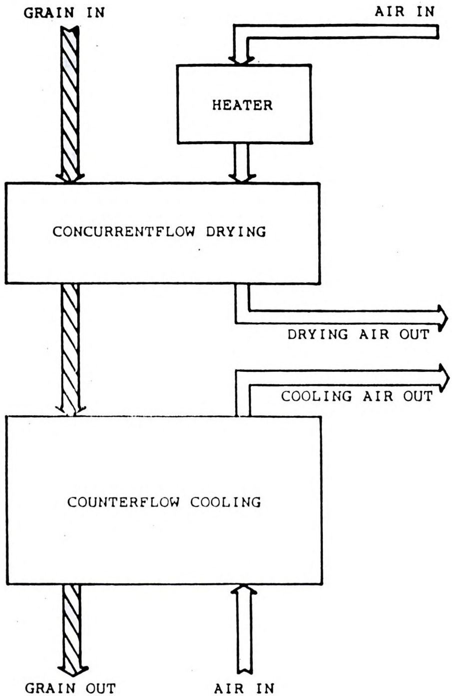


Figure 3.3 Block Diagram of a Single-Stage Concurrent-Flow Dryer with a Counterflow Cooler (Brooker et al., 1974).

drying and cooling sections, concurrent-flow dryers produce a higher quality grain than other dryer types(Bakker-Arkema et al., 1981; Fontana et al., 1982).

The energy efficiency of concurrent-flow dryers with and without air-recirculation ranges from 3000 to 3800 kJ/kg (1293 to 1637 Btu/lb) of moisture removed(Nellist, 1982; Bakker-Arkema et al., 1982). Thus, concurrent-flow dryers are energy efficient in comparison to crossflow dryers.

The design of multi-stage concurrent-flow dryers allows the use of high grain velocities and high inlet-air temperatures. Increased dryer capacity, improved grain quality, dryer controllability, and improved thermal efficiency are the advantages of multi-stage concurrent-flow dryers compared to single-stage units.

3.1.3 Mixed-Flow Dryers

In mixed-flow dryers, grain is dried by crossflow, concurrent-flow, and counter-flow. Grain flows over rows of alternate inlet and exhaust air ducts. Due to the combined effect of different drying mechanisms, mixed-flow dryers can be modeled as series of crossflow, concurrent-flow, and counter-flow submodels (Parry, 1985).

The inlet air temperature in mixed-flow dryers can be higher than those used in crossflow dryers, since grain is not subject to the high temperature for long period of time.

3.2 Modeling of Continuous-Flow Dryers

3.2.1 Single-Kernel Drying Models

Some biological products when dried as single particles under constant external conditions, exhibit a constant-rate drying during the initial drying period, followed by a falling-rate drying period. A critical moisture content separates the two drying periods.

During the constant-rate drying period, the material remains at the wet bulb temperature of the air. The rate of surface evaporation is determined by the rate of diffusion of water vapor through the film of air surrounding the product; thus, the drying rate is proportional to the difference between the partial pressure of the water vapor of the material and that of the drying air. The mechanism of moisture removal is equivalent to evaporation from a body of water and is essentially independent of the nature of the solid.

The magnitude of the constant-rate drying depends upon three factors: (1) the heat or mass transfer coefficient; (2) the area exposed to the drying medium; and (3) the difference in the vapor pressure between the gas stream and the boundary layer surrounding the wet surface of the solid. The three factors are external; thus, the internal mechanism of liquid flow does not affect the constant-rate drying period.

For individual grain kernels, the constant-rate drying only occurs when the moisture content is sufficiently high to maintain a surface layer of free water(Parry,1985). For corn, this only happens at moisture contents over 50%. Thus, harvested grain kernels dry entirely within the falling-rate drying periods.

Theoretical, semi-theoretical, and empirical models have been developed to describe the transport of moisture from the interior to the surface of a grain kernel during the falling-rate drying period.

Luikov(1966) proposed a number of physical mechanisms to describe the transfer of moisture in capillary-porous products such as grains:

(1) liquid movement due to surface forces(capillary flow);

(2) liquid movement due to a moisture concentration difference (liquid diffusion);

(3) liquid movement due to diffusion of moisture on the pore surfaces(surface diffusion);

(4) vapor movement due to a moisture concentration difference (vapor diffusion);

(5) vapor movement due to a temperature difference (thermal diffusion); and

(6) water and vapor movement due to a total pressure difference (hydrodynamic-flow).

Based on the above mechanisms, Luikov(1966) developed a mathematical model for describing the drying of capillary porous products. The model equations are a system of partial differential equations :

$$\frac{\partial M}{\partial t} = \nabla^2 K_{11} M + \nabla^2 K_{12} \theta + \nabla^2 K_{13} P \qquad (3.1)$$

$$\frac{\partial \theta}{\partial t} = \nabla^2 K_{21} M + \nabla^2 K_{22} \theta + \nabla^2 K_{23} P \qquad (3.2)$$

$$\frac{\partial P}{\partial t} = \nabla^2 K_{31} M + \nabla^2 K_{32} \theta + \nabla^2 K_{33} P \qquad (3.3)$$

where K_{11}, K_{22}, and K_{33} are the phenomenological coefficients while the other K-values represent the coupling coefficients. The coupling results from the combined effects of the moisture, temperature, and total pressure gradients on the moisture, energy, and mass transfer.

Although, a modified form of Luikov's model was used in analyzing drying of rough rice (Husain et al., 1973), lack of knowledge of the phenomenological coefficients hindered the application of Luikov's model to cereal grains.

The liquid/vapor diffusion theory has been used extensively in grain drying studies by different researchers, with the grain kernel shape assumed as a sphere. The following partial differential equations describe the moisture diffusion in spherical and rectangular coordinates:

spherical $$\frac{\partial M}{\partial t} = \frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 D \frac{\partial M}{\partial r} \right) \tag{3.4}$$

rectangular $$\frac{\partial M}{\partial t} = \frac{\partial}{\partial x} \left(D \frac{\partial M}{\partial x} \right) + \frac{\partial}{\partial y} \left(D \frac{\partial M}{\partial y} \right) + \frac{\partial}{\partial z} \left(D \frac{\partial M}{\partial z} \right) \tag{3.5}$$

Bakker-Arkema and Hall(1965), Becker and Sallans(1955), Chittenden and Hustrulid(1966), Chu and Hustrulid(1968), Hamdy and Barre(1969), Henderson and Pabis(1961,1962), Rowe and Gunkel(1972), Steffe and Singh(1980), Watson and Bhargava(1974), and Young and Whitaker(1971), used the diffusion theory to analyze drying of different grain types. The major assumptions made by these researchers are:

1. the grain kernels are homogeneous and isotropic;

2. the diffusion coefficient is constant, or varies with temperature and/or moisture content;

3. the mass transfer coefficient at the kernel surface is infinite, finite, or varies with time;

4. the initial moisture content distribution is uniform; and

5. the temperature gradient in the kernels during drying is negligible.

Results have shown that the estimate of the diffusion coefficient(D) depends on the grain and the co-ordinate system of the diffusion equation. However, the general solution to the diffusion equation has the form of a series of negative exponential terms, regardless of the particle geometry or the boundary conditions (Moon and Spencer, 1961) :

$$MR = \frac{M - M_e}{M_o - M_e} = \sum_{i=1}^{\infty} A_i e^{-B_i t} \qquad (3.6)$$

where,

M = average moisture content of grain at time t (d.b)

A_i = constant, characteristic of the material being dried, dimensionless

B_i = constant, characteristic of the material being dried, hr^{-1}

M_o = initial moisture content of the material,(d.b)

M_e = equilibrium moisture content,(d.b).

A moisture relationship analogous to Newton's law of cooling is often used in single-kernel drying analysis (Brooker et. al, 1974). Thus, the rate of moisture loss of a grain kernel is proportional to the difference between the kernel moisture and its equilibrium moisture content :

$$\frac{dM}{dt} = -k\ (M - M_e) \qquad (3.7)$$

where

k= drying constant, hr^{-1}.

When the drying air is at constant temperature and relative humidity, M_e is constant. Thus, solving equation (3.7) gives:

$$MR = \frac{M - M_e}{M_o - M_e} = e^{-kt} \qquad (3.8)$$

Several purely empirical drying equations have been developed for cereal grains. Thompson (1968) proposed the following thin layer equation for shelled corn over the temperature range from 140 to 300 degrees F :

$$t = A \ln MR + B \ln (MR)^2 \qquad (3.9)$$

$$A = -1.862 + .00488\ T$$

$$B = 427.4 \exp(-.033\ T)$$

where t is the drying time in hrs, MR is the moisture ratio, T is corn temperature in ^{o}F, and A and B are empirical coefficients that are functions of temperature.

Flood et al.(1972) proposed the following empirical drying equation for shelled corn over the range 36 to 70 degrees F:

$$MR = \exp(-k\ t^{.664}) \qquad (3.10)$$

$$\text{where } k = \exp(-x\ t^{y}) \qquad (3.11)$$

x,y are nonlinear functions of relative humidity and temperature:

$$x = (6.0142+.0001R^2)^{1/2} - 0.01T(3.353+.001R^2)^{1/2}$$

$$y = 0.1245 - .0022R + 2.3*10^{-5}RT - 5.8*10^{-5}T$$

R = relative humidity, decimal

T = temperature, F

Henderson and Henderson (1968), Nellist and O'Callaghan (1971), Rowe and Gunkel(1972), Henderson(1974) and Nellist(1976) have fitted a two term series of negative exponentials to experimental thin-layer drying data for rice, rye grass seeds, alfalfa hay, shelled corn, and rye grass seeds, respectively. The time response equation has the general form :

$$MR = A_o \, e^{-B_o t} + A_1 \, e^{-B_1 t} \qquad (3.12)$$

Sharaf-Eldeen et al. (1980) found the two-term exponential model accurate over the whole range of drying for fully exposed ear corn. The model predicted the drying behavior of ear corn to within 1% moisture content of the experimental values.

3.2.2 Deep Bed Drying Models

Deep bed drying of cereal grain has received major attention from researchers during the past 20 years. The moving bed is characteristic of continuous-flow dryers whereas the stationary bed is characteristic of batch dryers.

Deep-bed drying models are generally divided into three types, logarithmic, heat and mass balance, and partial differential equation models. The three types have some common features which suggest the division is arbitrary.

Hukill(1954) made a simplified analysis of deep-bed drying and derived the one equation model :

$$G_a \, C_a \frac{\partial T}{\partial x} = \rho_p h_{fg} \frac{\partial M}{\partial t} \qquad (3.13)$$

where G_a = mass flow rate of moist air, kg/ m^2-sec

C_a = specific heat of moist air , J/kg-degree c

x = depth, m

t = time, sec

ρ_p = density of grain, kg/m^3

M = moisture content of product, d.b.

h_{fg} = latent heat of vaporization of water, J/kg

Using exponential temperature and moisture boundary conditions, Hukill developed the following solution to eqn. (3.13):

$$MR = \frac{2^x}{2^x + 2^t - 1} \qquad (3.14)$$

where x and t are dimensionless depth and time variables, respectively.

Hukill's model underestimates the time required to dry grain to a specified moisture content. Hukill suggested that this is due to inaccuracy in the boundary condition used for M_e.

Young and Dickens (1975) used Hukill's model to estimate the costs of grain drying in fixed bed and crossflow systems.

Baughman et al.(1971) proposed a relationship between the temperature and moisture gradients in a stationary bed of grain:

$$G_a\, C_a \frac{\partial T}{\partial x} = - Q\, h_{fg} \frac{\partial M}{\partial x} \qquad (3.15)$$

where Q is the rate of advance of the drying zone. Using equations 3.13 and 3.15 they obtained a simplified drying equation:

$$\frac{\partial (MR)}{\partial t} = \frac{-1}{1-MR(0,\tau)} \frac{\partial (MR)}{\partial X} \qquad (3.16)$$

where τ=kt, X= $\frac{h_{fg} k \rho_p (M_o - M_e) x}{G_a C_a (T_o - T_e)}$, and k is a drying constant.

Barre et al.(1971) solved equation 3.16 assuming initial and boundary condition of the form

$$MR\ (0,\tau) = \exp(-\tau) \qquad (3.17a)$$

$$MR\ (X,0) = 1 \qquad (3.17b)$$

to model a crossflow dryer. They found the model to be fairly reliable in predicting the deep-bed drying in a crossflow dryer. The model was also used to compare the relative influence of parameters such as temperature, airflow, moisture content, and air humidity on the efficiency and capacity of a crossflow drying system.

Sabbah et al. (1979) employed the log model to simulate the solar drying of grain.

Thompson et al. (1968) developed a series of deep-bed drying models based on heat and mass balances of a series of thin grain layers. Steady state crossflow, concurrent-flow, and counter-flow drying were simulated with good accuracy. Boyce(1966), and Henderson and Henderson (1968) used similar simulation procedures to simulate the drying of stationary deep beds of grains.

A more fundamental approach, based on the laws of simultaneous heat and mass transfer and resulting in a series of coupled partial differential equations, was developed by Bakker-Arkema et al.(1974) at Michigan State University (MSU). Separate sets of three partial differential equations (PDE), plus an appropriate thin-layer rate equation, were employed to model various stationary and continuous flow drying systems. The MSU steady-state crossflow drying model is shown in Table 3.2.

Equations 3.18-3.22 can be solved by numerical integration employing an explicit finite difference technique. The PDE for crossflow, concurrent flow, and counter flow dryers are similar in form to the fixed-bed drying model. Laws and Parry (1983) presented the MSU PDE models in a general form. The PDE models have a sound thermo-mechanical basis in contrast to the other types of deep bed drying models(Parry, 1985).

Table 3.2 MSU steady state crossflow drying model

$$\frac{\partial T}{\partial x} = -\frac{h\ a}{V_a \rho_a C_{am}} (T-\theta) \tag{3.18}$$

$$\frac{\partial \theta}{\partial y} = \frac{h\ a}{V_p \rho_p C_{pm}} (T-\theta) + \left[\frac{C_v (T-\theta)}{C_{pm} V_p} + \frac{h_{fg}}{C_{pm} V_p}\right] \frac{\partial M}{\partial t} \tag{3.19}$$

$$\frac{\partial W}{\partial x} = -\frac{\rho_p}{V_a \rho_a} \frac{\partial M}{\partial t} \tag{3.20}$$

$$\frac{\partial M}{\partial y} = -\frac{1}{V_p} \frac{\partial M}{\partial t} \tag{3.21}$$

$$\frac{\partial M}{\partial t} = \text{an appropriate thin-layer equation} \tag{3.22}$$

Boundary Conditions:
$T(0,y) = T(\text{inlet})$
$\theta(x,0) = \theta(\text{initial})$
$W(0,y) = W(\text{inlet})$
$M(x,0) = M(\text{initial})$

3.3 Control of Continuous-Flow Dryers

3.3.1 Basic Background in Control Theory

Automatic control has played a vital role in the advancement of engineering and science. In addition to its extreme importance in space-vehicle, missle-guidance, and aircraft-piloting systems, automatic control has become an integral part of modern industrial manufacturing. For example, automatic control is essential in controlling pressure, temperature, humidity, viscosity, and flow in the food processing industry.

3.3.2 Definitions

The terminology used in describing control systems includes the following terms (Ogata, 1970; Baumeister et al., 1978):

(1) Plant: A plant is a piece of equipment performing a particular operation.

(2) Process: A process is an operation or development marked by a series of gradual changes which succeed one another in a relatively fixed way and lead toward a particular result or end.

(3) System: A system is a combination of components which act together and perform a certain objective.

(4) Disturbance: A disturbance is a signal which tends to adversely affect a system.

(5) Feedback Control: A feedback control is an operation which, in the presence of a disturbing influence, tends to reduce the difference between the output of a system and the reference input.

(6) Feedback Control System: A feedback control system is one which maintains a prescribed relationship between the output and the reference input by using the difference as a means of control.

(7) Servo-mechanism: A servo-mechanism is a feedback control system in which the output is a valve position, velocity, or acceleration.

(8) Automatic Regulating System: An automatic regulating system is a feedback control system in which the reference input or the desired output is either constant or slowly varying with time, and in which the primary task is to maintain the output at a desired value in the presence of a disturbance.

(9) Process Control System: A process control system is an automatic regulating system in which the output is a variable such as temperature, pressure, flow, liquid level, or moisture content.

(10) Closed-Loop Control System: A closed-loop control system is a system in which the output signal has a direct effect upon the control action.

(11) Open-Loop Control Systems: An open-loop control system is a system in which the output has no effect upon the control action.

(12) Adaptive Control System. : An adaptive control system is a system which has the ability to self-adjust or self-modify under unpredictable changes in input or environmental conditions.

(13) Controlled Variable: A controlled variable is the variable of the controlled system which is directly measured or controlled.

(14) Response Time: The response time is the time required for the controlled variable to reach a specified value after the application of a disturbance.

(15) Peak Time: The peak is the time required for the controlled variable to reach a maximum following the application of a stepwise disturbance.

(16) Rise Time: The rise time is the time required for the controlled variable to increase from 10 to 90%, 5 to 95%, or 0 to 100% of its final value, following the application of a stepwise disturbance.

(17) Settling Time: The settling time is the time required for the absolute value of the difference between the controlled variable and

its final value to become (and remain) less than a specified value, following the application of a step disturbance.

(18) Transfer Function: The transfer function, G(s), of a linear system is the ratio of the output transform, Y(s), to the input transform, U(s), given the initial system conditions are zero.

3.3.3 Classical Control Theory

Classical control theory deals with single input-single output (SISO) linear systems, and utilizes the block diagram approach for system representation. Figures 3.4 and 3.5 show simple and detailed block diagrams of a closed-loop feedback control system, respectively. The system components are described by the transfer functions of each component. The closed-loop transfer function of the control system is used for analysis, design and synthesis of the control system.

The closed-loop transfer functions of the two control systems shown in Figures 3.4 and 3.5 result in the following two equations:

$$\frac{C(s)}{R(s)} = G(s) = \frac{G_c(s)\ G_p(s)}{1+G_c(s)\ G_p(s)\ G_h(s)} \tag{3.23}$$

$$C(s) = \frac{A\ G_c(s)\ G_v(s)\ G_p(s)}{1+G_c(s)\ G_v(s)\ G_p(s)\ G_h(s)} R(s)$$

$$+ \frac{G_p(s)\ G_d(s)}{1+G_c(s)\ G_v(s)\ G_p(s)\ G_h(s)} D(s) \tag{3.24}$$

The transfer function of a linear system (G(s)), whether it is closed or open, can be written as follows (Manetsch and Park, 1982):

$$G(s) = \frac{b_m S^m + b_{m-1} s^{m-1} + \ldots + b_0}{S^n + a_{n-1} S^{n-1} + \ldots\ldots + a_0} = \frac{Y(s)}{U(s)} \qquad (3.25)$$

$$m < n$$

or

$$G(s) = \frac{Y(s)}{U(s)} = \frac{b_m (s+B_1)\ (s+B_2)\ \ldots (s+B_m)}{(s+A_1)\ (s+A_2)\ \ldots\ldots (s+A_n)} \qquad (3.26)$$

where $S^n + a_{n-1}S^{n-1} + \ldots\ldots + a_o = 0$ is called the characteristic equation of G(s); $S = -A_1$, $S = -A_2$, . . ., $S = -A_n$ are the poles, and $S = -B_1$, $S = -B_2$, . . . , $S = -B_m$ are the finite zeros.

<u>3.3.3.1 Stability of Classical Control Systems</u>

There are many definitions of system stability (Manetsch and Park, 1982).One of the more useful stability criterion is that of the Bounded Input Bounded Output (BIBO).

A system is said to be BIBO stable if the output is bounded (finite) for a bounded (finite) input. The definition does not "blame" a system if an unbounded input drives the system output to an unbounded value. A linear system is <u>BIBO Stable</u> if all roots of the characteristic equation (system poles) are located in the left half of the S-plane. Also, a linear system is <u>marginally BIBO Stable</u> if all roots of the characteristic equation lie in the left half of the S-plane with the exception of one or more simple poles on the jw axis (simple poles exist if system poles and input do not combine to produce multiple poles on the jw axis).

The system output is unbounded if the system and input poles combine

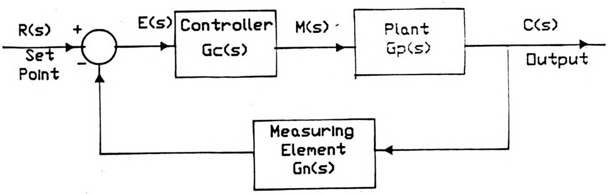


Figure 3.4 Closed-Loop Control System.

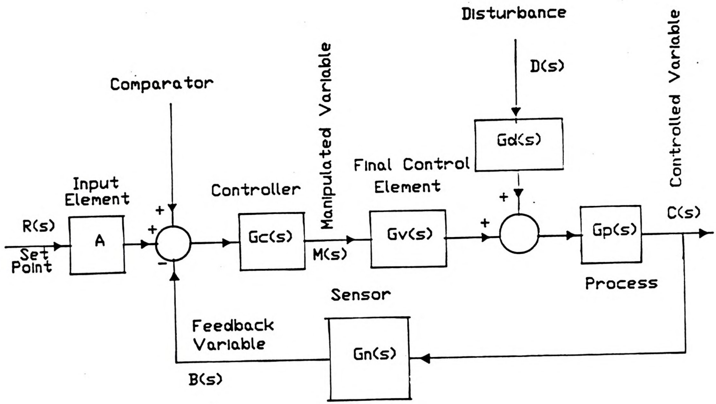


Figure 3.5 Block Diagram of a Control-Loop.

to produce multiple jw axis poles and are bounded otherwise. Thus, a linear system with poles in the left half plane and multiple poles on the jw axis is clearly unstable since the multiple jw axis poles give rise to a time response of the form t^{p-1}, $p > 1$.

The key to determine whether a linear system is stable, unstable or marginally stable is to locate the system poles in the S-plane by solving the system characteristic polynomial explicitly for the system poles. An alternative method which does not require solution of the characteristic equation has been proposed by Routh(1877). The Routh's Stability criterion is based on the value and sign of the elements of the first column of the Routh array. If the elements of the first column are positive and non zero, the system is stable. If any of the elements is negative, the system is unstable. Thus, the Routh stability criterion eliminates solving the characteristics equation, but requires the system to have a polynomial characteristic equation.

3.3.3.2 Design of Classical Control System

Figure 3.6 shows a block diagram of a feedback control system which will be used in the discussion of classical control system design. $G_p(s)$ is the given transfer function of the process being controlled with C(s) as the control variable. R(s) is the the desired (reference) value for C(s), E(s) is the error signal and U(s) is the controllable input to the process represented by $G_p(s)$. Transfer functions $G_c(s)$ and H(s) are transfer functions which can be specified by the designer to achieve a desired behavior for the controlled variable, C(s). The closed-loop transfer function for the system in Figure 3.6 with feedback control is:

$$\frac{C(s)}{R(s)} = \frac{G_c(s)\ G_p(s)}{1+H(s)\ G_c(s)\ G_p(s)} \qquad (3.27)$$

The three control (design) objectives are:

1) system stability under all system operating conditions;

2) "good" steady-state error performance;

3) "good" system dynamic or transient performance.

The Routh criterion is helpful in determining the $G_c(s)$ and $H(s)$ values which result in the desired stability. However, design stability is often considered along with the design of dynamic performance.

Design of steady-state error performance starts with the application of the final value theorem which requires that the limit of the error exists as time goes to infinity. The steady state error performance tends to worsen as the number of poles at S=0 of the input increases; it tends to improve as the number of poles at S=0 of $G_p(s)$ increases. Since $G_p(s)$ is usually fixed, poles at S=0 are added to the controller function $G_c(s)$ by the so-called "proportional plus integral control". In proportional plus integral control, the input u(t) is computed as a function of the error and the integral of the error:

$$u(t) = K_p e(t) + K_I \int_0^t e(\tau)\, d\tau \tag{3.28}$$

or

$$U(s) = K_p E(s) + \frac{K_I\ E(s)}{S} \tag{3.29}$$

where u(t) = input from the controller

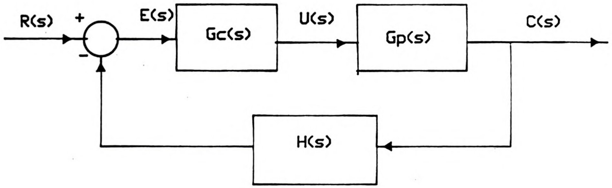


Figure 3.6 Feedback Control System.

K_p = proportional parameter

K_I = integral parameter

e(t) (E(s)) = error between the set point and the actual output.

The drawback of adding integral control to a system with proportional control is the tendency of integral control to reduce the range of parameter values (K_p,K_I) for which the system is stable (Manetsch and Park, 1982).

Design of dynamic performance is usually an objective for systems which have to adjust quickly to input changes. There are several dynamic performance criteria which should be measured when a step change occurs in the system input:

1. rise time (see section 3.3.2);

2. settling time: the time required for the output to reach and remain within a given percentage ± a % of the input; and

3. maximum overshoot: the maximum overshoot of the output as a proportion of the input value.

To achieve the above three dynamic performance measures, the Root Locus design technique can be used to choose $G_c(s)$ (and perhaps H(s)) so that the resulting pole locations will result in the desired values for the dynamic performance measures (Manetsch and Park, 1982).

A basic technique for improving the dynamic performance of a system is the use of derivative control along with proportional control (Manetsch and Park, 1982). Proportional plus derivative control is represented by the following equation:

$$u(t) = K_p e(t) + K_r \frac{de}{dt} \qquad (3.30)$$

where u(t) = input from the controller to the plant

K_p = proportional parameter

K_r = derivative parameter

e(t) = error between set point and the plant output.

In control problems requiring improvement in both dynamic performance and steady state error, it is common to use the so-called PID control (Proportional-Integral-Derivative Control) (Manetsch and Park, 1982). Integral control is used for steady state error improvement while the derivative control operates to improve dynamic performance:

$$u(t) = K_p e(t) + K_I \int_0^t e(\tau)\, d\tau + K_r \frac{de}{dt} \qquad (3.31)$$

U(s) then becomes:

$$U(s) = K_p E(s) + \frac{K_I E(s)}{S} + S\, K_r E(s) \qquad (3.32)$$

The transfer function $G_c(s)$ (of equation 3.32) is:

$$G_c(s) = \frac{U(s)}{E(s)} = \frac{K_r(S^2 + S\, K_p / K_r + K_I / K_r)}{S} \qquad (3.33)$$

The main effect of the PID control is to introduce one pole (at S=0) and two zeros into the S-plane. By properly choosing K_p, K_r and K_I, the control engineer has the option of locating two zeros in the S-plane.

3.3.4 Feedforward Control Systems

In all processes the point at which the material enters the process and the point at which it leaves the process are not the same. The longer it takes for a material to move from the entrance to the exit of a process, the more difficult it is to control the process. Thus, the longer the process dead-time, the more difficult it is to maintain the controlled variable at the desired set point. This is especially true when the load variables of a process change frequently, and the rate of change is large.

To control a long dead-time process, it is desirable to account for a variation in the load at the time the variation takes place. This is done in so-called feedforward control systems. The elements needed in implementing a feedforward control are shown in Figure 3.7; they include a process model, a dynamic compensator, and a feedback corrector.

The feedforward process model is developed by using material and energy balances, and several empirical relationships. The manipulated variable is computed as a function of the measured variable and the set point. Changes in the load are corrected by the feedforward controller. If the load variables are measured correctly and the relationships between the manipulated variables are exactly known, perfect control can be achieved.

Major load variables are identified according to the frequency of change and the magnitude of the change. The major load variables are always measured; the minor load variables are not because they cause only small disturbances in the process.

When the load and the manipulated variables enter the process at different locations, a dynamic imbalance may take place, and dynamic compensation in the form of lag, lead/lag and/or dead-time is required to minimize the effect of the dynamic imbalance. Dynamic compensation greatly improves the performance of a feedforward control system (Badavas, 1984).

A feedforward control system can provide excellent control if the process can be modeled accurately. Inadequate feedforward control results from:

(1) inadequate modeling of the process; (2) inaccuracy in the load-variable measurements; and (3) computational errors.

The cumulative effect of errors in feedforward control computations results in an offset of the controlled variable from the set point. To eliminate the offset, a feedback controller must be added to the control system. The feedforward controller corrects the variations in the major load variables while the feedback controller corrects errors due to the minor load variables. The feedback controller has a smaller corrective action than the feedforward part, and is referred to as the feedback "trim".

The feedback trim can provide an adjustment to a model coefficient, and thus can result in a major change to the controlled variable.

3.3.5 Optimal Control Theory

In conventional(classic) control theory, the analysis and design of a control system is carried out with transfer functions and graphical techniques. A major disadvantage of the classical control theory is the fact that it is limited to linear time-invariant systems with a single input and single output. Thus, conventional control is powerless for time-varying systems, non-linear systems, and multiple-input-multiple-output (MIMO) systems.

Due to the complex nature of many engineering systems, a new approach has been developed to analyze and design control systems for such systems. The approach is based on the state variable concept (smallest set of variables which determine the state of a system). It is applicable to MIMO linear, nonlinear, time-invariant or time-variant MIMO systems.

Application of optimal control requires the selection of a performance index and a design procedure which can yield an optimum within the limits imposed by the physical constraints. The performance index results in a number which indicates the "goodness" of performance. It is optimal if the values of the parameters are chosen so that the selected performance index has reached a minimum or maximum. A quadratic performance index is frequently used in optimal control systems. The performance index determines the optimal system configuration. It must be pointed out that an optimal control system operating under a given performance index is not optimal under other performance indexes. Thus, in practical systems, it is more sensible to seek optimal control which is not rigidly tied to a single performance index.

Analysis of a given optimal control strategy is important since it aids the designer in determining whether a performance index is realistic for a given system and set of constraints.

Controllability and observability are the two most important questions regarding the existence of an optimal control point. A system is said to be controllable at time t_o if it is possible to transfer the system from an initial state $x(t_o)$ to another state in a finite interval of time. A system is said to be observable at time t_o if it is possible to determine the state of the system by observing its output over a finite time interval.

The concepts of controllability and observability are important in the optimal control of multivariable systems. The solution of an optimal control problem may not exist if the system is not controllable. Although most physical systems are controllable and observable, corresponding mathematical models may not possess the

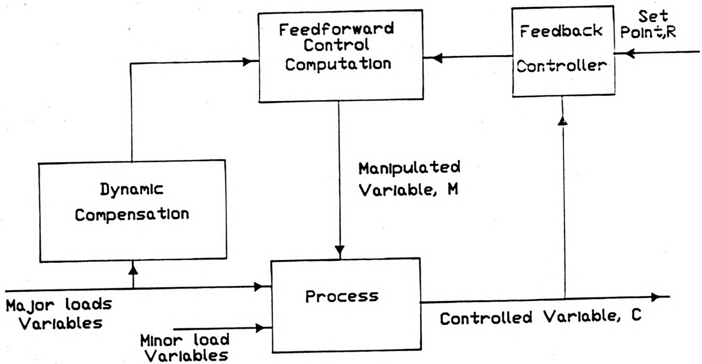


Figure 3.7 Components of a Feedforward Control System.

property of controllability and observability. Therefore, it is necessary to analyze the conditions under which a system is controllable and observable.

3.3.6 Adaptive Control Systems

The interest in adaptive control systems has increased rapidly. The term adaptive system has a variety of meanings, but usually implies that the system is capable of accommodating changes, whether these changes arise within or external to the system. Adaptive control has a great advantage to the system designer since it tolerates moderate design errors or uncertainties.

In most feedback control systems, small deviations of a parameter value from the design value do not cause problems in the normal operation of the system, provided the parameter is inside the loop. If a parameter varies widely with environmental changes, the control system may respond satisfactorily to one environmental condition but may be unstable under other conditions.

If a model parameter can be estimated continuously, variations in modeling can be compensated by adjusting the controller parameters so that satisfactory system performance is achieved under various environmental conditions. Such an adaptive approach is useful for solving a problem in which the plant parameters change from time to time.

Different definitions of adaptive control systems can be found in the literature. The vagueness surrounding the definitions and classification of adaptive systems is due to the large variety of mechanisms by which adaptation can be achieved. The various definitions arise because of the different classifications and definitions which divide control systems into adaptive and non-adaptive systems.

An adaptive control system can be defined as a system which measures continuously and automatically the dynamic characteristic of the plant. The difference between the measured and the desired dynamic characteristics is used to generate an actuating signal so that optimal performance is maintained regardless of an environmental change. Also, such a system may continuously measure its own performance according to a given performance index and modify its own parameters (Ogata, 1970).

3.3.6.1 Adaptive Controllers

An adaptive controller has the following three functions: (1) the estimation of the dynamic characteristics of the process; (2) the decision-making based on the estimated parameters of the process; and (3) the modification or actuation based on the decision.

If the process model is not well known due to random time-varying parameters or the effect of an environmental change on the plant dynamic characteristics, identification, decision, and modification procedures must be carried out continuously, or at intervals of time based on the rate of change of the plant parameters.

A block diagram representation of an adaptive control system is shown in Figure 3.8. In this system, the process is identified and the performance index measured continuously or periodically. The performance is compared with the optimum, and the decision is made based on the actuating signal needed to achieve the optimum.

The dynamic characteristic of the process must be measured and estimated continuously, or at least frequently. Estimation of the process parameters may be made from normal operating data of the process or by use of test signals.

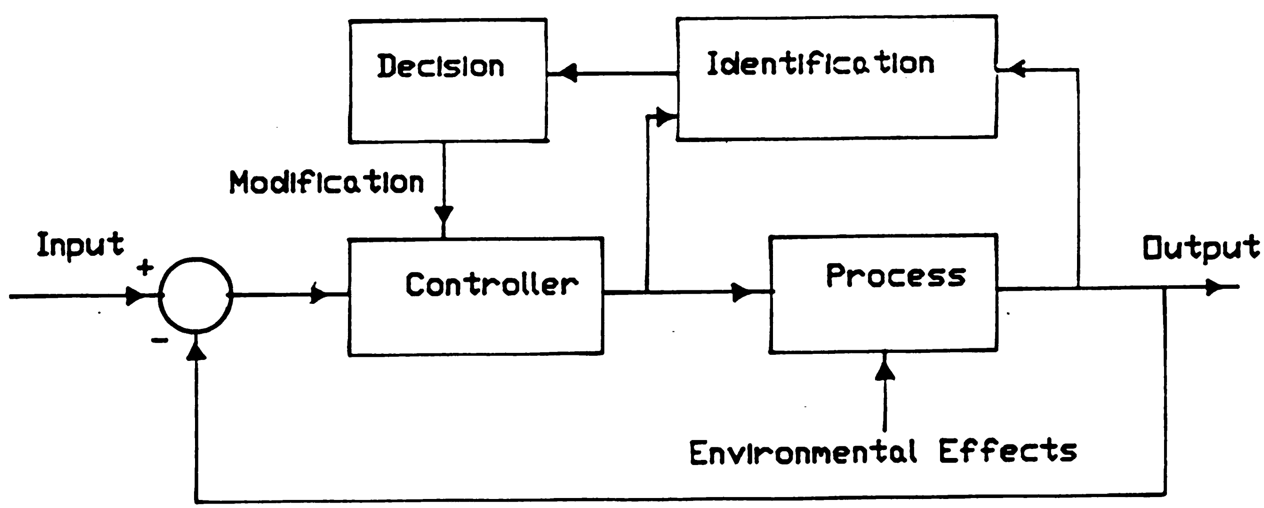


Figure 3.8 Block Diagram Representation of an Adaptive Control System.

Parameter estimation must be rapid to account for any variation in the process parameters. Estimation time should be short compared to the environmental changes.

Once the process has been estimated, it is compared with the desired characteristic. Subsequently, the decision is made how to vary the adjustable parameters in order to obtain the desired performance.

The control signals are modified according to the results of the estimation and decision. In most schemes, the decision and modification are conceptually a single operation with the modification consisting of a means of mechanizing the transformation of a decision output signal into a control signal(the input to the process).

The control or input signal to the process can be modified in two ways. The first approach is to adjust the controller parameter in order to compensate for changes in the process dynamics. This is called controller parameter modification. The second approach is to synthesize the optimal control signal based on the process transfer function, the performance index, and the desired transient response. This is called control signal synthesis.

The choice between controller parameter modification and control signal synthesis is primarily a hardware decision since the two methods are conceptually equivalent. In cases in which reliability is important, the use of parameter change adaptation is favored over the use of control signal synthesis (Ogata, 1970).

In conclusion, most control systems which require precise performance over a wide range of operating conditions are adaptive to some extent. When high adaptability is required, an estimation-decision-modification system is needed with either sequential or continuous modification, depending on the rate of change of the varying parameters.

3.3.7 Control of Grain Dryers

The optimum operation of grain dryers is accomplished by obtaining the desired grain moisture content at minimum energy use and grain deterioration and at maximum capacity. A considerable amount of extra energy is consumed during incorrect operation, such as overdrying. In addition to a waste of energy, overdrying impairs grain quality, and increases fuel cost, labor, and maintenance.

The control of grain dryers is usually achieved manually. In manually-controlled dryers, the dryer operator adjusts the grain flow rate and/or the drying-air temperature so that the desired moisture content is reached. A skillful operator is required for adequately controlling a grain dryer.

Automatic control of grain dryers has recently become a popular research topic. The literature on automatic grain dryer control can be divided into two catogeries:

1. control of in-bin low-temperature grain dryers; and
2. control of continuous-flow high-temperature grain dryers.

3.3.7.1 Control of In-Bin Low-Temperature Grain Dryers

Kranzler (1976) developed a control scheme for low-temperature drying of shelled corn using long-term weather data and simulation of several control modes. The control schemes were wired into an array of integrated circuit elements. The operator can input an anticipated combination of harvest conditions. The control system then determines the humidistat and fan control strategy at the optimum operating points.

Morey et al.(1978) simulated for the Corn Belt region of the US several different fan-management strategies for ambient drying systems by using a low-temperature drying model and the appropriate weather data. They concluded that continuous fan operation proved to be more energy efficient than fan control based on relative humidity, temperature or time.

Simonton et al. (1981) investigated a microprocessor-based grain drying control system. Their objective was to predict the performance of a low-temperature drying system using a simulation based on the logrithmic drying model. They also developed a method for controlling the output moisture of a continuous-flow dryer; grainflow rate was used in controlling the dryer output. The control algorithm was implemented using a microprocessor, a digital-to-analog (D/A) converter, interfacing circuitry, an analog-to-digital (A/D) converter, and a motor controller. The grain flow rate was controlled by varying the motor speed of the unload auger. The Simonton control system is yet to be implemented on a continuous flow grain dryer.

Derret and Allison (1981) reported experimental results of a microprocessor-based control for an in-bin grain drying system. Bin radius, grain depth, air flow rate, initial grain moisture content, desired grain final moisture content, and allowable drying time were input variables used in the drying algorithm. The control algorithm of Simonton et al.(1981) was utilized with the drying air as the control variable. They obtained at the laboratory level acceptable agreement between the calculated and measured moisture contents.

A low-temperature corn drying control system was investigated by Mittel and Otten (1983). Ambient air temperature and relative humidity were used as the drying parameters in the control algorithm; a microcomputer with a dual disc drive and 48k memory was employed. The relative humidity and temperature sensors were interfaced to the microcomputer through analog to digital converters and a timer-counter board. The authors utilized the the thin-layer drying and wetting equation of Mishra and Brooker (1979), the desorption equilibrium moisture content equation of Gustafson and Hall (1974), and the sorption equilibrium moisture content of Thompson as quoted by Morey et al. (1979).

The Mittel-Otten control algorithm is based on five indices to be specified before drying is started:

1. the relative humidity to control the drying fan;
2. the relative humidity to start searching for alternatives other than continuous fan operation without supplemented heat;
3. the relative humidity to control the heater;
4. the initial time period for which continuous fan operation is acceptable; and
5. the moisture content in the upper 10% of the bin.

The above indices are used in making the following decision and control steps:

a) If the relative humidity of the air is less than the set relative humidity to control the drying fan or the total drying time is less than the set time at which the continuous fan operation is acceptable, the drying fan is on but the the heater and aeration fan remain off.

b) If the relative humidity of the air is greater than the set relative humidity to control the drying fan and less than or equal to the set relative humidity at which alternatives other than operating the fan without supplemental heat is searched for, the heater is turned on to decrease the relative humidity.

c) If the ambient air relative humidity is greater than the relative humidity at which alternatives other than the continuous operation of the drying fan without supplemental heat is searched for, the heater and the dryer fan are turned off and the aeration fan is started, or the fans and heater are turned off depending on the moisture content of the grain at the upper 10% of the bin.

The Mittel-Otten simulation results of the control algorithm show that 5 to 31% of the energy can be saved compared with high-temperature drying, and 10 to 19% compared with uncontrolled low-temperature drying, depending on the weather conditions. The control algorithm was not tested on an actual low-temperature drying system.

3.3.7.2 Control of Continuous-Flow High-Temperature Grain Dryers

The first significant paper on the automatic control of continuous-flow grain dryers was co-authored by Zachariah and Isaacs (1966). Classical control theory was applied to a crossflow dryer. Three control systems were tested -- a proportional-integral-derivative (PID) system, a feedforward system with feedback trim, and an on-off feedback system; the drying process was modeled by Hukill (1954) deep-bed drying equation. Due to the unavailability of on-line computing and moisture measurement in the sixties, the Zachariah/Isaacs control system was simulated, but not implemented on commercial dryers.

Holtman and Zachariah (1969a) compared the Hukill drying model with limited experimental data, and with an empirical model in which the moisture content in the continuous-flow dryer is assumed to vary linearly with time. The linear model was recommended for dryer-control applications on the basis of accuracy and simplicity. In a later study, Holtman and Zachariah designed an optimal control system for a crossflow grain dryer using quadratic programming in conjunction with the linear drying model. The Holtman-Zachariah optimal control system could not be implemented due to the excessive on-line calculation requirements.

Borsum et al. (1982) utilized microprocessor-based technology for the automatic control of a concurrent-flow grain dryer. An inferential proportional-integral feedback control algorithm, based on the outlet air and the outlet grain temperatures, was experimentally tested.

Although acceptable control-accuracy was reached, the authors recommended development of a continuous moisture-content meter to be used in conjunction with a feedforward controller for control of the varying dead-times and reaction rates in commercial-scale dryers.

Schisler et al. (1982) investigated the optimal dryer-control strategy for concurrent-flow drying assuming the inlet grain moisture content and the outlet grain temperature are measured continuously. The control algorithm is based on the transient solution of the partial-differential-equation steady-state drying model. Lack of an inlet moisture-measuring device prevented implementation of the control system.

Forbes et al. (1984) first employed a continuous-flow moisture meter for the control of a commercial grain dryer. They compared two exponential-decay model-based feedforward controllers with a PID feedback controller and a lead/lag feedforward controller, using simulation. The first of the model-based controllers employed the inlet grain moisture content as the load variable, while the second utilized for this quantity the average of the moisture content of the inlet grain and of the grain presently in the dryer; the second controller best controlled the outlet grain moisture, and was subsequently tested successfully on a commercial scale.

Adaptive control was investigated for continuous-flow grain drying by Nybrant and Regner (1985) and by Nybrant (1986); they developed a microprocessor controller based on the dryer air-exhaust temperature. A linear-difference form of a time-discrete model constitutes the process model; it combines recursive least-square identification with minimum variance control law. The controller was implemented on a laboratory-scale crossflow wheat dryer. Nybrant and Regner suggested that a controller based on direct moisture measurements might lead to an improvement of the adaptive dryer control.

Marchant (1985) reviewed the state of continuous-flow dryer control, and concluded that proportional-integral (PI) controllers are unlikely to meet the control requirements of grain dryers. He conducted a simulation study of a model-based control algorithm containing an exponential drying equation of similar form as utilized by Forbes et al.(1984). No experimental data was presented by Marchant; he suggested intermittent measurement of the moisture content every five minutes if a continuous moisture meter was developed.

A partial-differential-equation steady-state simulation model of a grain dryer was adapted by Whitfield (1986) to predict the unsteady states resulting from varying inputs; the approach is similar to that of Schisler et al. (1982). The simulated data formed the basis for the choice of the parameters in a feedback PI controller. The non-linearities in the drying process are not taken into account in this controller-type; therefore, the PI controller is unstable under certain operating conditions.

In conclusion, it is clear that automatic control of grain dryers requires microcomputer process-control in conjunction with continuous or semi-continuous measurement of the controlled variable (i.e. grain moisture content). Because of the long (1-3 hours) dead-times and the frequent and large load upsets, feedforward controllers have innate advantages for continuous-flow grain dryers over proportional, PI and PID controllers. Feed-forward controllers require a model for the (i.e. moisture content) which calculates the correct control signal for the present input-load condition and set point A number of drying models (i.e. linear, exponential, adaptive) have been proposed but none has thus far proven to be superior for the control of continuous-flow grain dryers.

CHAPTER 4

4. THEORY

The theoretical part of this investigation is divided into two sections. In the first section, the modeling of the crossflow dryer during steady and unsteady state operation is discussed. In the second section, the design of the control system for crossflow dryers is considered.

4.1 Modeling of Crossflow Dryers

4.1.1 Introduction

Drying of agricultural products such as grain depends on the contact between the drying-air stream and the bed of grain kernels during which both heat and mass transfer take place. The heat transfers from the hot air to the cold grain, while the moisture is transferred from the grain to the air. Heat and mass balances are made to develop mathematical models to describe the drying process. The models are derived with certain assumptions to facilitate their development, solution and applications.

Equations 3.18-3.22 represent the simulation model for crossflow grain drying obtained from energy and mass balances. The model is a steady-state model; it used extensively in analyzing and designing crossflow grain dryers (Brooker et al., 1974). However, due to the steady-state nature of the model, it is not suitable for use in automatic control of crossflow grain dryers. Thus, an unsteady-state model for crossflow dryers needs to be developed. The development of this model is presented in the following section.

4.1.2 Development of Unsteady-State Grain Drying Equations

Unsteady-state energy and mass balances for air and grain are written on a differential volume located at an arbitrary position in the grain bed of a crossflow dryer. Figure 4.1 shows the control volume along with the air and grain as they enter and leave the control volume.

In developing the unsteady-state crossflow drying equations the following assumptions are made:

1. no appreciable volume shrinkage occurs during the drying process;
2. no temperature gradients exist within the grain particles;
3. particle to particle conduction is negligible;
4. air and grain flowrates are plug type;
5. dryer walls are adiabatic with negligible heat capacity;
6. the heat capacities of moist air and grain are constant;and
7. V_p is constant during a dt time step.

Assumption (1) is disputable since shrinkage occurs during drying. The shrinkage effect has been considered by Spencer(1972) in simulating wheat drying in a fixed-bed dryer; however, he did not indicate whether correction for shrinkage improves the simulation results.

The other assumptions have been shown to be valid for continuous-flow dryers (Bakker-Arkema et al., 1974).

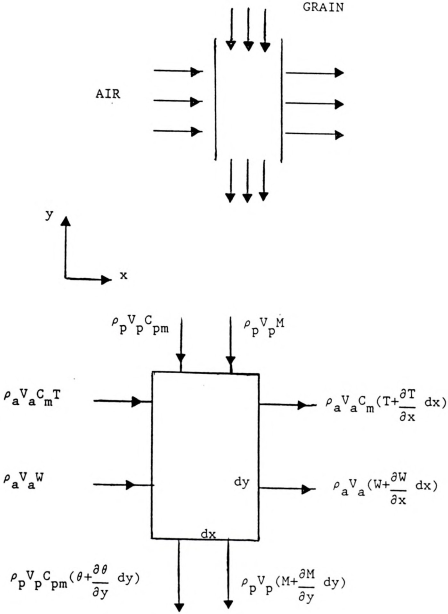


Figure 4.1 Mass and Energy Balances on a Control Volume Within a Crossflow Grain Dryer

4.1.2.1 Energy Balance-Air

energy in - energy out - energy transferred = energy accumulated

$$\rho_a V_a C_m \; T \; dydt - \rho_a V_a C_m \; (T + \frac{\partial T}{\partial x} dx) \; dydt - h \; a \; (T-\theta) \; dxdydt$$

$$= \epsilon \rho_a C_m \frac{\partial T}{\partial t} \; dx \; dydt$$

or,

$$\epsilon \rho_a C_m \frac{\partial T}{\partial t} = \rho_a V_a \; C_m \frac{\partial T}{\partial x} - h \; a \; (T-\theta)$$

or,

$$\frac{\partial T}{\partial t} = - \frac{V_a}{\epsilon} \frac{\partial T}{\partial x} - \frac{h \; a}{\epsilon \rho_a C_{am}} (T-\theta) \qquad (4.1)$$

$$\text{where } C_m = C_a + W \; C_v$$

4.1.2.2 Energy Balance-Product

energy in + energy transferred = energy out + energy to evaporate water + change in sensible heat of grain w.r.t. time + change in sensible heat of water vapor

$$\rho_p V_p \; C_{pm} \theta dxdt + h \; a(T-\theta)dxdydt = \rho_p V_p \; C_{pm}(\theta + \frac{\partial \theta}{\partial y} \; dy)dxdt + \; h_{fg}(- \; \rho_p \frac{\partial M}{\partial t}$$

$$dxdydt) + \rho_p C_{pm} \frac{\partial \theta}{\partial t} \; dxdydt + (C_v(T-\theta))(- \; \rho_p \frac{\partial M}{\partial t} \; dxdydt)$$

or,

$$h \; a \; (T-\theta) + (\rho_p C_v \; (T-\theta) + \rho_p h_{fg}) \frac{\partial M}{\partial t} - \rho_p V_p \; C_{pm} \frac{\partial \theta}{\partial y} = \rho_p C_{pm} \frac{\partial \theta}{\partial t}$$

$$\frac{\partial\theta}{\partial t} = \frac{h\ a}{\rho_p C_{pm}}(T-\theta) + \left(\frac{C_v(T-\theta)}{C_{pm}} + \frac{h_{fg}}{C_{pm}}\right)\frac{\partial M}{\partial t} - V_p\frac{\partial\theta}{\partial y} \qquad (4.2)$$

where $C_{pm} = C_p + C_w M$

4.1.2.3 Mass Balance-Air

water vapor in - water vapor out + change of water vapor in the air within the control volume = rate of water vapor evaporated from the grain

$$\rho_a V_a W\ dydt - \rho_a V_a\left(W + \frac{\partial W}{\partial x}\ dx\right)dydt + \epsilon\rho_a\frac{\partial W}{\partial t}\ dxdydt$$

$$= \frac{\partial M}{\partial t}\ dxdydt$$

$$\frac{\partial W}{\partial t} = \frac{V_a}{\epsilon}\frac{\partial W}{\partial x} + \frac{\rho_p}{\epsilon\rho_a}\frac{\partial M}{\partial t} \qquad (4.3)$$

4.1.2.4 Mass Balance-Product

water in solids in - water in solids out = change of MC of the solids in the control volume w.r.t. time

$$V_p\ M\ dxdt - \rho_p V_p\left(M + \frac{\partial M}{\partial y}\ dy\right)dxdt = \rho_p dxdydt\ \frac{\partial M}{\partial t}$$

or,

$$\frac{\partial M}{\partial t} = -V_p\frac{\partial M}{\partial y} \qquad (4.4)$$

4.1.3 Computation Procedure

The finite difference technique is used to solve equations 4.1 - 4.4 along with the empirical thin-layer equation for corn proposed by Thompson (1968), the DeBoer empirical equation for the equilibrium moisture content (Bakker-Arkema et al.,1974), and the SYCHART package for moist air properties given by Bakker-Arkema et al. (1974).

The following finite difference terms are substituted for the corresponding partial differential terms:

$$\frac{\partial T}{\partial x} = \frac{T_{x+\Delta x,y,t+\Delta t} - T_{x,y,t+\Delta t}}{\Delta x} \tag{4.5}$$

$$\frac{\partial T}{\partial t} = \frac{T_{x+\Delta x,y,t+\Delta t} - T_{x+\Delta x,y,t}}{\Delta t} \tag{4.6}$$

$$\frac{\partial \theta}{\partial y} = \frac{\theta_{x+1/2\Delta x,y+\Delta y,t} - \theta_{x+1/2\Delta x,y,t}}{\Delta y} \tag{4.7}$$

$$\frac{\partial \theta}{\partial t} = \frac{\theta_{x+1/2\Delta x,y,t+\Delta t} - \theta_{x+1/2\Delta x,y,t}}{\Delta t} \tag{4.8}$$

$$\frac{\partial M}{\partial t} = \frac{M_{x+1/2\Delta x,y,t+\Delta t} - M_{x+1/2\Delta x,y,t}}{\Delta t} \tag{4.9}$$

$$\frac{\partial M}{\partial y} = \frac{M_{x+1/2\Delta x,y+\Delta y,t} - M_{x+1/2\Delta x,y,t}}{\Delta y} \tag{4.10}$$

$$\frac{\partial W}{\partial x} = \frac{W_{x+\Delta x,y,t+\Delta t} - W_{x,y,t+\Delta t}}{\Delta x} \tag{4.11}$$

$$\frac{\partial W}{\partial t} = \frac{W_{x+\Delta x,y,t+\Delta t} - W_{x+\Delta x,y,t}}{\Delta t} \qquad (4.12)$$

Equations 4.5-4.12 are substituted into equations 4.1-4.4. Three equations are formed for three of the four unknowns, namely θ, W, and T:

$$\theta_{i,j,k+1} = (1-A_6)*\theta_{i,j,k} + A_3*THT/B3 - A_5*(C_v*THT+h_{fg})*(W_{i+1,j,k} - W_{i,j,k})/B3 + A_6*TP \qquad (4.13)$$

$$W_{i+1,j,k+1} = (W_{i+1,j,k} - A1*W_{i,j,k+1})/A_8 - A_4*(M_{i,j,k+1} - M_{i,j,k})/A_8 \qquad (4.14)$$

$$T_{i+1,j,k+1} = (T_{i+1,j,k} + A1*T_{i,j,k} + B1*\theta_{i,y,k+1})/B2 \qquad (4.15)$$

$M_{i,j,k+1}$ is calculated using the thin-layer equation evaluated at the following temperature, specific humidity, and relative humidity values:

$$\text{Temperature} = \frac{\theta_{i,j,k} + T_{i,y,k+1}}{2}$$

$$\text{Specific humidity} = \left(\frac{W_{i,j,k} + W_{i+1,j,k}}{2} + W_{i,j,k+1}\right)/2$$

Relative humidity = RH (Temperature, Specific humidity)

where,

the subscripts i,j,k are equivalent to x+1/2Δx,y,t for M and θ, and to x,y,t for T and W. Other subscripts should be interpreted accordingly.

Also,

$A1 = G_a * \Delta t / (\rho_a*\epsilon*\Delta x)$

$A2 = h * a * \Delta t / (\rho_a * \epsilon)$

$A3 = h * a * \Delta t / \rho_p$

$A4 = \rho_p / \epsilon * \rho_a$

$A5 = \rho_a * \Delta t / (\Delta x * \rho_p)$

$A6 = \rho_p * \Delta t / (\rho_p * \Delta y)$

$A7 = \rho_p / \rho_a$

$A_8 = 1 - A_1$

$B1 = A2 / (C_a + C_v * (W_{i,j,k+1} + W_{i+1,j,k})/2)$

$B2 = 1 + A1 + B1$

$B3 = C_p + C_w * M_{i,j,k}$

$THT = (T_{i,j,k} + T_{i+1,j,k}) / 2 - \theta_{i,j,k}$

$TP = (\theta_{i,j,k} + \theta_{i,j+1,k})/2$

The following calculation scheme is followed after the first time step and during which V_p is <u>assumed to be constant</u>:

1. increment dryer depth;
2. increment time;
3. calculate $\theta_{i,j+1,k+1}$ using equation (4.13);
4. calculate $M_{i,j+1,k+1}$ using the thin layer equation, (3.9);
5. calculate $W_{i+1,j+1,k+1}$ using equation (4.14);
6. calculate $T_{i+1,j+1,k+1}$ using equation (4.15);

7. increment x and repeat steps 3 through 6 until the air exit has been reached;

8. read the new value for V_p; and

9. go back to step 1 unless the total length of the dryer or grain exit has been reached.

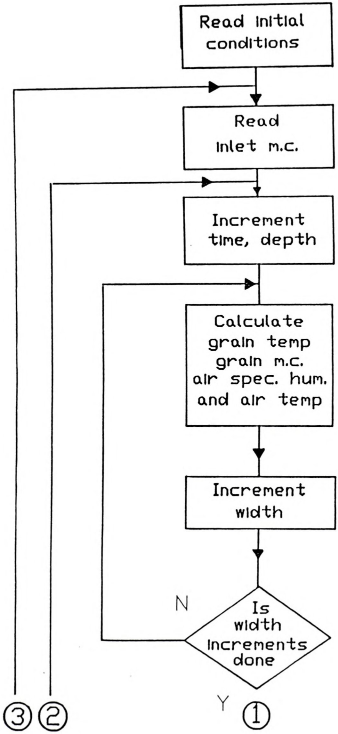
The above scheme along with the equations for the four unknowns are implemented in a computer program written in Fortran. Figure 4.2 shows the flow diagram of the computer program. The program simulates the unsteady state drying of a crossflow dryer and acts as the basis for the simulated portion of the automatic control of the crossflow dryer.

The values of Δx, Δt, and Δy along with the physical properties for air and corn are given in Table 4.1. The values for Δx and Δt are kept constant due to stability reasons. At $\Delta t = .006$ hrs (21.6 secs) the program is stable for all grain flow rates used during the simulation (i.e. 5.6 to 13.7 m/hr). The simulation program is not affected by a change in Δy (.034 to .082 m) due to changes in the grain flow rate.

The heat transfer coefficient is assumed to vary with the airflow rate only. Since the air flow rate is constant, the heat transfer coefficient is also constant. This may introduce an error due to the lack of information on how the heat transfer coefficient varies with grain flow rate.

The surface area of corn per unit volume of bed is assumed to be constant. In the development of the unsteady-state model one, of the assumptions is that no shrinkage occurs during drying. As discussed earlier, shrinkage does occur but is considered to be of minor influence.

The remaining properties (i.e. specific heat, density, etc) for air and grain may vary with temperature. It is assumed that the variations


Read initial conditions
Read inlet m.c.
Increment time, depth
Calculate grain temp grain m.c. air spec. hum. and air temp
Increment width
Is width increments done
N
Y
1
2
3

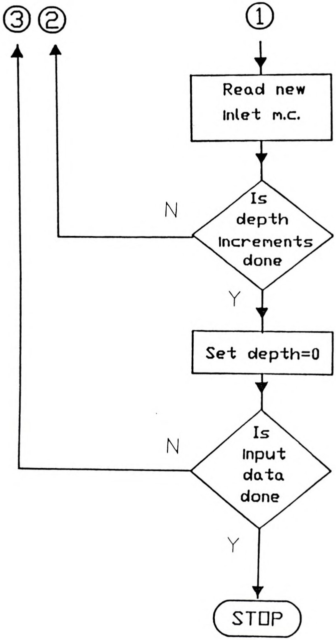


Figure 4.2 Flow Diagram of the Unsteady-State Computer Program.

are small and result in negligible errors in the simulation results.

A sample output of the unsteady-state simulation model is shown in Table 4.2. The Table shows the relationship between the inlet moisture content, the outlet moisture content, and the residence time.

4.2 Design of The Crossflow Dryer Control System

Commercial grain dryers are characterised by large dead-times and frequent inlet moisture content variations, especially at terminal grain elevators. This creates a difficulty in controlling dryers with regular feedback controllers, since dead-time represents an interval during which the control system has no information about the effect of a previously taken control action.

A better control system will be one that corrects for the variation in the grain inlet moisture content by measuring the load variable at the dryer inlet. Such a control system is known in the literature as a feedforward control (Badavas, 1984). A feedforward control strategy is used in this study for the control system of commercial crossflow dryers.

To design and implement a feedforward control system, three elements are needed; (1) a process model, (2) a dynamic compensation model, and (3) a feedback correction model (see Section 3.3.4). The three elements are investigated below with reference to the control of continuous-flow grain dryers.

4.2.1 Dryer (Process) Model

The partial differential equation model developed in Section 4.1 to model the crossflow dryer is accurate, but needs main-frame capability

Table 4.1 Δt, Δx, Δy, and physical properties of air and corn used in the unsteady-state simulation model.

Parameter	Units	Value
Δt	hr	.006
Δx	ft	.01
Δy	ft	.11 to .27
a	ft^{-1}	239
C_a	Btu/lb ^oF	.242
C_p	Btu/lb ^oF	.268
C_v	Btu/lb ^oF	.45
C_w	Btu/lb ^oF	1.0
h	Btu/ hr-ft^2-^oF	$.363*GA^{.59}$ for GA < 500 $.69*Ga^{.49}$ for Ga ≥ 500
h_{fg}	Btu/lb	1000 for M ≥ .17 $(1094-57\theta)[1+4.35\exp(-28.25M)]$ for M < .17
ρ_a	lb/ft^3	.075
ρ_p	lb/ft^3	38.7
ϵ	dimensionless	.45

Table 4.2 Simulated outlet moisture contents and residence times for different inlet moisture contents; model equations 4.1-4.4.

Inlet M.C (%,w.b.)	Outlet M.C. (%,w.b.)	Residence Time (hr)
20.00	11.34	1.13
20.00	11.74	1.06
20.00	12.42	0.95
20.00	13.27	0.83
20.00	14.04	0.72
20.00	14.35	0.68
22.00	12.03	1.28
22.00	12.36	1.22
23.00	10.78	1.64
23.00	13.84	1.12
23.00	14.04	1.09
23.00	14.53	1.02
23.00	15.05	0.95
23.00	15.44	0.89
23.00	15.85	0.84
24.00	18.18	0.67
24.00	18.03	0.68
24.00	17.49	0.75
24.00	16.91	0.82
24.00	16.49	0.88
25.00	12.52	1.60
25.00	14.19	1.33
25.00	18.49	0.74
25.00	18.40	0.76
25.00	18.10	0.79
26.00	13.62	1.55
26.00	14.69	1.38
27.00	18.90	0.93
27.00	18.47	0.98
27.00	18.05	1.04
27.00	17.72	1.08
27.00	17.36	1.13
28.00	15.71	1.49
30.00	16.49	1.64

Note: Grain Velocity 5.6 to 13.7 m/hr
Column Length 9.1 m (30 ft)
Dryer Width .305 m (1 ft)
Airflow Rate 24.4 m^3/m^2-mi¬ (80 CFM/ft^2)
Air Temperature 104.4 ^{o}C (220 ^{o}F)
Air Specific Humidity .0032
Initial Grain Temp. 4.4 ^{o}C (40 ^{o}F)

to be used for on-line calculation. Thus, a simple dryer model, accurate enough for control purposes, needs to be developed if a feed-forward dryer control system is to be used (Holtman and Zachariah, 1969a).

Two empirical dryer models have been proposed in the literature for the design of control systems for grain dryers:

an exponential model (Matthews, 1985)

$$\frac{M(t)}{M(0)} = \exp(-\beta_1 t) \qquad (4.16)$$

and a linear model (Holtman and Zachariah, 1969a)

$$\frac{M(t)}{M(0)} = \beta_2 + \beta_3 t \qquad (4.17)$$

The two empirical models compare well with the partial differential equation model for the crossflow dryer (see Section 6.2.2). The parameters in equations (4.16) and (4.17) are computed every time the grain outlet moisture content, grain inlet moisture content, and the unloading auger rpm are measured.

The value of β_1 in equation (4.16) is calculated using the following equation:

$$\beta_1 = (\ln \frac{M(0)}{M(t)})/t \qquad (4.18)$$

where,

t is the residence time of the grain exiting the dryer, hours; M(t) is the outlet moisture content, decimal (w.b.) corresponding to the inlet moisture content M(0) for the given residence time t.

The two parameters β_2 and β_3 in equation (4.17) can not be estimated directly, since only one set of measurements is available each time the two parameters have to be estimated. To estimate the two parameters with one set of data, a sequential least square estimation method is employed (Beck and Arnold, 1977):

$$A_1 = X_1P_{11} + X_2P_{12} \tag{4.19}$$

$$A_2 = X_1P_{12} + X_2P_{22} \tag{4.20}$$

$$\Delta = A_2X_2 + A_1X_1 + \sigma^2 \tag{4.21}$$

$$P_{11} = -\frac{A_1^2}{\Delta} + P_{11} \tag{4.22}$$

$$P_{12} = -\frac{A_1A_2}{\Delta} + P_{12} \tag{4.23}$$

$$P_{22} = -\frac{A_2^2}{\Delta} + P_{22} \tag{4.24}$$

$$\frac{e}{\Delta} = \frac{Y-X_1b_1-X_2b_2}{\Delta} \tag{4.25}$$

$$b_1 = A_1\frac{e}{\Delta} + b_1 \tag{4.26}$$

$$b_2 = A_2\frac{e}{\Delta} + b_2 \tag{4.27}$$

where, $X_1 = 1$

$X_2 = T$

$$Y = \frac{M(t)}{M(0)}$$

b_1 and b_2 are estimates of β_2 and β_3, respectively.

The initial conditions are

$b_1 = b_2 = 0.$

$P_{11} = P_{22} = 100000.$

$P_{12} = 0.$

$\sigma^2 = 1.$

Because of the inaccuracy in estimating b_1 and b_2 during the initial dryer start up, the parameters are not used in the dryer control decision until the estimates are converging.

4.2.2 Dynamic Compensation

Dynamic compensation is needed when dynamic imbalance exists in a system. Dynamic imbalance is the result of the different response of the controlled variable to changes in the manipulated variable compared to changes in the load variable. To improve the performance of the feedforward control system, a dynamic compensation is required.

In grain dryers, the dynamic imbalance is the result of the large dead-time which varies with the grainflow rate. When the manipulated variable (grainflow rate) is adjusted due to a major load change (i.e. the inlet moisture content), the adjustment affects the grain already in the dryer to a different degree based on how long a layer of grain has been in the dryer. To reduce the dynamic effect, a pseudo inlet moisture content is defined.

The pseudo inlet moisture content (M_{ps}) is defined as a weighted average of the moisture content of the inlet grain and the grain currently in the dryer (Olesen, 1976; Forbes et al., 1984). The weights are chosen such that the incoming grains and the grain at or near the top of the dryer, have a larger influence than the grain near or at the bottom of the dryer. The pseudo inlet moisture content is calculated from the following equation:

$$M_{ps} = b_1M(1) + b_2M(2) + \ldots\ldots + b_nM(n) \qquad (4.28)$$

where,

$$b_1 + b_2 + \ldots\ldots + b_n = 1.0$$

where n = the number of samples used in the calculation of the pseudo inlet moisture content, the subscript 1 = the present inlet moisture content, and the subscript n = the moisture content of the grain near the outlet of the dryer.

The value of n was chosen between 10-20 depending on the residence time, and thus the length of the drying column and flow rate of the grain.

Different values for b_1, b_2, ..., b_n were investigated in the calculation of the pseudo inlet moisture content; $b_1 = 1/(1+\sum_{i=2}^{n} 2/i)$ and $b_i = (2/i)/(1+\sum_{i=2}^{n} 2/i)$ were found to give a value for M_{ps} which results in excellent automatic control of a crossflow dryer.

4.2.3 Feedback Correction

A feedforward control system controls the dryer perfectly if the drying process is modeled correctly, and accurate measurements and computations are made. However, errors do occur due to inaccurate assumptions in the drying model, inaccuracies in the moisture content measurements, changes in the minor loads variables (grain test weight, wind effects, BCFM, etc.), and due to computation errors. The feedback correction corrects for feedforward model inaccuracies.

The feedback correction is achieved by incorporating the present value of the estimated parameters in the control decision for the next time interval. For the exponential model (see eqn. 4.16), an exponential smoothing is used to "correct" the parameter, β_1 (Montgomery and Johnson, 1976):

$$\beta_{1c}(n) = (1-A)*\beta_1 + A*\beta_{1c}(n-1) \qquad (4.29)$$

where,

$\beta_{1c}(n)$ = the parameter value used in the present control decision

$\beta_{1c}(n-1)$ = the parameter value used in the previous control decision

β_1 = the present estimated parameter value

A = the smoothing constant ($0 \leq A \leq 1$).

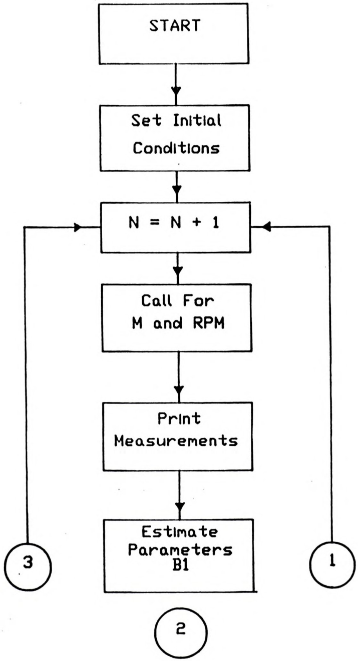
For the linear model, no filtering is necessary since sequential parameter estimation provides filtered estimates of the parameters (Beck and Arnold, 1977).

4.2.4 Crossflow Dryer Control Algorithm

The control system algorithm is a feedforward model-based type with feedback correction and dynamic compensation. The control algorithm for the crossflow dryer is shown in Figure 4.3. The flow chart is drawn for the exponential model, and is equally valid for the linear model.

The calculation scheme for the control algorithm (Figure 4.3) is as follow:

1. initial conditions (rpm, set point, inlet MC) are set;
2. Inlet and outlet moisture contents of grain and unload auger rpm are measured;
3. β_1 is estimated by equation (4.18)and used to calculate β_{1c}(equation 4.29);
4. the pseudo inlet MC is calculated using equation (4.28);
5. the required residence time is calculated using M_{ps} and β_{1c};
6. the residence time is converted to its equivalent voltage and send to the SCR ; and
7. go back to step 2.


START
Set Initial Conditions
N = N + 1
Call For M and RPM
Print Measurements
Estimate Parameters B1
3
1
2

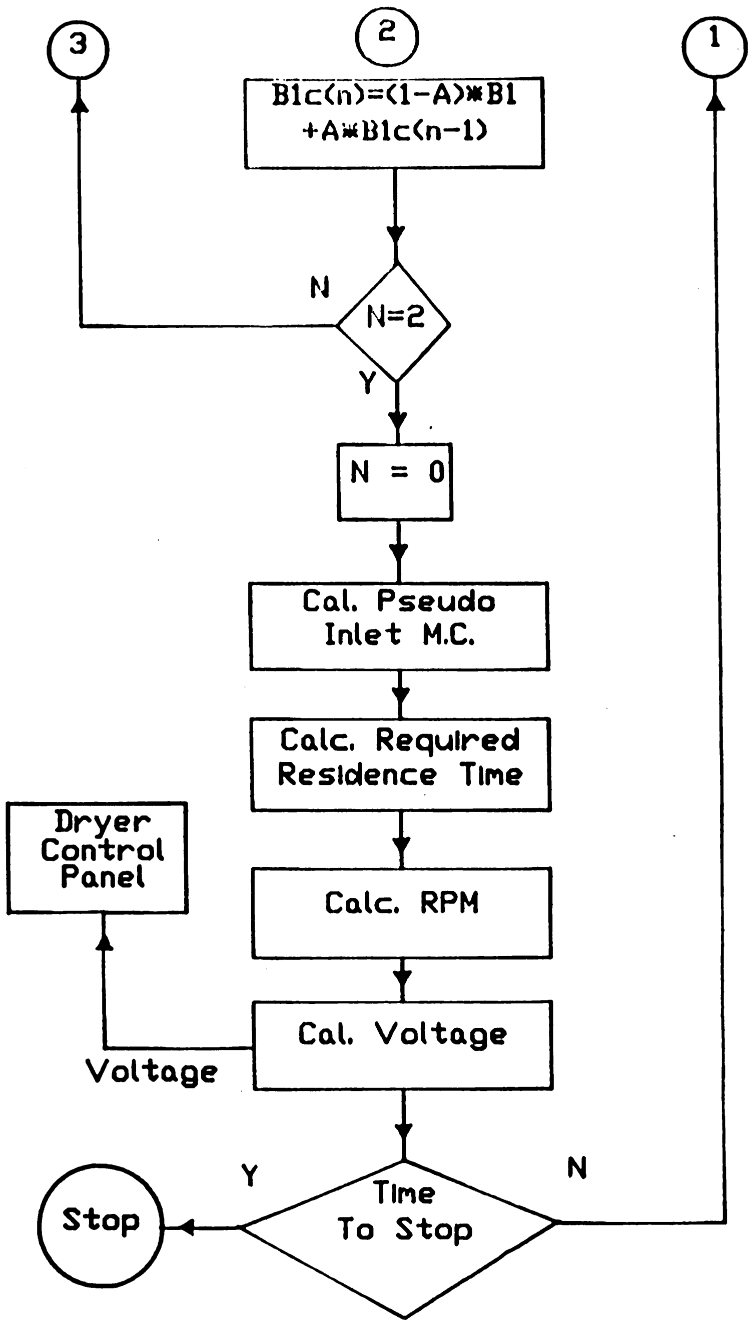


Figure 4.3 Control Algorithm for Crossflow Grain Dryers.

CHAPTER 5

5. EXPERIMENTAL INVESTIGATION

5.1 Equipment

The crossflow dryer control system was implemented on two commercial crossflow dryers manufactured by Meyer-Morton, Inc.(P.O. Box 352 Morton, Illinois 61550) and Zimmerman, Inc.(P.O. Box 331, Litchfield, Illinois 62056).

A schematic of the Meyer-Morton 850 dryer is shown in Figure 5.1. The dryer specifications are listed in Table 5.1 (Anderson, 1985). The heating section is 27.5 feet in length, the cooling section is 11.5 feet. The grain column thickness is 10 inches at the upper and 12 inches in the lower part of the dryer. The dryer is modified to incorporate a heat recovery enclosure for air recycling. Air to the heater is a combination of ambient air and recycled air. The recycled air is a mixture of air exhausted from the cooler and part of the air exhausted from the drying section. The rated capacity is 1400 bushels of wet corn per hour at 5 point moisture removal.

The Zimmerman ATP 5000 dryer is shown schematically in Figure 5.2. The dryer specifications are listed in Table 5.2 (Anderson, 1985). The length of the of the heating section is 66.8 feet, of the cooling section 18.5 ft. The column thickness is 12 inches over the entire dryer length. A grain exchanger is located at the mid-point in the heating section; it splits the grain column to allow grain inside of the column to be moved to the outside of the column, and vice versa. The air flow in the cooling section is reversed compared to that in the heating section. Air from the cooling section is mixed with the ambient air before introduction to the burners. The rated capacity is 5000 bushels of wet corn per hour at 5 point moisture removal.

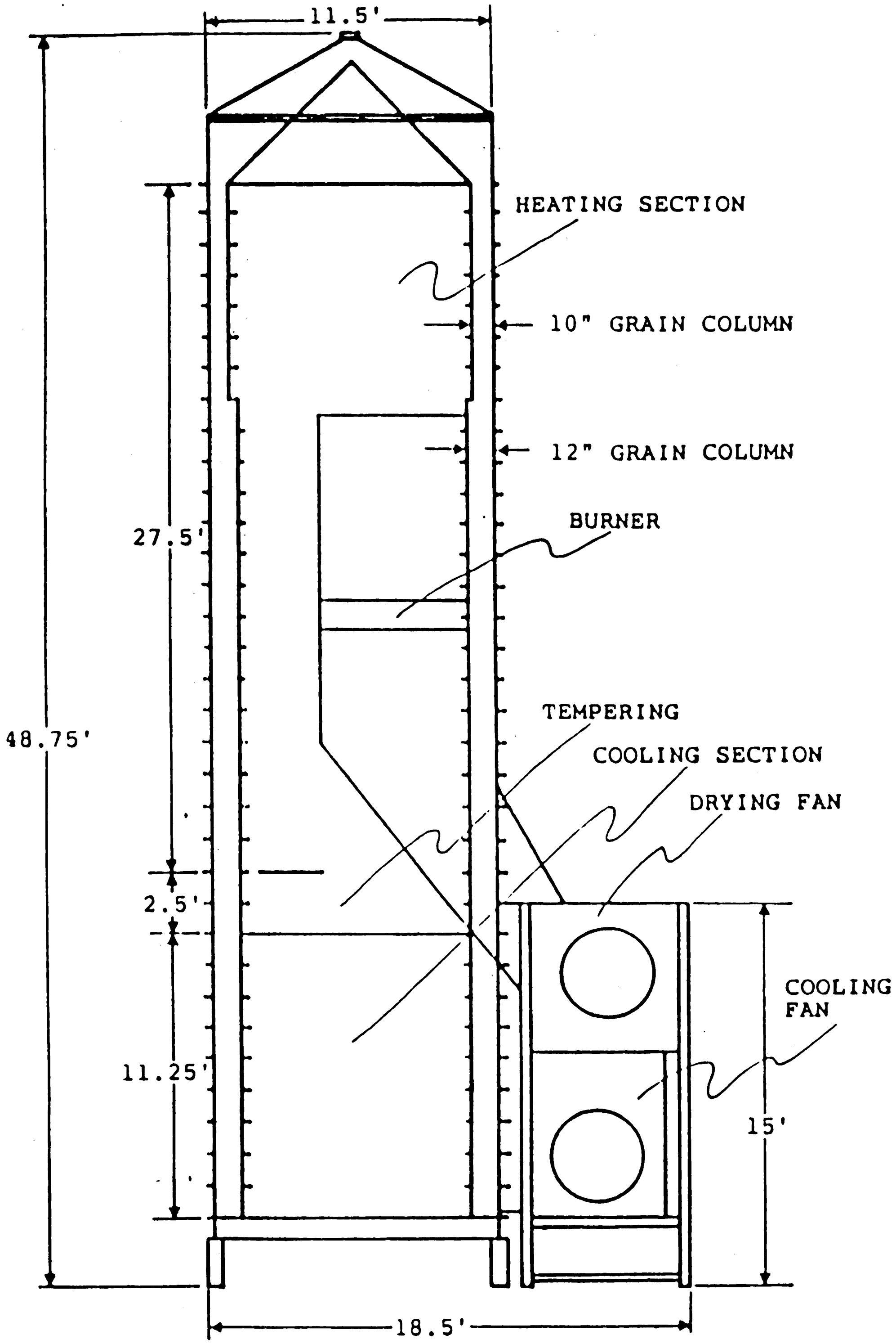


Figure 5.1 Schematic Of The Meyer-Morton 850 Dryer.

Table 5.1 Dryer specifications for the Meyer-Morton 850 crossflow dryer.

Airflow heat section, cfm/bu	122
Airflow cooling section, cfm/bu	142
Airflow heat section, cfm/ft^2	102
Airflow cooling section, cfm/ft^2	126
Static pressure heat section, in. of WC	3.0
Static pressure cooling section, in. of WC	3.0
Column cross sectional area, ft^2	33
Column widths, in.	10 & 12
Grainflow, ft/hr at 5 point moisture removal	65.5
Recommended drying temperature, deg. F	230
Rated capacity at 20% - 15% MC, bu/hr	1400
Retention time at rated capacity, hr	0.63
Burner capacity, million of Btu/hr	8.7
Fuel type	LP

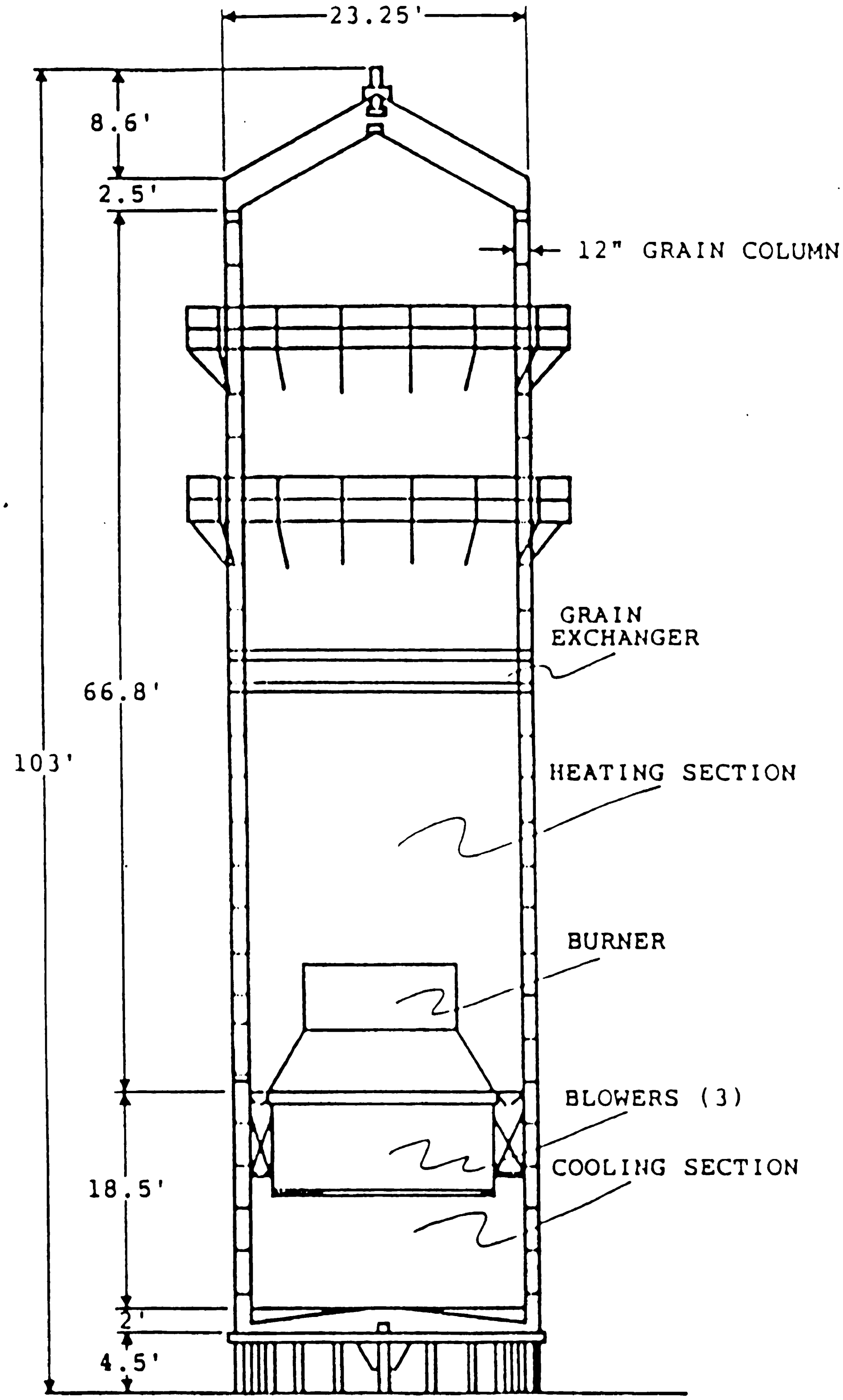


Figure 5.2 Schematic of the Zimmerman ATP 5000 Dryer.

Table 5.2 Dryer specification for the Zimmerman ATP 5000 crossflow dryer.

Airflow heat section, cfm/bu	69
Airflow cooling section, cfm/bu	132
Airflow heat section, cfm/ft^2	61
Airflow cooling section, cfm/ft^2	111
Static pressure heat section, in. of WC	1.5
Static pressure cooling section, in. of WC	1.5
Column cross sectional area, ft^2	70.1
Column width, in.	12
Grainflow, ft/hr at 5 point moisture removal	85.3
Recommended drying temperature, degree F	180
Rated capacity at 20%-15% MC, bu/hr	5000
Retention time at rated capacity, hr	1
Burner capacity, million of Btu/hr	54.2
Fuel type	Natural Gas

5.2 Instrumentation and Control System Implementation

Figure 5.3 is a schematic of the control system for a continuous crossflow dryer. The system consists of: (1) a microcomputer, (2) a tachometer, (3) an automatic moisture meter, (4) A/D and D/A converters, (5) SCR (Silicon Controlled Rectifier) for unload auger motor control, (6) system software (i.e. Basic), and (7) applications software (i.e. data collection and control algorithm).

An Apple IIe microcomputer with 128 K RAM and floating point Basic language in read-only memory (ROM) constitutes the heart of the system. Operating data is displayed on a 12 inch screen for operator checking. A hard copy of the collected data is provided on an Epson dot-matrix printer.

An AD/DA interface card is used in conjunction with the Apple. It enables the control and collecting of data from instruments that accept voltage as input or send voltage as output. The card contains a 12 bit analog to digital (A/D) converter and digital to analog (D/A) converter with an overall accuracy of 0.1%. The A/D and D/A converters can send or accept a voltage up to 4 volts. The specifications for the data acquisition system components are listed in Appendix C.

An incremental optical encoder measures the unload auger rpm. The encoder outputs 500 cycles per revolution, and is powered by 5 volts supplied by the Apple microcomputer. The rpm is calculated by counting the number of cycles within a specified period of time, and then dividing the total number of cycles by 500 and by the specified period in minutes.

A semi-continuous moisture meter, developed by Shivvers, Inc(P.O. Box 467, Corydon, Iowa 50060) automatically measures the inlet and

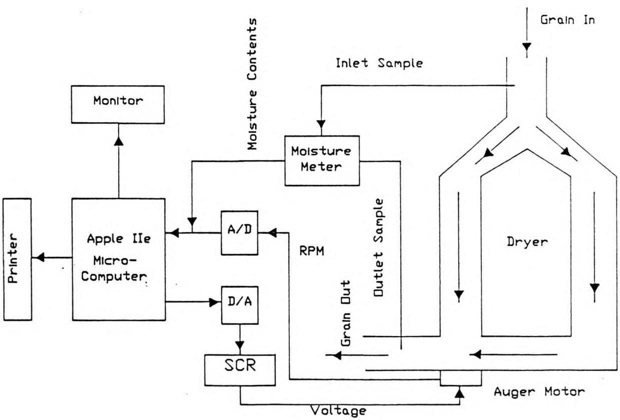


Figure 5.3 Schematic of the Control System for a Crossflow Dryer.

outlet grain moisture contents every 5-10 minutes. A microprocessor built into the moisture meter collects the moisture content data, and periodically transfers the information to the Apple.

The moisture meter is calibrated with the use of a standard moisture meter. The calibration adjustment value is stored in the moisture meter microprocessor memory for adjustment of each moisture content measurement.

Figure 5.4 shows a comparison between MC values obtained with the Shivvers's moisture meter (COMP-U-DRY), a Motomco moisture meter, and an air-oven during a control test. Note that the Shivvers's moisture meter was calibrated using Motomco as the standard meter. The results show good agreement between the Motomco and Shivvers meters. The oven values slightly differ from the other two. The average outlet moisture content was 15.06% with a SD (standard deviation) of .67, 14.31 with a SD of .36, and 16.07 with a SD of .94, as measured by the Shivvers, Motomco, and oven methods, respectively.

The variation in corn inlet moisture content as measured by the two moisture meters and air-oven is shown in Figure 5.5. Again the Motomco and COMP-U-DRY meters show good agreement but are 2-3 points lower than the value obtained with the oven method. The average corn inlet moisture content as measured by the three meters, COMP-U-DRY, Motomco, and oven, are, 21.08% with a SD of .37, 21.53 with a SD of .36, and 23.88 with a SD -.2, respectively. The error in measuring the inlet moisture content is not as serious as the error in measuring the outlet moisture content because of the ability of the controller to account for the error through the dryer model parameter(s).

The fact that the Shivvers moisture meter can be calibrated with an off-line moisture meter makes it attractive as an on-line moisture meter. Also, the sampling technique used in the moisture meter

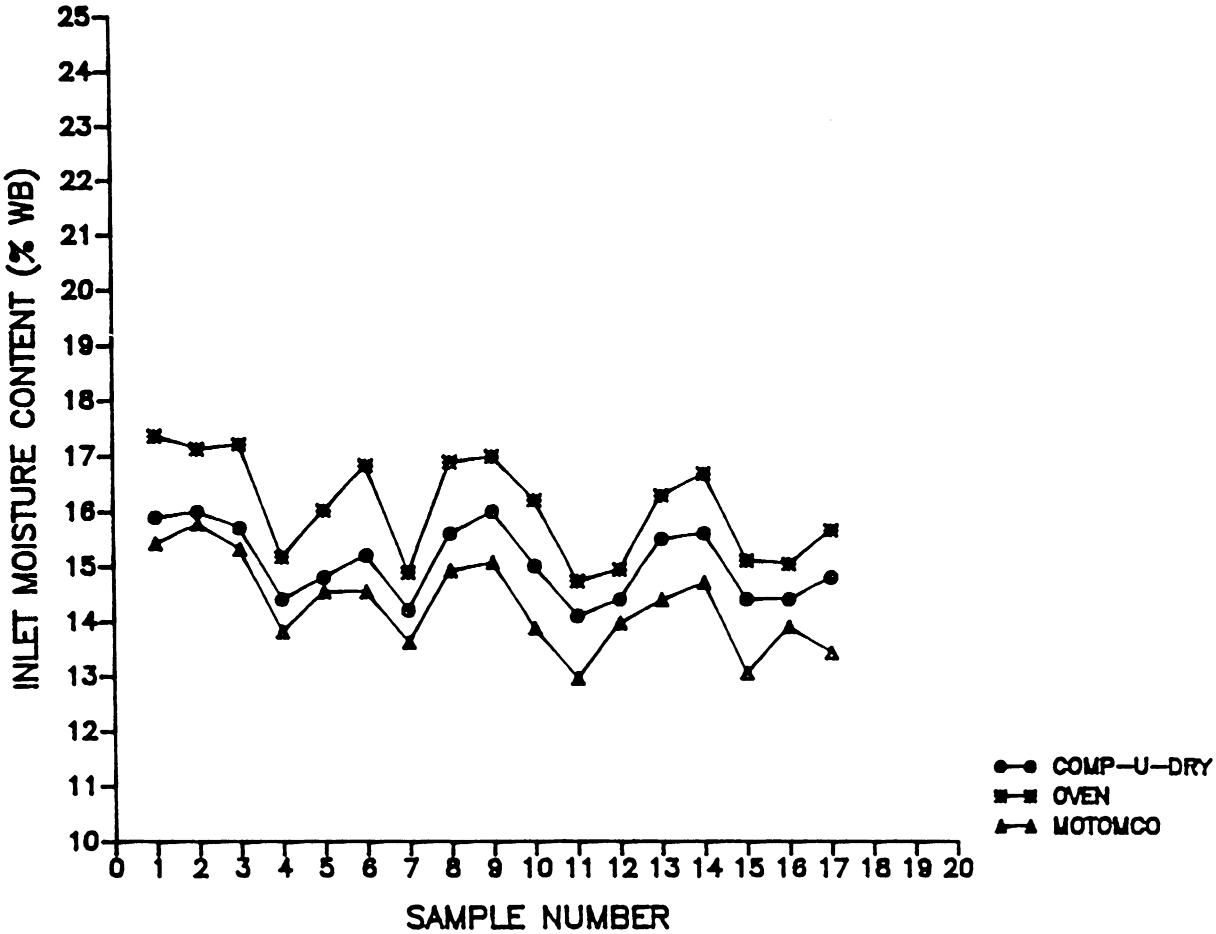


Figure 5.4 Corn Outlet Moisture Content Comparison (Oven, COMP-U-DRY, Motomco).

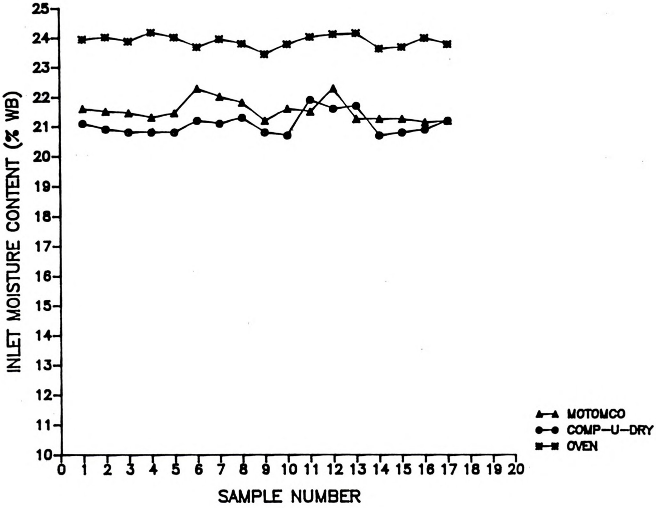


Figure 5.5 Corn Inlet Moisture Content Comparison (Oven, COMP-U-DRY, Motomco).

enhances the calibration process, since the same sample will be measured by both meters.

The following parameters are measured and are used in the crossflow dryer control system: (1) the grain inlet moisture content; (2) the grain outlet moisture content; and (3) the unloading-auger rpm. The inlet and outlet moisture contents and the rpm are transferred through a shielded cable to the Apple microcomputer.

The controller model determines the required residence time for the grain using one of the following two equations:

$$T = \left(\ln \frac{M_{ps}}{W_{set}}\right) / \beta_{1c} \qquad (5.1)$$

or,

$$T = \left(\frac{M_{ps}}{W_{set}} - \beta_2\right) / \beta_3 \qquad (5.2)$$

M_{ps} is given by equation (4.28), β_{1c} by equation (4.29), β_2 by equation (4.26), and β_3 by equation (4.27).

The residence time of the grain in the dryer is achieved by sending a voltage, corresponding to the specific residence time, to the unload auger. The non-linear relationship between the auger rpm and the residence time varies with dryer design. The relationships between the residence time and the auger rpm, the auger rpm and SCR voltage for the Meyer-Morton 850 dryer were found experimentally and are given by equations 5.3-5.5, respectively:

$$\text{Residence time} = 16.8 - 2.3 \log(\text{RPM}) \qquad (5.3)$$

$$\text{RPM} = 1524.5 \exp(-.4343\ \text{Residence time}) \qquad (5.4)$$

$$\text{Voltage} = .565 + .002543\ (\text{RPM}) \qquad (5.5)$$

The relationships between the residence time and the auger rpm, the auger rpm and SCR voltage for the Zimmerman ATP 5000 dryer are:

$$\text{Residence time} = 1063*(\text{RPM})**(-.917) \tag{5.6}$$

$$\text{RPM} = 2085*(\text{Residence time})**(-1.0954) \tag{5.7}$$

$$\text{Voltage} = .0058*(\text{RPM})**(.8818) \tag{5.8}$$

The voltage to be send to the SCR is converted to its digital equivalent by equation (5.9), and then input to the D/A converter which sends it to the SCR in the dryer control panel. The SCR then adjusts the auger rpm accordingly:

$$V = \text{Volt} * (2047) / 4 \tag{5.9}$$

where,

Volt = analog voltage

V = digital equivalent of Volt.

5.3 Procedure

The following procedure was followed in conducting the controller tests performed on each of the two crossflow dryers:

1. the dryer is manually started with a constant rpm for a period of time equal to the residence time equivalent to the initial rpm. During this period moisture content and rpm data is continuously transferred to the Apple computer to be used by the control system during the subsequent automatic control;

2. after the start-up period has ended, the control system is switched to automatic;

3. at the end of each test the data is analyzed.

CHAPTER 6

6. RESULTS AND DISCUSSION

The simulation and experimental results of this study on "Automatic Control of Crossflow Grain Dryers" are presented and analyzed in this chapter. First, the unsteady state differential equation model for crossflow grain drying is validated. This treatise is followed by the verification of the two empirical process models. Subsequently, the experimental data obtained from two commercial crossflow dryers, each equipped with the new automatic controller, are presented. Finally, several forms of a performance index for evaluating the dryer control system are analyzed. The chapter closes with a section highlighting the main results of this study.

6.1 Simulation

The unsteady state differential-equation crossflow dryer model and the crossflow dryer control algorithm have been combined to form the simulation model for the control system of a crossflow dryer. The grain outlet moisture content and the unload auger rpm as functions of time are the outputs of the automatic crossflow dryer simulation model.

The computer program is implemented on a VAX/VMS minicomputer system. The computer program uses excessive CPU time. Table 6.1 shows the CPU time used for different amounts of moisture removed and set points. The CPU time increases with an increase in the amount of moisture to be removed. The CPU time is longer than the drying time for all the inlet moisture content ranges used in the control system simulation model.

Table 6.1 CPU time for different amounts of moisture removed and set points.

Amount of Moisture Removed (%, w.b.)	Set Point (%, w.b.)	CPU Time hrs	Simulated Drying Time hrs
2.54	14.5	11.67	8.00
4.70	14.5	17.40	8.00
7.20	14.0	21.40	7.73
8.00	15.5	23.13	11.18

Note: type of dryer is a Meyer-Morton (see Section 5.1); for Δx, Δy, Δt, etc. see Table 4.1.

6.1.1 Unsteady-State Model Verification

To check the accuracy of the differential equation simulation model, two data sets obtained from tests #1 and #7 in the Meyer-Morton 850 dryer were used as input into the simulation model. The simulation results of the two tests are shown in Tables B.1 and B.2 in Appendix B. Test #1 represents a moderate variation in corn inlet moisture content while test #7 represents a large variation. The comparisons between simulation and the experimental results are shown in Figures 6.1 through 6.4.

Figure 6.1 shows a plot of experimental versus simulated outlet moisture contents for test #1; the simulated results agree well with the experimental values. Theoretically, if the simulated values perfectly match the experimental values, a 45^{o} angle is formed by the

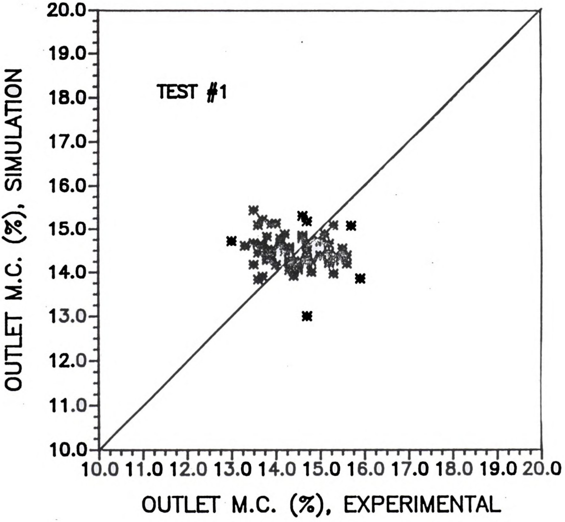


Figure 6.1 Simulation vs Experimental for Test #1 with the Meyer-Morton Dryer; differential-equation model used.

line connecting the data points and the x-axis. Furthermore, since the dryer is automatically controlled, the data points should converge to one point, the set point. The simulated results of test #1 have the above characteristics which proves the ability of the differential-equation simulation model to simulate the dryer control system close to its actual performance. This is also shown in Table 6.2 in which the means of the simulated and experimental outlet moisture contents are tested statistically for equality. The test results show that the two means are equal and that the deviations are the result of random error. A plot of the differences between experimental and simulated outlet moisture content values versus time is shown in Figure 6.2. The differences are randomly scattered between ± 2.5%; most of the data points show a difference of less than 1% point compared to the theoretical value. The simulation model predicts an average outlet moisture content of 14.49% with a standard deviation of .38%; experimentally, values of 14.44% and of 0.63% were obtained.

Figure 6.3 shows the simulated versus the experimental outlet moisture contents for experiment #7. The simulated points were calculated using the differential-equation crossflow drying model. The data points are not as close to the theoretical line as for experiment #1. One reason is the larger variation in the inlet moisture content in experiment #7 than in experiment #1. In an actual dryer, some mixing takes place which reduces the variability between adjacent layers of corn at the dryer exit. In the case of the simulation model, the layers are accurately tracked until they exit from the dryer (i.e. no mixing is assumed to take place in the dryer control simulation).

Figure 6.4 shows a plot of the differences between the experimental and simulated outlet moisture contents as a function of time for test

Table 6.2 Testing the hypothesis with the Student t-test that the mean of the experimental and simulated grain outlet moisture contents for test #1 are equal.

---

1. Ho : $\mu_1 = \mu_2$ or $\mu_1 - \mu_2 = 0$

2. H1 : $\mu_1 \neq \mu_2$ or $\mu_1 - \mu_2 \neq 0$

3. α = .1, .2, .4

4. Critical regions:

   a) T < -1.658 and T > 1.658

   b) T < -1.289 and T > 1.289

   c) T < -.845 and T > .845, where

$$T = \frac{(x_1 - x_2) - d_o}{S_p \surd (1/n1 + 1/n2)}$$

with ν = n1 + n2 - 2 = 81 + 81 - 2 = 160

5. Computations : x_1 = 14.44%, s_1 = .63%, n1 = 81 and

   x_2 = 14.49%, s_2 = .38%, n2 = 81

hence $S_p = \surd(.63^2(80)+.38^2(80))/(81+81-2) = .271$

$t = ((14.44-14.49)-0)/(.271\surd(1/81+1/81) = -.612$

6. Conclusion : Accept Ho and conclude that the means of the two sets are equal.

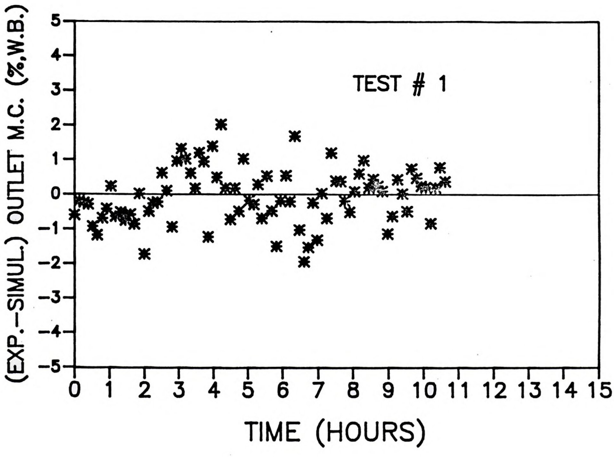


Figure 6.2 The Difference between Experimental and Simulated Grain Outlet Moisture Content vs Time for Test #1.

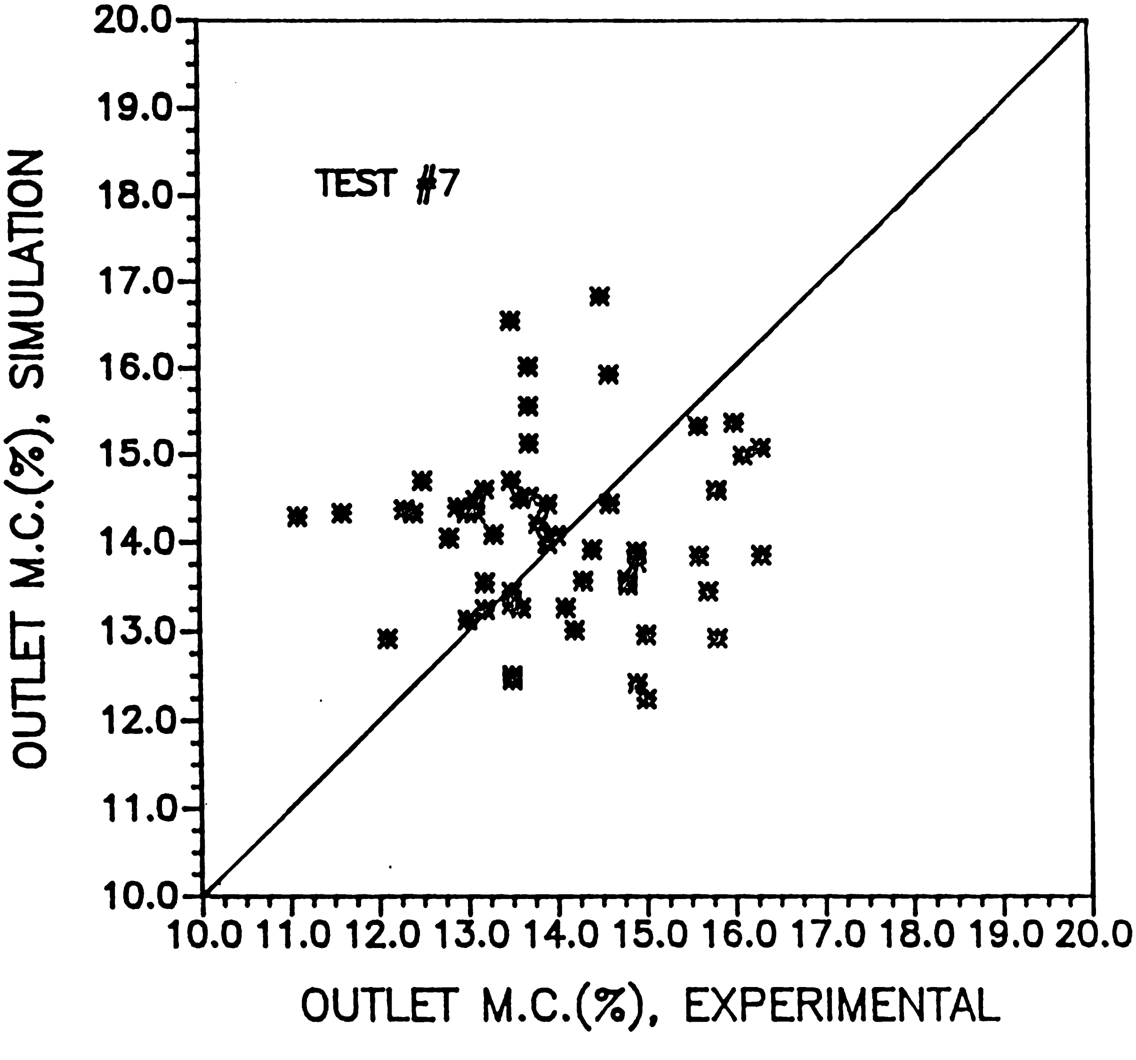


Figure 6.3 Simulation vs Experimental for Test #7; the Differential-Model was Used for the Simulation.

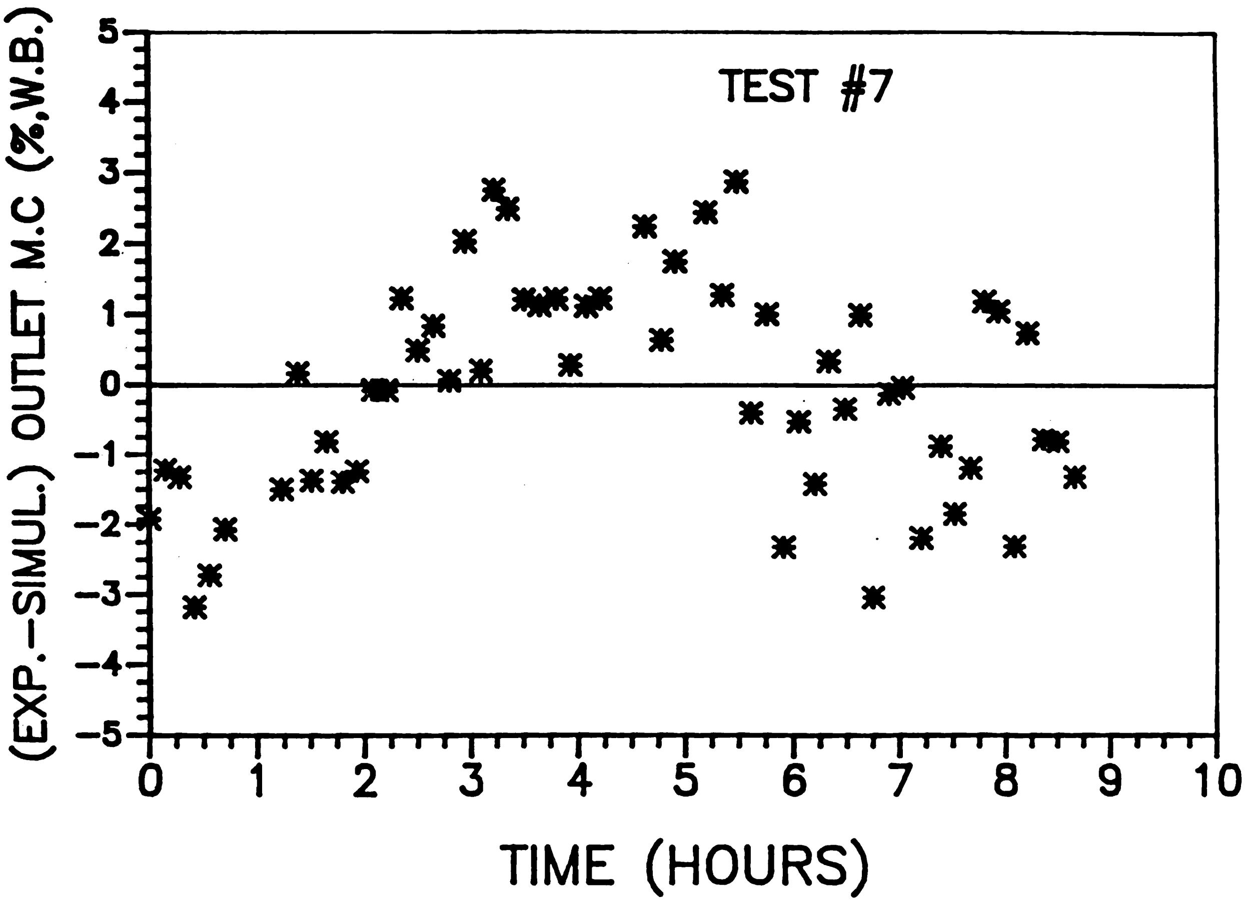


Figure 6.4 The Difference between Experimental and Simulated Grain Outlet Moisture Content vs Time for Test #7.

#7. The differences are not randomly scattered but are negative for about two hours time, then become positive for four hours, and finally become negative again for three hours. The trend is similar to the inlet moisture content variation in test #7. This supports the argument that the inlet moisture content affects the accuracy of the simulation. Thus, a comparison of individual data points is not a good measure of how well the simulated and experimental results compare to each other when large variations in the inlet moisture content occur. A more objective measure is to compare the average outlet moisture content and the standard deviation. Assuming that the simulated and experimental outlet moisture contents are normally distributed with equal variances, the hypothesis to be tested is that the two sets of data have the same mean outlet moisture content. The Student's t test along with the average and SD of the outlet moisture content of the two data sets are used in testing the above hypothesis. Table 6.3 shows the calculations and the results of the test. There is no significant difference in the mean of the two tests at .1, .2, and .4 level of significance. Thus, the differential-equation simulation model accurately predicts the average outlet moisture content obtained experimentally, and any deviation within the data is the result of randomness. It can thus be concluded that the simulation model for crossflow dryers is acceptable for analyzing the effect of a load variable such as the inlet moisture content variation on the performance of the dryer control system.

6.1.2 Empirical Model Verifications

Next,the unsteady state differential-equations model for crossflow drying developed in Section 4.1 was used to test the adequacy of the empirical models in describing the drying process of crossflow dryers. The outlet moisture content and residence time for a given inlet moisture content generated by the unsteady state model were used in estimating the model parameters in the empirical equations discussed in Chapter 4 (eqns 4.16 and 4.17). Tables 6.4 and 6.5 show the values of the estimated parameters along with the estimates of the grain outlet moisture contents.

6.1.2.1 Exponential

Figure 6.5 shows a plot of outlet moisture content predicted by the exponential model and the unsteady-state differential-equation model. The values of the exponential model parameter vary with the inlet and outlet moisture contents, and residence time. The values of β_1 (Table 6.4) decrease steadily with the increase in the inlet moisture content which suggest that β_1 has some correlation with the inlet moisture content. An average value = 0.42 is used for β_1 when the exponential model is used to predict the outlet moisture content. The outlet moisture contents predicted by the exponential equation agree well with the unsteady-state model. A plot of the exponential model outlet moisture content vs the unsteady-state model outlet moisture content (Figure 6.6) proves the good agreement of the two models. This should be expected since drying can be considered as a chemical reaction process, and thus can be described by an exponential relationship (Berglund, 1987).

6.1.2.2 Linear

Figure 6.7 shows the outlet moisture contents predicted by the linear model and unsteady-state differential-equation. The parameters used in the calculation are the average values for the parameters estimates excluding the first eight values (see Table 6.5). The first eight values of the linear model parameters vary widely due to the nature of the sequential least square estimation method at the early stages of the estimation, and thus are excluded from the calculation.

Table 6.3 Testing the hypothesis with the Student t-test that the mean of the experimental and simulated grain outlet moisture contents for test #7 are equal.

---

1. Ho : $\mu_1 = \mu_2$ or $\mu_1 - \mu_2 = 0$

2. H1 : $\mu_1 \neq \mu_2$ or $\mu_1 - \mu_2 \neq 0$

3. $\alpha = .1, .2, .4$

4. Critical regions:

   a) T < -1.658 and T > 1.658

   b) T < -1.289 and T > 1.289

   c) T < -.845 and T > .845, where

$$T = \frac{(x_1 - x_2) - d_o}{S_p \surd(1/n1 + 1/n2)}$$

with $\nu = n1 + n2 - 2 = 55 + 55 - 2 = 110$

5. Computations : $x_1 = 14.03\%$, $s_1 = 1.2\%$, $n1 = 56$ and

   $x_2 = 14.13\%$, $s_2 = .98\%$, $n2 = 56$

   hence $S_p = \surd(1.2^2(55)+.98^2(55))/(56+56-2) = 1.1$

   $t = ((14.03-14.13)-0)/(1.1\surd(1/56+1/56) = -.48$

6. Conclusion : Accept Ho and conclude that the means of the two sets are equal.

Table 6.4 Parameter estimates for the exponential model (eqn. 4.16 using data simulated by the unsteady state model (see Table 4.2) in drying shelled corn.

Inlet M.C. (%,w.b.)	Outlet M.C. (%,w.b.)	Residence Time (hrs.)	β_1 (1/hrs)	Est. Outlet M.C. (%,w.b.)
20.0	11.3	1.13	0.50	12.5
20.0	11.7	1.06	0.50	12.8
20.0	12.4	0.95	0.50	13.4
20.0	13.3	0.83	0.49	14.1
20.0	14.0	0.72	0.49	14.8
20.0	14.4	0.68	0.49	15.0
22.0	12.0	1.28	0.47	12.9
22.0	12.4	1.22	0.47	13.2
23.0	10.8	1.64	0.46	11.6
23.0	13.8	1.12	0.45	14.4
23.0	14.0	1.09	0.45	14.6
23.0	14.5	1.02	0.45	15.0
23.0	15.1	0.95	0.45	15.4
23.0	15.4	0.89	0.45	15.8
23.0	15.9	0.84	0.44	16.2
24.0	18.2	0.67	0.41	18.1
24.0	18.0	0.68	0.42	18.0
24.0	17.5	0.75	0.42	17.5
24.0	16.9	0.82	0.43	17.0
24.0	16.5	0.88	0.43	16.6
25.0	12.5	1.60	0.43	12.8
25.0	14.2	1.33	0.43	14.3
25.0	18.6	0.73	0.40	18.4
25.0	18.5	0.74	0.41	18.3
25.0	18.4	0.76	0.40	18.2
25.0	18.1	0.79	0.41	17.9
26.0	13.6	1.55	0.42	13.6
26.0	14.7	1.38	0.41	14.6
27.0	18.9	0.93	0.38	18.3
27.0	18.5	0.98	0.39	17.9
27.0	18.1	1.04	0.39	17.5
27.0	17.7	1.08	0.39	17.2
27.0	17.4	1.13	0.39	16.8
28.0	15.7	1.49	0.39	15.0
30.0	16.5	1.64	0.36	15.1
Average			0.42	

Table 6.5 Parameter estimates for the linear model (eqn. 4.17) using data simulated by the unsteady state model (see Table 4.2).

Inlet M.C. (%,w.b.)	Outlet M.C. (%,w.b.)	Residence Time (hrs)	β_2	β_3 (1/hrs)	Est. Outlet M.C. (%,w.b.)
20.0	11.3	1.13	0.25	0.28	12.6
20.0	11.7	1.06	0.89	-0.29	13.0
20.0	12.4	0.95	0.92	-0.31	13.6
20.0	13.3	0.83	0.96	-0.35	14.2
20.0	14.0	0.72	0.96	-0.35	14.8
20.0	14.4	0.68	0.98	-0.39	15.1
22.0	12.0	1.28	0.91	-0.28	12.9
22.0	12.4	1.22	0.87	-0.25	13.3
23.0	10.8	1.64	0.83	-0.22	11.3
23.0	13.8	1.12	0.88	-0.25	14.5
23.0	14.0	1.09	0.89	-0.25	14.7
23.0	14.5	1.02	0.89	-0.26	15.2
23.0	15.1	0.95	0.91	-0.26	15.6
23.0	15.4	0.89	0.91	-0.27	16.0
23.0	15.9	0.84	0.92	-0.27	16.3
24.0	18.2	0.67	0.95	-0.29	18.1
24.0	18.0	0.68	0.95	-0.29	18.1
24.0	17.5	0.75	0.94	-0.29	17.6
24.0	16.9	0.82	0.94	-0.28	17.2
24.0	16.5	0.88	0.94	-0.28	16.8
25.0	12.5	1.60	0.94	-0.27	12.5
25.0	14.2	1.33	0.92	-0.26	14.4
25.0	18.6	0.73	0.95	-0.28	18.5
25.0	18.5	0.74	0.95	-0.28	18.4
25.0	18.4	0.76	0.95	-0.28	18.3
25.0	18.1	0.79	0.94	-0.28	18.1
26.0	13.6	1.55	0.96	-0.28	13.4
26.0	14.7	1.38	0.94	-0.27	14.6
27.0	18.9	0.93	0.97	-0.29	18.5
27.0	18.5	0.98	0.96	-0.29	18.1
27.0	18.1	1.04	0.97	-0.29	17.7
27.0	17.7	1.08	0.97	-0.29	17.4
27.0	17.4	1.13	0.97	-0.29	17.0
28.0	15.7	1.49	1.01	-0.31	14.9
30.0	16.5	1.64	1.00	-0.27	14.7
Average*			0.94	-0.28	

* Note: average does not include the first 8 values.

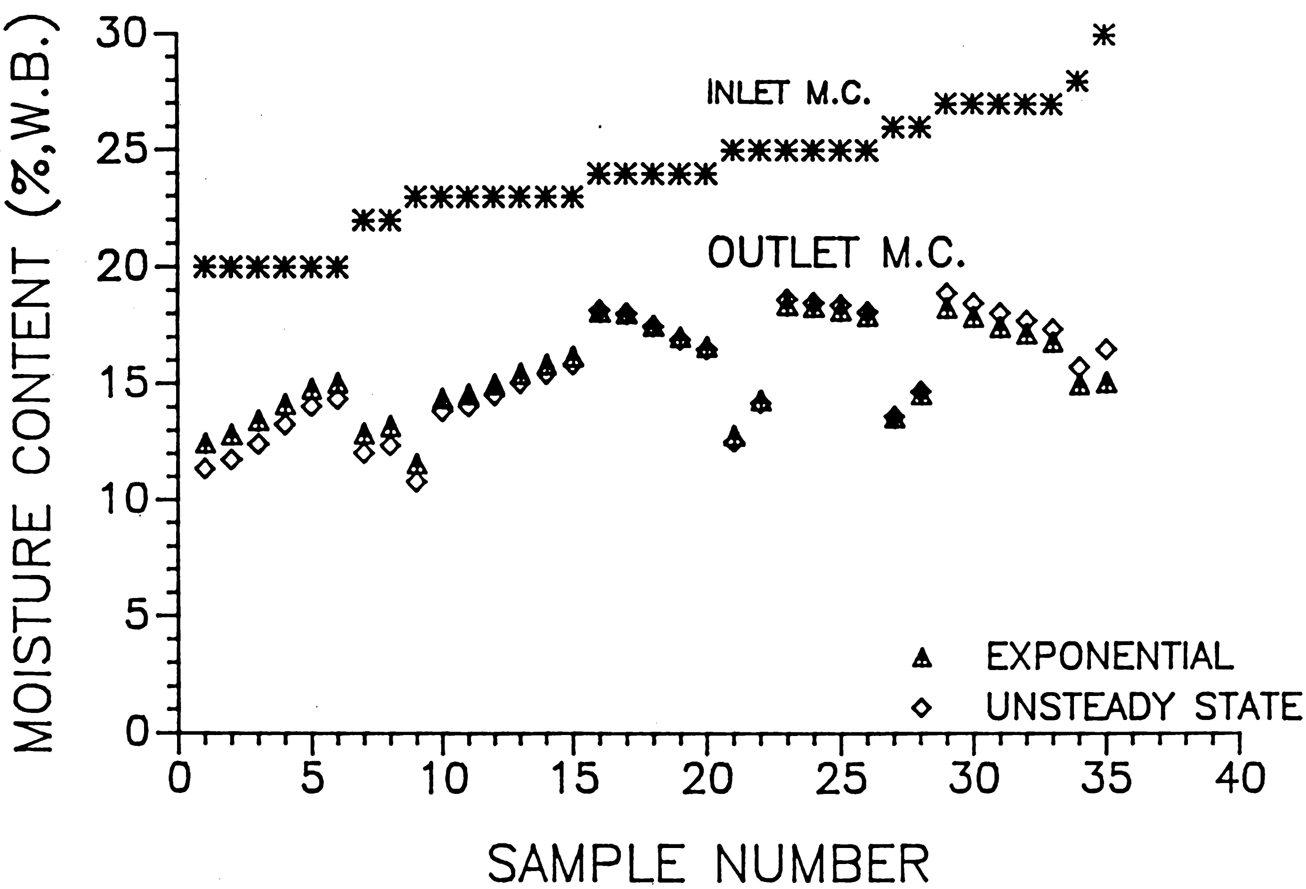


Figure 6.5 The Exponential Model vs the Unsteady-State Differential-Equation Model for the Drying of Corn in the 850 Meyer-Morton Dryer.

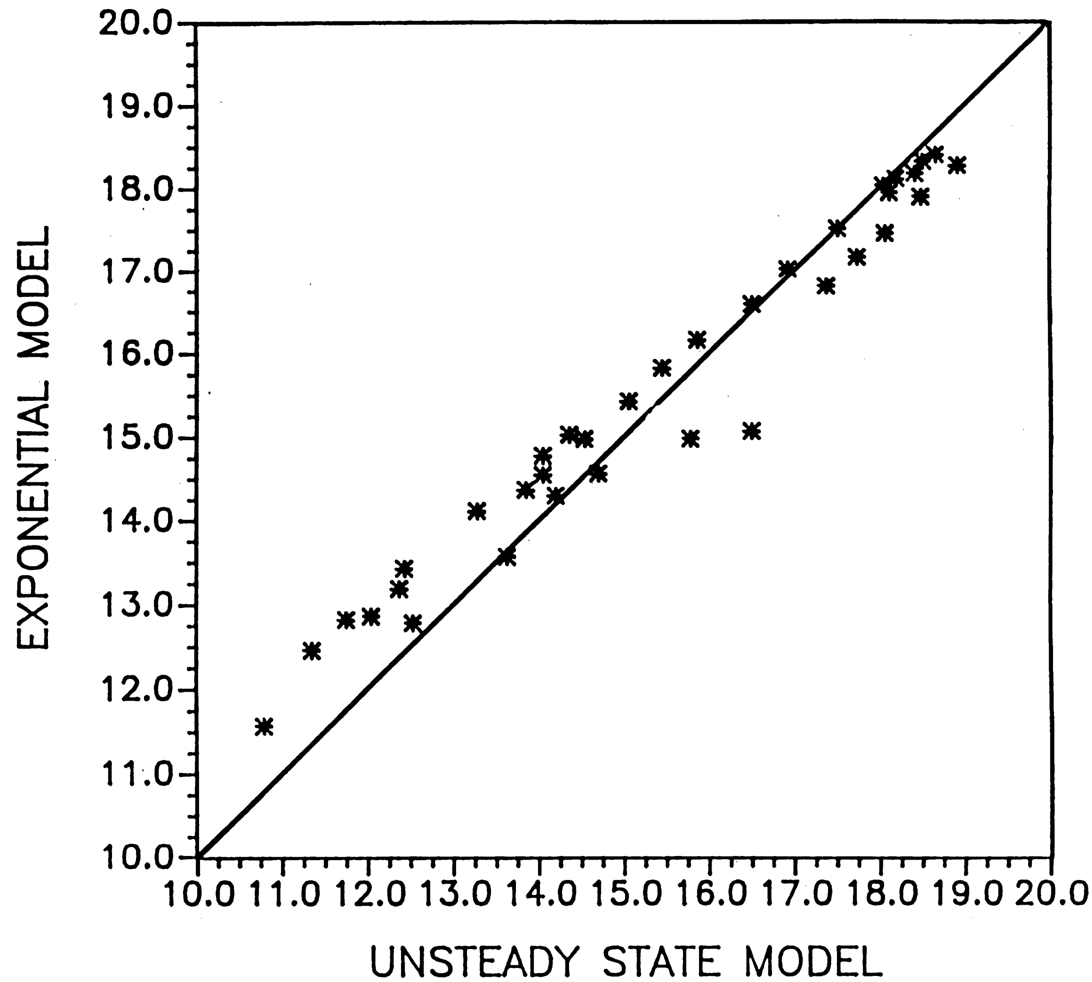


Figure 6.6 Exponential Model Outlet Moisture Content vs Unsteady-state Model Outlet Moisture Content in Drying Shelled Corn in the Meyer-Morton 850 Dryer.

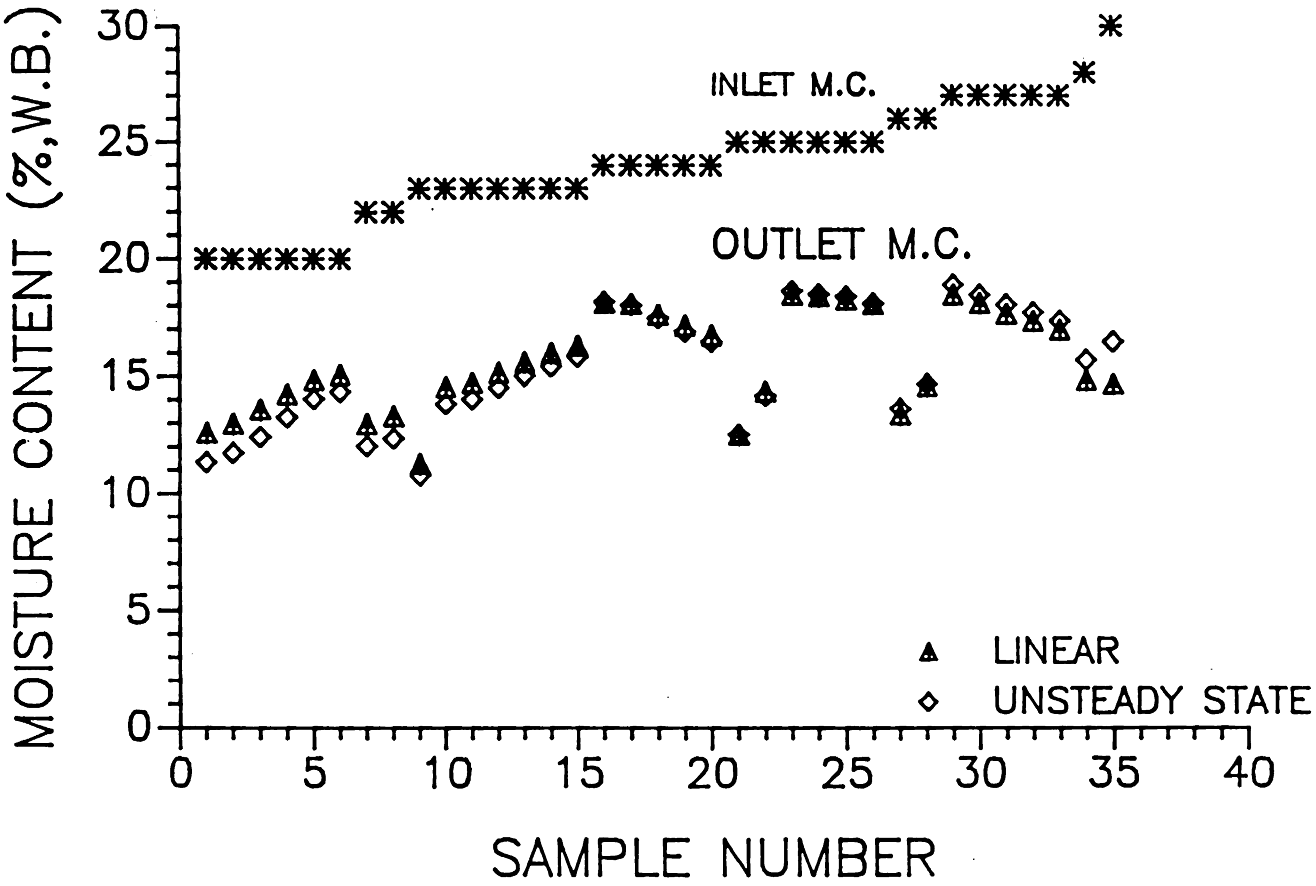


Figure 6.7 The Linear Model vs the Unsteady-State Differential-Equation Model for the Drying of Corn in the 850 Meyer-Morton Dryer.

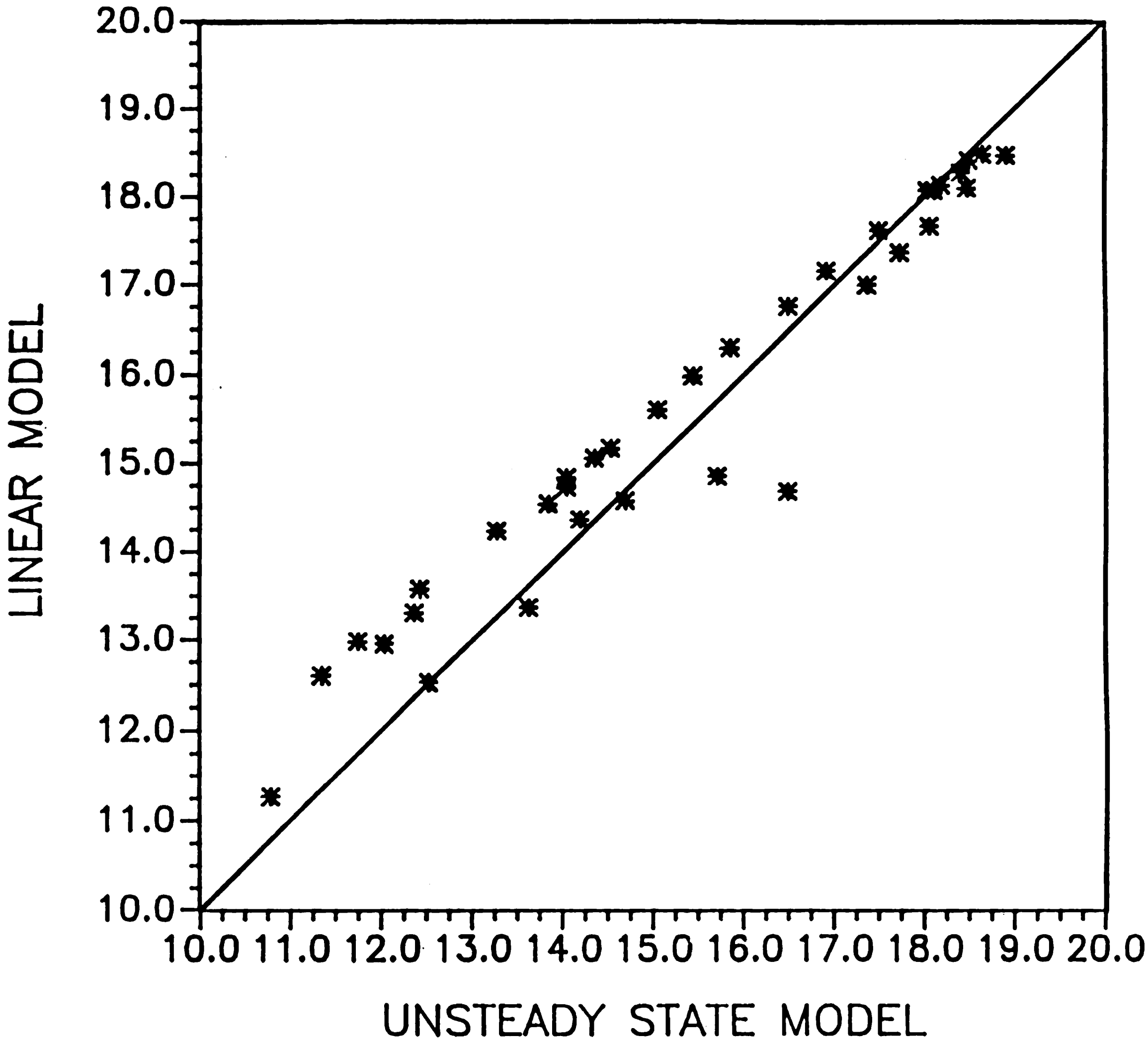


Figure 6.8 The Linear Model Outlet Moisture Content vs the Unsteady-State Model Outlet Moisture Content in Drying Shelled Corn in the Meyer-Morton 850 Dryer.

The outlet moisture contents predicted by the linear equation agree well with the values obtained by the unsteady state model. A plot of the linear model outlet moisture content versus the unsteady state model outlet moisture (Figure 6.8) proves the good agreement between the two models.

In conclusion, the two empirical models evaluated in the two sections are simple in their formation, and thus efficient for on-line calculations. They predict the grain outlet moisture content in crossflow dryers well. As process models for crossflow dryers control system they appear to have great promise.

6.1.3 Controller Stability Tests

Table 6.6 shows eight inlet moisture content ranges used in the theoretical analysis of the automatic control system of crossflow dryers. The exact nature of the inlet moisture variations along with the outlet MC and the rpm values are shown in Tables B.1-B.8.

Sets #1 and #2 are actual inlet moisture contents encountered in the Meyer-Morton dryer in tests #7 and #1, respectively (see Section 6.2.1). The results are shown in Figures 6.9 and 6.10. The two sets are compared in Section 6.1.1 to their experimental counterparts. The controller predicts the experimental values well and was found to be stable. Thus, it can be used for the analysis of other inlet moisture content sets.

Figure 6.11 shows the results obtained using inlet moisture content variation from set #3 (same inlet moisture content as that in test #12, Section 6.1.2). The inlet moisture content ranges between 19.9% and 23.5%. The average grain outlet moisture content after 10 hours of simulation is 17.1% for a set point of 17.5%. Overdrying by .4% agrees with the .5% overdrying which occurred in test #12 (see section 6.2.2).

Table 6.6 Inlet moisture content sets used as inputs in the simulation of crossflow grain dryers.

Set Number	Av. M.C. (%)	Min (%)	Max (%)	SD (%)	Period (hrs)
1	26.8	23.8	31.0	1.8	-
2	22.2	20.8	23.6	0.7	-
3	21.4	19.9	23.5	0.8	-
4	21.0	19.7	22.3	0.9	4
5	21.0	19.7	22.3	0.9	2
6	25.0	22.6	27.3	1.7	4
7	25.0	22.6	27.3	1.7	2
8	28.0	24.0	32.0	2.8	-

During the 10 hours of simulation, the dryer is operated at maximum auger speed 3/5 of the time, causing the grain outlet moisture content to remain below the set point.

Figure 6.12 shows the results obtained from the simulation model with set #4 (Table B.4) as the inlet moisture content input. The inlet moisture content varies sinusoidally with an average of 21%, a maximum of 1.5% above the average, and a period of 4 hours. During the 8 hours of simulation, the average outlet moisture content is 14.4% (with a set point of 14.5%). The outlet moisture content is very close to the set point at all times.

Figure 6.13 shows the simulation results obtained using a sinusoidal variation in the inlet moisture content with an average and maximum equal to that of set #4 and a period of 2 hours. The average outlet moisture content is 14.5% with a damped sinusoidal shape with a period of 2 hours. Although the average outlet moisture content is equal to the set point, the variation in the outlet moisture content of the individual samples is larger than that of set #4. Thus, the period affects the damping in the outlet moisture content of a controller subjected to a variation in the inlet moisture content.

The simulation results of a sinusoidal inlet moisture content variation with an average of 25%, a maximum of 3% above the average, and a period of 4 hours (set #6) are shown in Figure 6.14. The average outlet moisture content is 14.6% for a set point of 14.5%. The outlet moisture content has a sinusoidal shape with a period of 4 hours and damping ratio of .5. The rpm variation is also sinusoidal with a period of 4 hours.

Figure 6.15 illustrates the simulation results obtained using the inlet moisture content variation given by set #7. Set #7 has a similar inlet moisture content variation as set #6 except for period which is 2

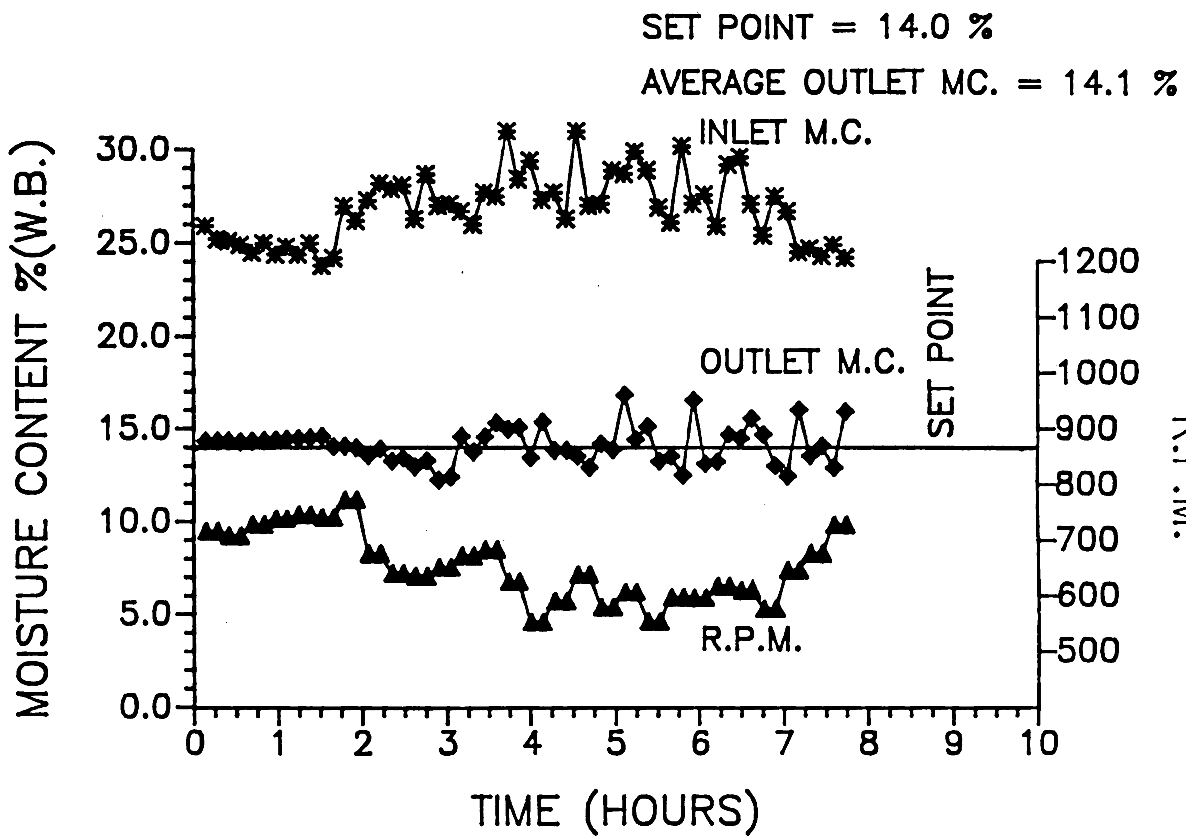


Figure 6.9 Simulation of the Automatic Control of the Meyer-Morton 850 Dryer(set #1).

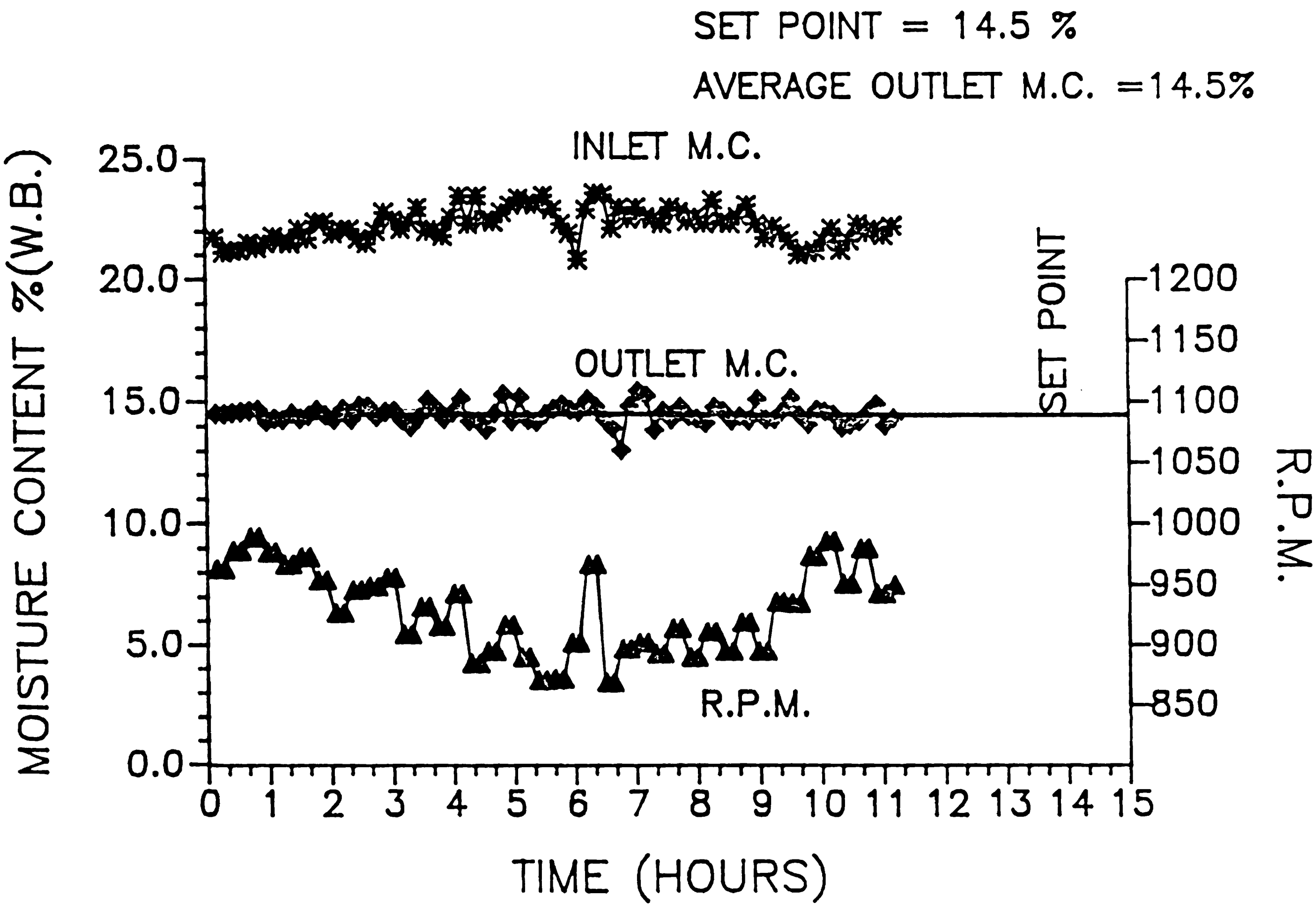


Figure 6.10 Simulation of the Automatic Control of the Meyer-Morton 850 Dryer(set # 2).

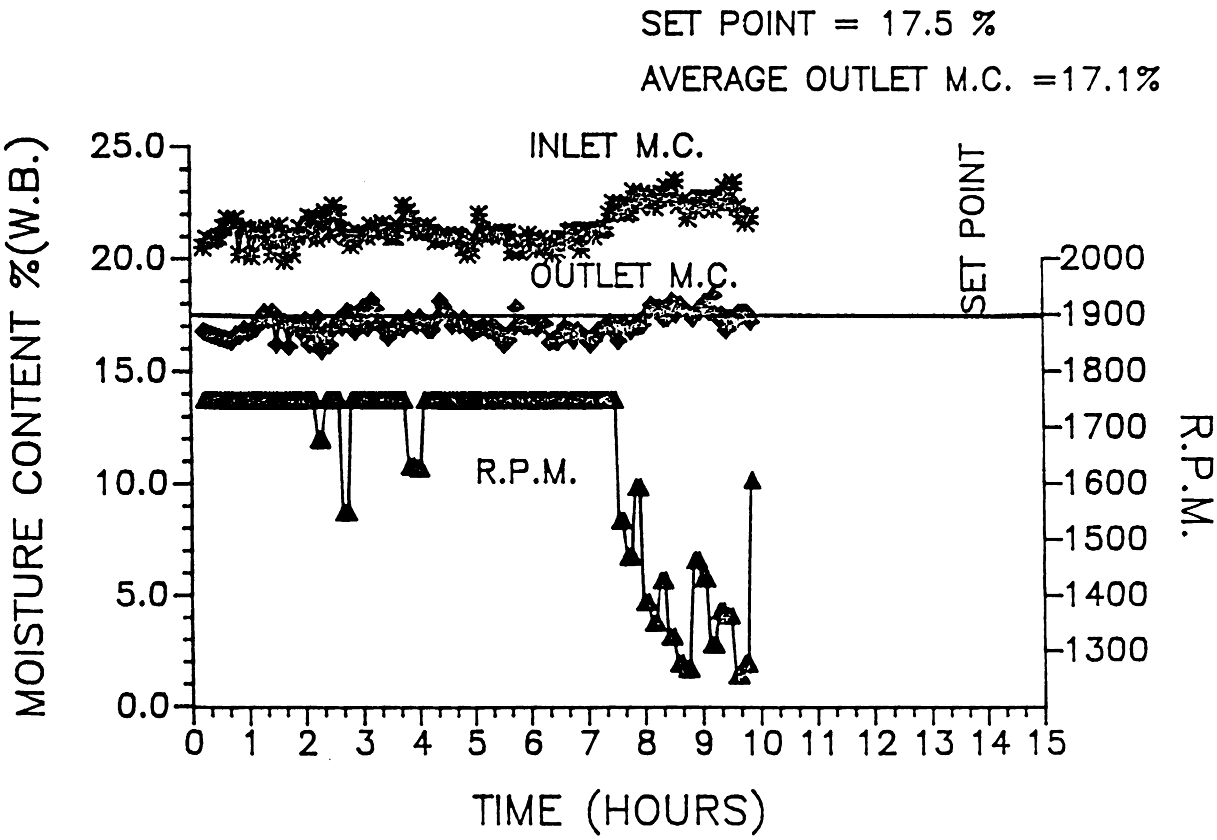


Figure 6.11 Simulation of the Automatic Control of the Zimmerman ATP 5000 Dryer(set #3).

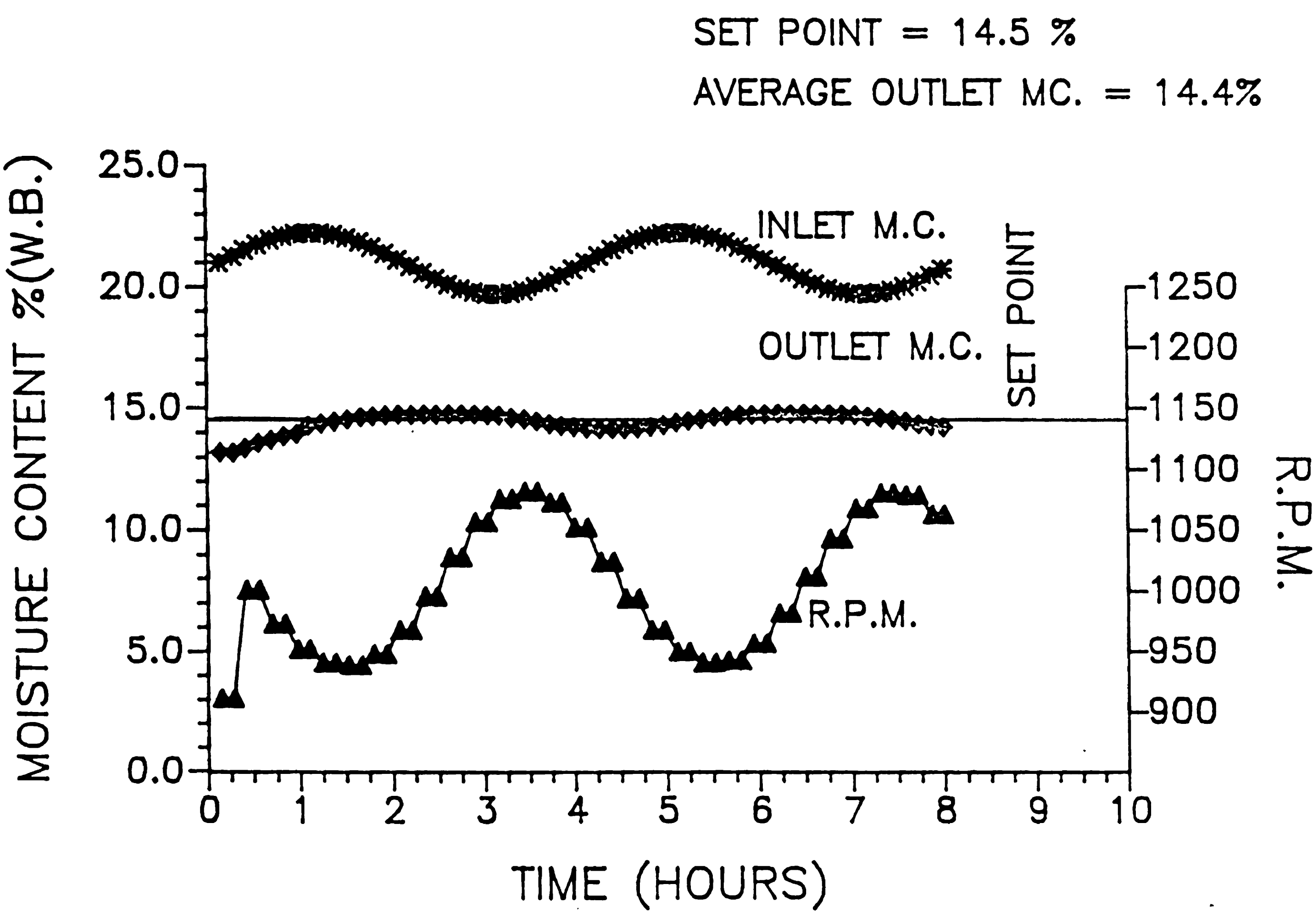


Figure 6.12 Simulation of the Automatic Control of the Meyer-Morton 850 Dryer(set #4).

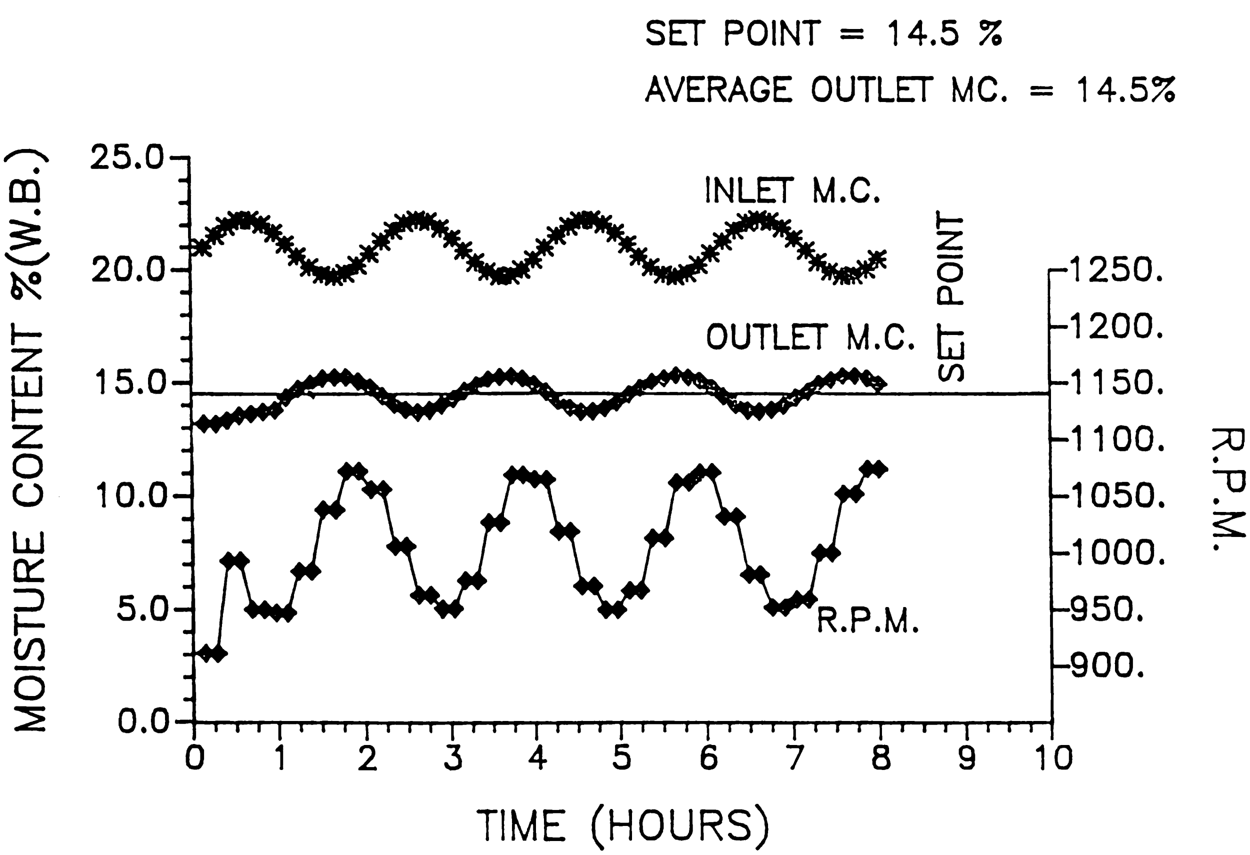


Figure 6.13 Simulation of the Automatic Control of the Meyer-Morton 850 Dryer(set #5).

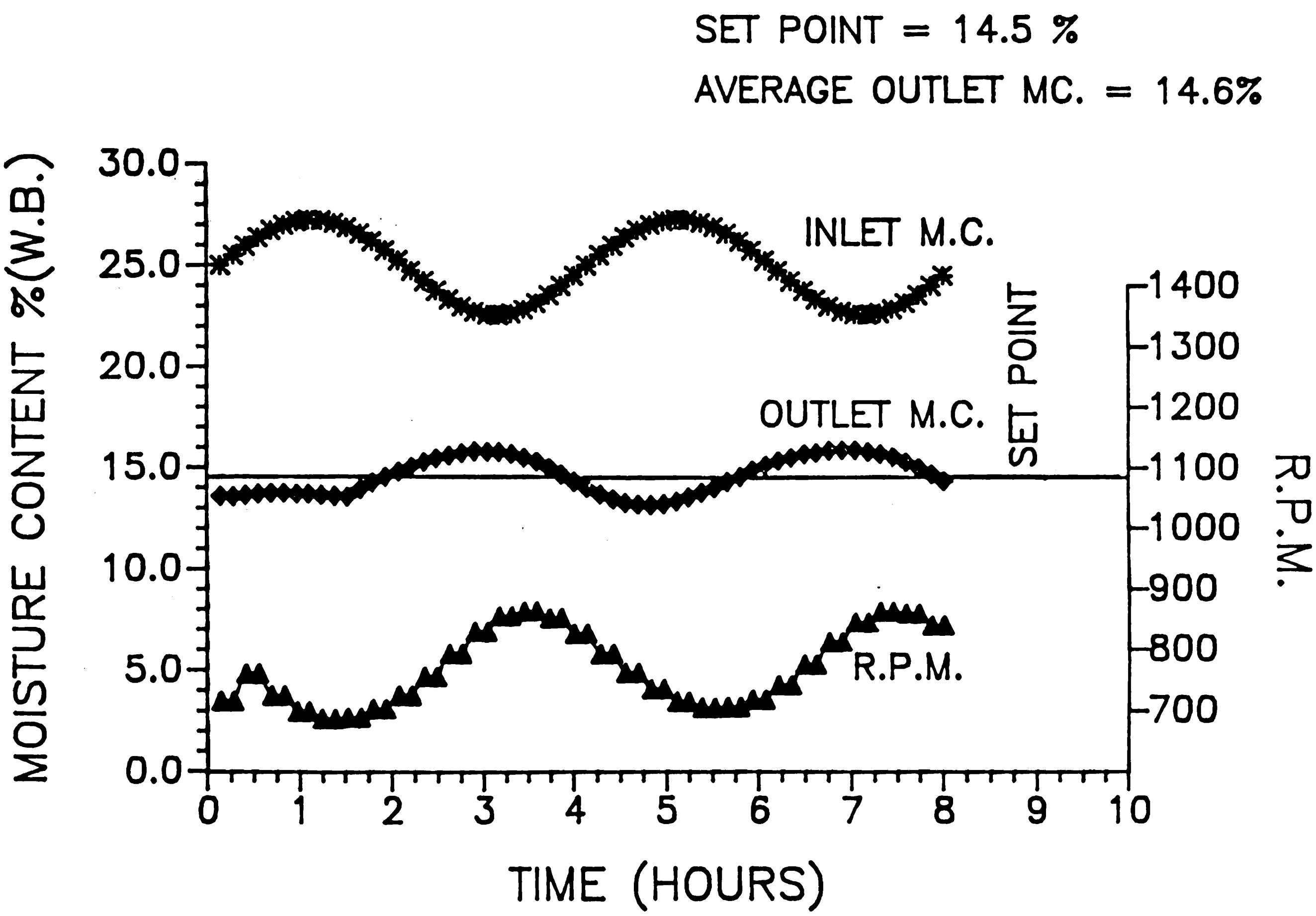


Figure 6.14 Simulation of the Automatic Control of the Meyer-Morton 850 Dryer(set #6).

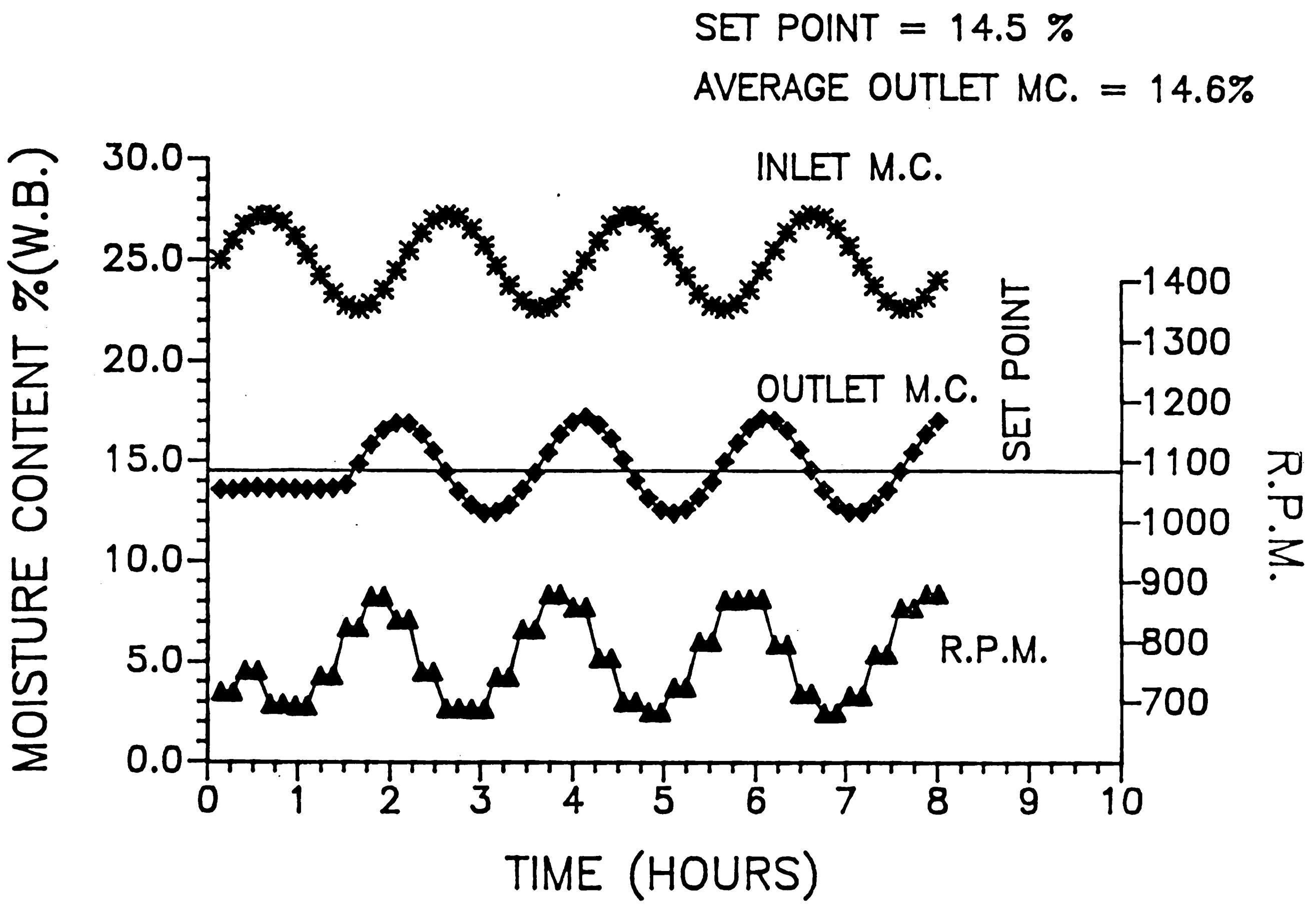


Figure 6.15 Simulation of the Automatic Control of the Meyer-Morton 850 Dryer(set #7).

hours. Although the average outlet moisture content is 14.6%, only .1% above the set point, the outlet moisture content is sinusoidal with a damping ratio of approximately one. A comparison of the simulation results of sets #7 and #6 shows that reducing the period of the sinusoidal inlet moisture content by 50% can increase the damping ratio by 50%.

Figure 6.16 shows simulation results for several step changes in the grain inlet moisture content. Step changes in the grain inlet moisture content are likely to occur in actual drying operations. The initial inlet moisture content is 28% for a three hours period. The average outlet moisture content during this period remains at the set point. After 3 hours of drying the inlet moisture content is suddenly decreased to 24%, and remains constant for 3 hours. The feedforward controller reacts to the change in the inlet moisture immediately when the inlet moisture content change occurs. The reaction of the controller results in the outlet grain being partially underdried and partially overdried. After six hours of simulation, the grain inlet moisture content is increased by 8% and remains constant for approximately 3 hours. The controller reacts to the large change in the inlet moisture content by decreasing the auger speed, resulting in momentary overdrying and underdrying. <u>Figure 6.16 proves the stability of the controller to control a crossflow grain dryer subjected to large variations in the inlet moisture content.</u>

<u>6.2 Experimental Results</u>

The experimental results consist of results obtained by performing drying tests on two crossflow dryers fitted with the new control system. The two crossflow dryers are, a Meyer-Morton model 850 and a Zimmerman model ATP 5000. The detailed descriptions of the two commercial crossflow dryers are given in Chapter 5.

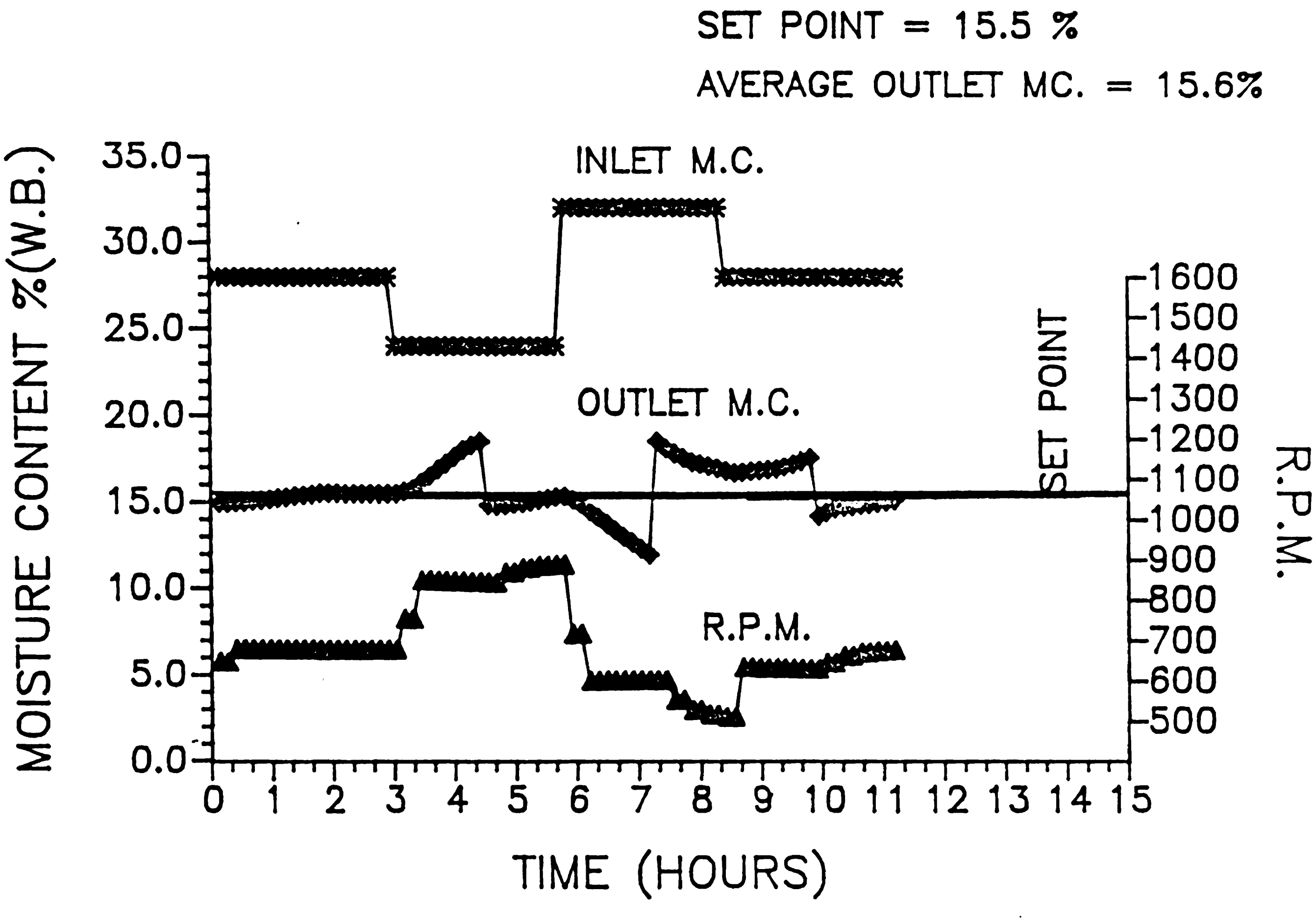


Figure 6.16 Simulation of the Automatic Control of the Meyer-Morton 850 Dryer(set #8).

6.2.1 Meyer-Morton Dryer

The tests were conducted with the Meyer-Morton dryer during the fall of 1985 and of 1986. Figures 6.17 through 6.28 and Tables A.1 through A.10 show the experimental results obtained during the drying of corn.

Figure 6.17 illustrates the controlability of manual control of the Meyer-Morton dryer. It shows the variation in the corn outlet moisture content, the corn inlet moisture content, and the unload auger rpm as a functions of time. The average outlet moisture content during the nine hours of drying was 13.6%(w.b)* at a set point of 14.5%. Overdrying by 0.9% point took place which is characteristic for manual dryer control. The variation in the corn inlet moisture content was typical for an on-farm dryer in Michigan in November. During the nine hours of drying, the rpm was changed three times which was insufficient to prevent the slight overdrying.

A second example of manual control is shown in Figure 6.18. The outlet moisture content of the grain was .68% below the set point (14.5%). Only during the 1-3 hours drying period did a significant change occur in the inlet moisture content. Still the outlet moisture content varied considerably. Due to the limited information a dryer operator has during the drying process, it is difficult to control the dryer adequately even for the best operators.

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* all the experimentally determined moisture content values in this Section are expressed on a wet basis.

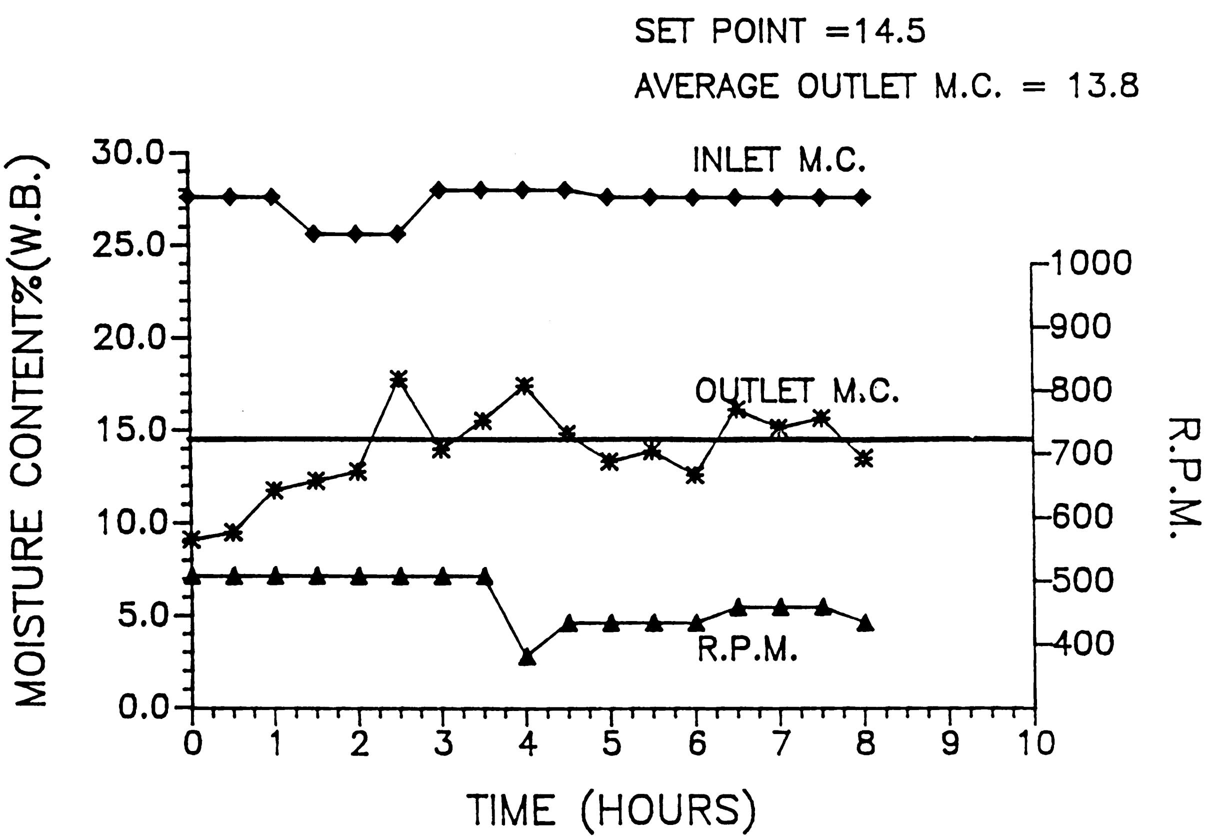

Figure 6.17 Inlet and Outlet Moisture Contents vs Time During Manual Control of the Meyer-Morton 850 Dryer (1984).

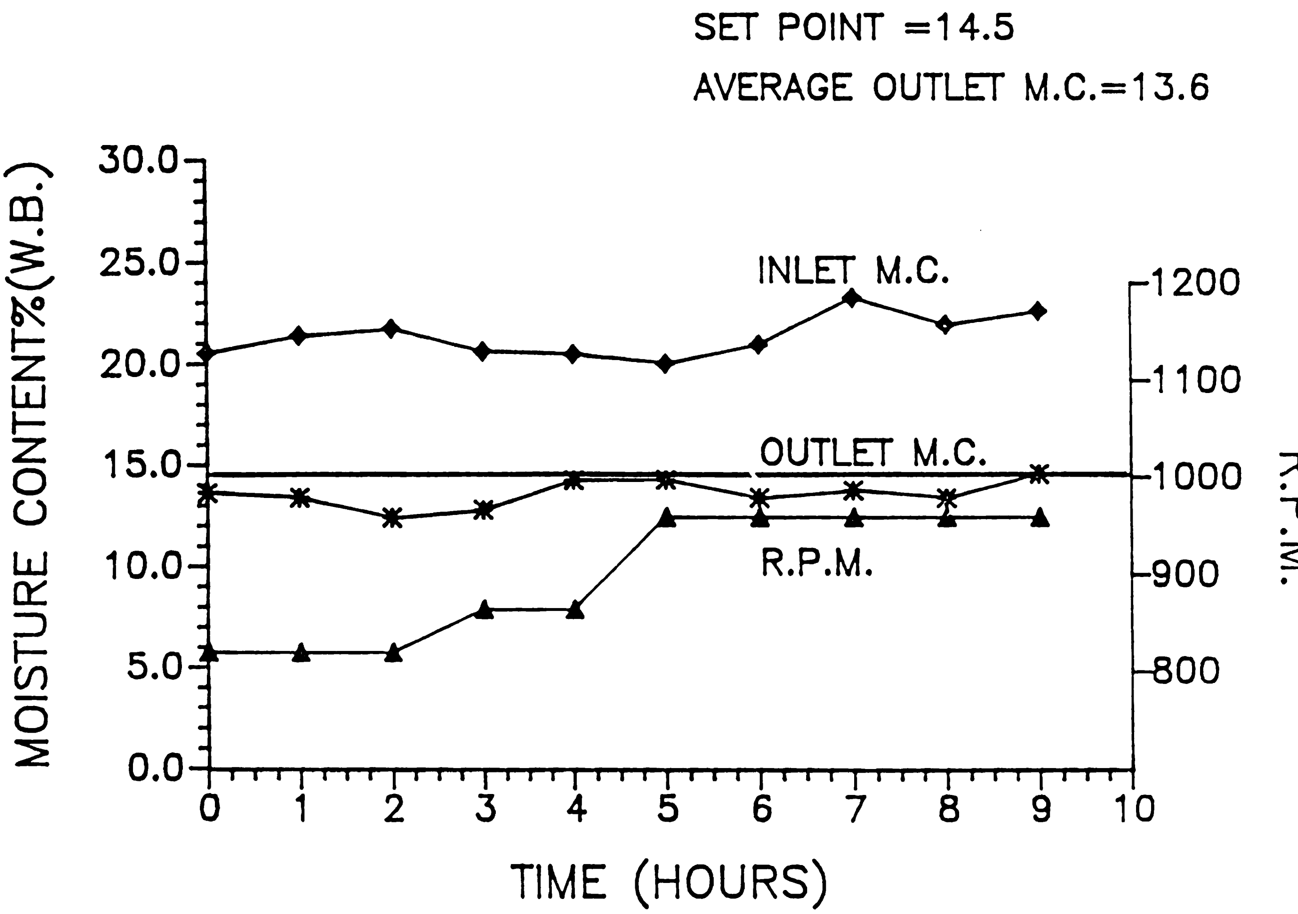

Figure 6.18 Inlet and Outlet Moisture Contents vs Time During Manual Control of the Meyer-Morton 850 Dryer (1985).

Figure 6.19 shows test #1 with the <u>automatic dryer control.</u> The average inlet moisture content was 22.24% with an standard deviation of .67%, the average outlet moisture content 14.47%, and the desired outlet moisture content 14.5%. Although, the variation in the inlet moisture content was small, the controller auger rpm varied from 698 to 960 to keep the outlet moisture content as close as possible to the set point. Control of the average outlet moisture content to within .03% from the set point can be considered excellent.

In Figure 6.20 test #2 is shown; the outlet moisture content at the beginning of the test was 2 1/2% above the set point. It slowly approached the set point as the test progressed. The high average outlet moisture content is due to the high values during dryer start up. This shows the importance of the start-up procedure. During the last six hours of the test the outlet (and inlet) moisture contents remained almost constant. However, over the total 7.5 hours of the test the average outlet moisture content was 14.94 , the set point 15.0% , and the average inlet moisture content 23.31%; the auger rpm was 717.

The results of test #3 are shown in Figure 6.21. The average inlet moisture content during 6.5 hours of drying was 21.43. The inlet moisture content was almost constant during the test. The controller controlled the outlet moisture content very well to an average value of 14.53% and thereby deviated by only .03% point from the set point. The average auger rpm was 722 with an standard deviation of only 19, this is an example of the operation of the controller under conditions of only small variations in the inlet moisture content.

In Figure 6.22 test #4 is shown; the inlet moisture content at the start of the test was 22.5%(w.b); it remained constant for two hours

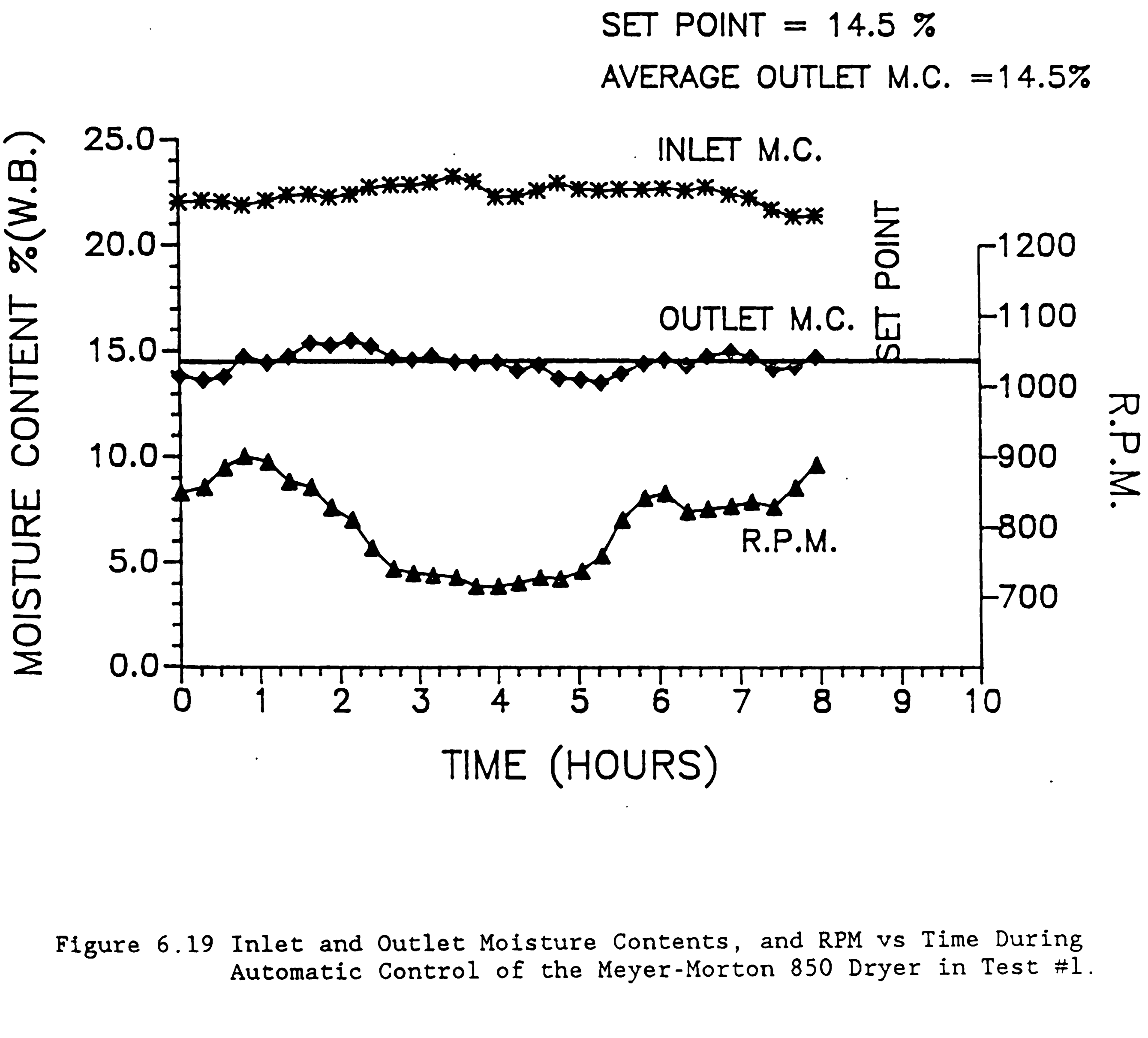

Figure 6.19 Inlet and Outlet Moisture Contents, and RPM vs Time During Automatic Control of the Meyer-Morton 850 Dryer in Test #1.

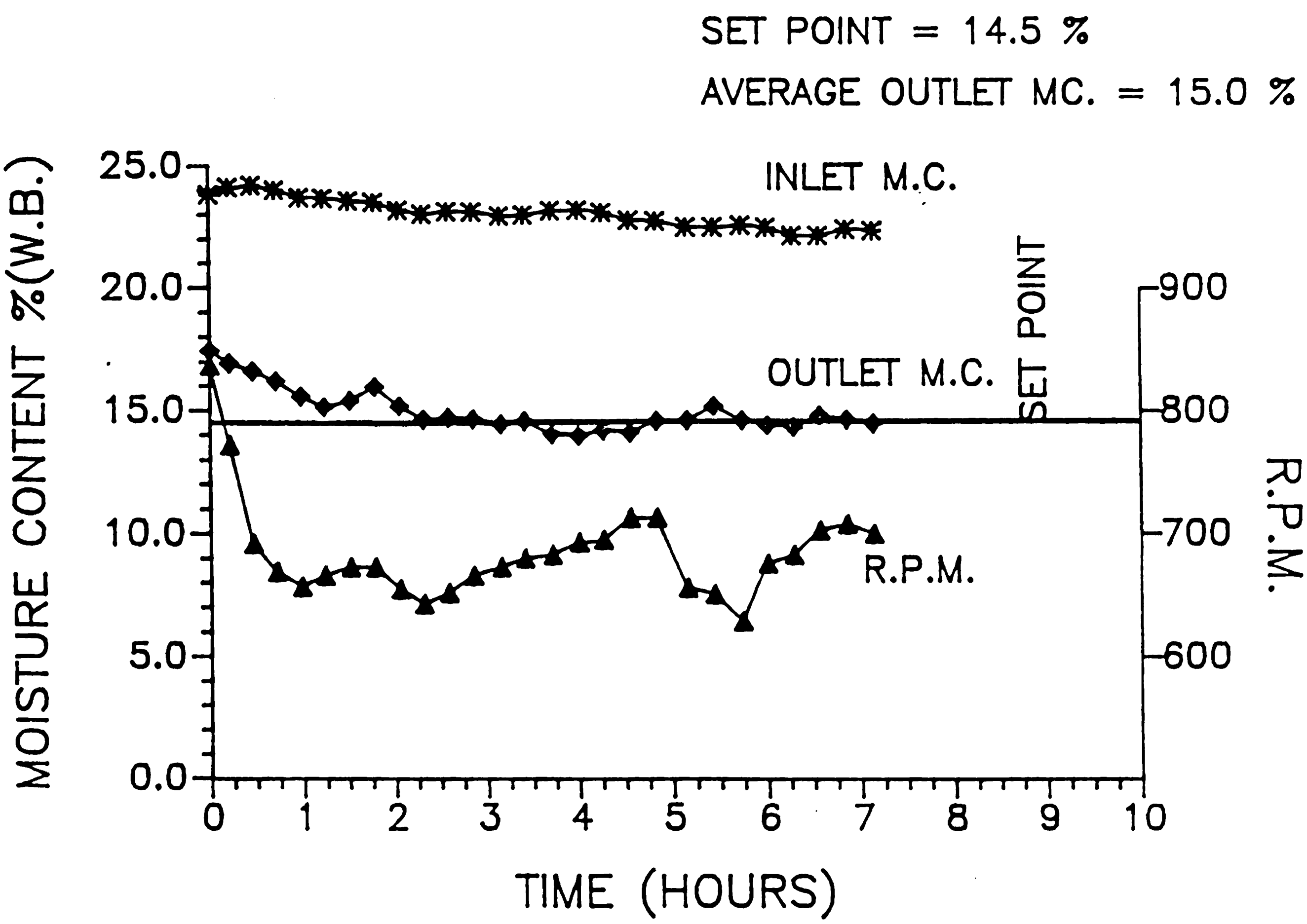

Figure 6.20 Inlet and Outlet Moisture Contents, and RPM vs Time During Automatic Control of the Meyer-Morton 850 Dryer in Test #2.

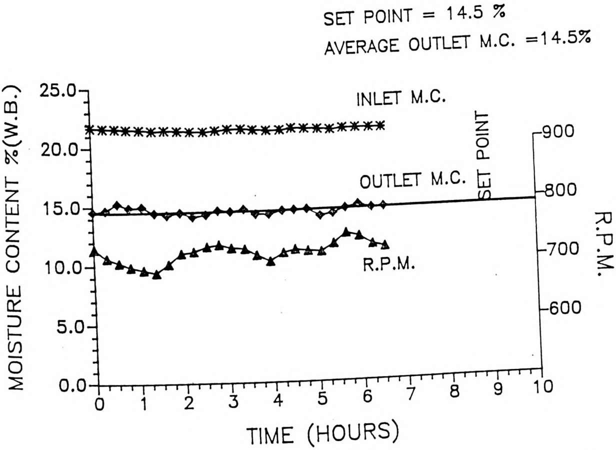

Figure 6.21 Inlet and Outlet Moisture Contents, and RPM vs Time During Automatic Control of the Meyer-Morton 850 Dryer in Test #3.

and then increased suddenly to 24%. It remained close to this value until the end of the test. Test #4 represents a step change in the inlet moisture content which is typical when a farmer moves from one parcel of land to another. The automatic controller reacted well to the sudden inlet moisture content change. The average outlet moisture content for 8 hours of dryer-operation was 14.94 at a set point of 15.0%. The auger rpm decreased steadily during the early drying time because the discharged grain was above the set point. The auger rpm decreased further as the inlet moisture content started to increase. Towards the end of the test, the change in the auger rpm become small due to the relatively constant values of the inlet and outlet moisture contents.

Figures 6.23 and 6.24 show the results of test #5 and test #6, respectively. In test #5 the auger rpm increased from 750 to 900 within three hours to reduce the overdrying at the early stages of the test. In contrast, in test #6 the auger rpm decreased from 850 to 700 within two hours due to underdrying during the early hours of the test. In both tests the grain inlet moisture content was fairly constant, and the average outlet moisture content was controlled to within .1% point from the set point. An accurate choice of the initial auger rpm would have resulted in even less underdrying or overdrying at the early stages of both tests. The controller controlled the drying process well in both tests and resulted in outlet moisture contents approximately equal to the set points.

Figures 6.25 and 6.26 show results obtained with large variations in the corn inlet moisture content. The grain inlet moisture content varied in test #7 from 31% to 19.8% and in test #8 from 34.3% to 19.5%.

In Figure 6.25, the variation in the inlet moisture content appeared to fluctuate randomly during the test. The fluctuation made it

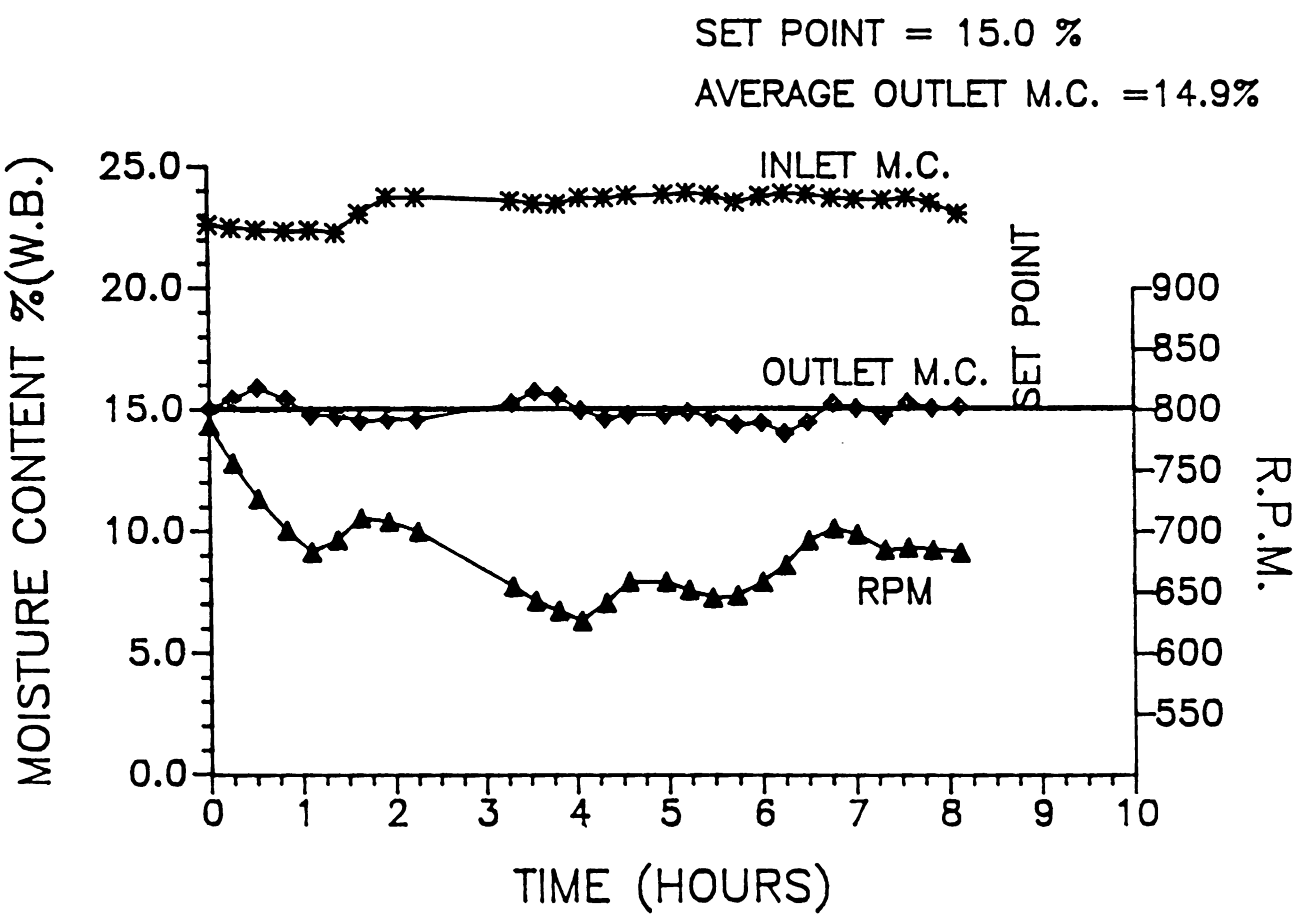

Figure 6.22 Inlet and Outlet Moisture Contents, and RPM vs Time During Automatic Control of the Meyer-Morton 850 Dryer in Test #4.

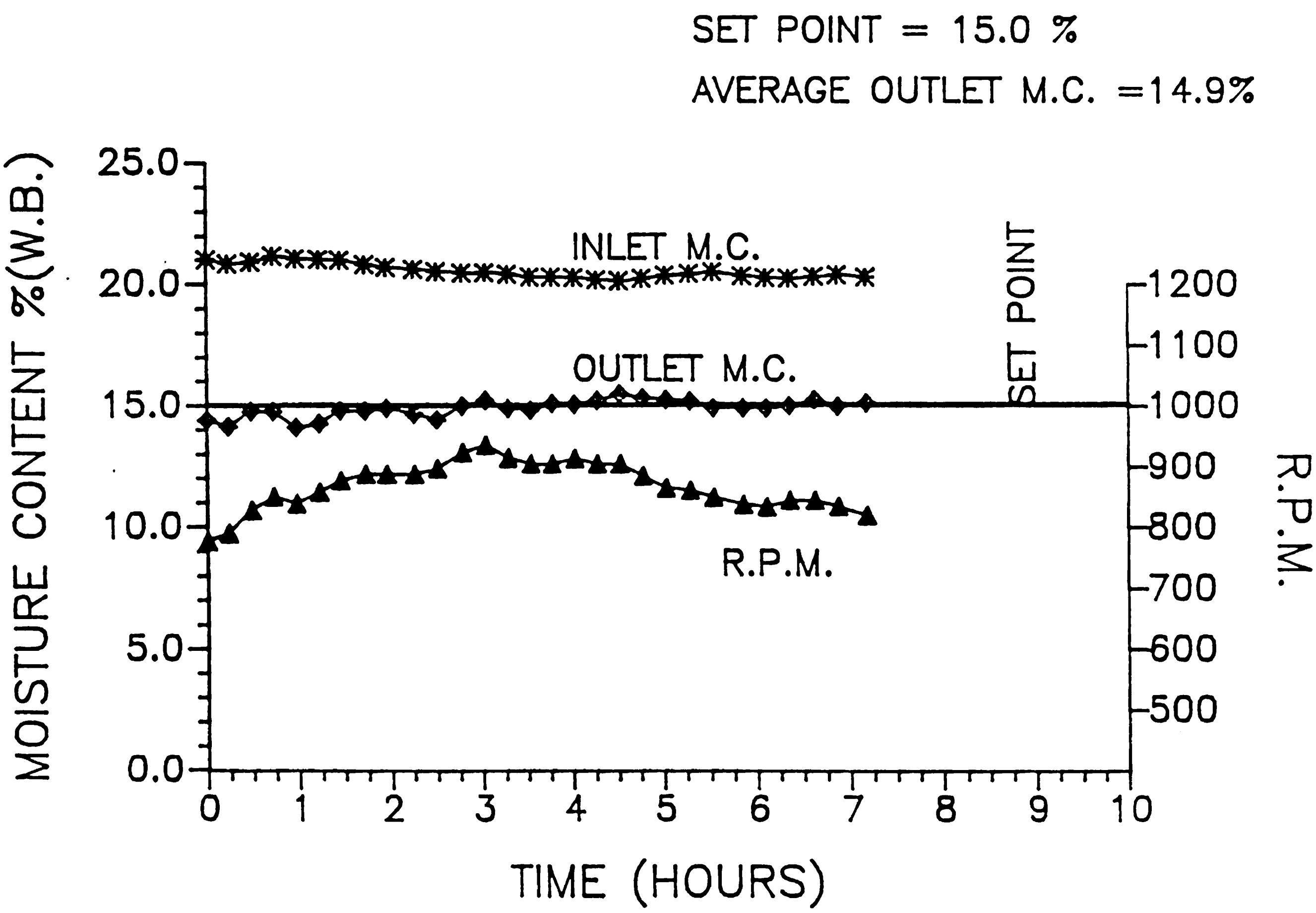

Figure 6.23 Inlet and Outlet Moisture Contents, and RPM vs Time During Automatic Control of the Meyer-Morton 850 Dryer in Test #5.

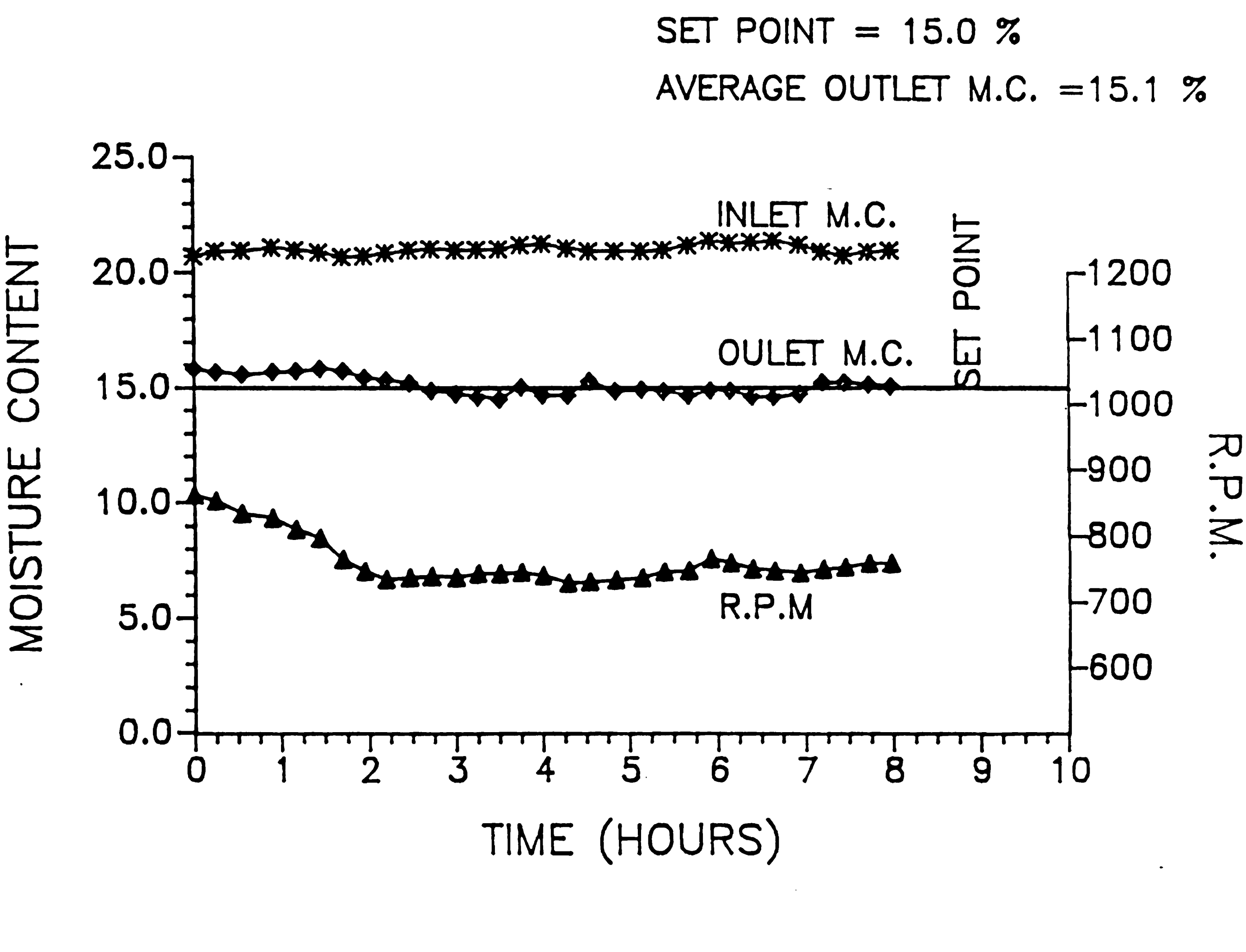

Figure 6.24 Inlet and Outlet Moisture Contents, and RPM vs Time During Automatic Control of the Meyer-Morton 850 Dryer in Test #6.

impossible to control the instantaneous grain outlet moisture content to exactly the desired value. The auger rpm was increased momentarily because of the overdrying and then decreased as the grain inlet moisture content increased and the outlet moisture content drifted above the set point. The average corn outlet moisture content (14.3%) was still acceptable to the set point. The controller performance can be described as excellent based on the average outlet moisture achieved at the large variation in the inlet moisture content encountered.

The grain inlet moisture content for test #8 (see Figure 6.26) varied widely during the first two hours and remained fairly constant over the last 6 hours of the test. The auger rpm was changed frequently in an effort to control the grain outlet moisture content as close to the set point as possible. The resulting average grain outlet moisture content was only .5% above the set point(14.5%). The .5% underdrying was a direct result of the large and rapid change in the corn inlet moisture content. The level of the control obtained is excellent taking into account the large and sudden variation in corn inlet moisture content during the first two hours of drying.

Tests #7 and 8 proved that if a controller encounters a large variation in the inlet moisture content, it is not be able to control the outlet moisture very close to the set point. This means that the grain inlet moisture content change and the rate of change have to be considered in evaluating a grain dryer control system.

The results of test #9 are shown in Figure 6.27. The inlet moisture content variation is small compared to the inlet moisture variation in tests #7 and 8. The average inlet moisture content was 19.2, the outlet moisture 14.6%, only .1% point above the set point. The variation in the auger rpm was small due to the limited variation in the grain inlet

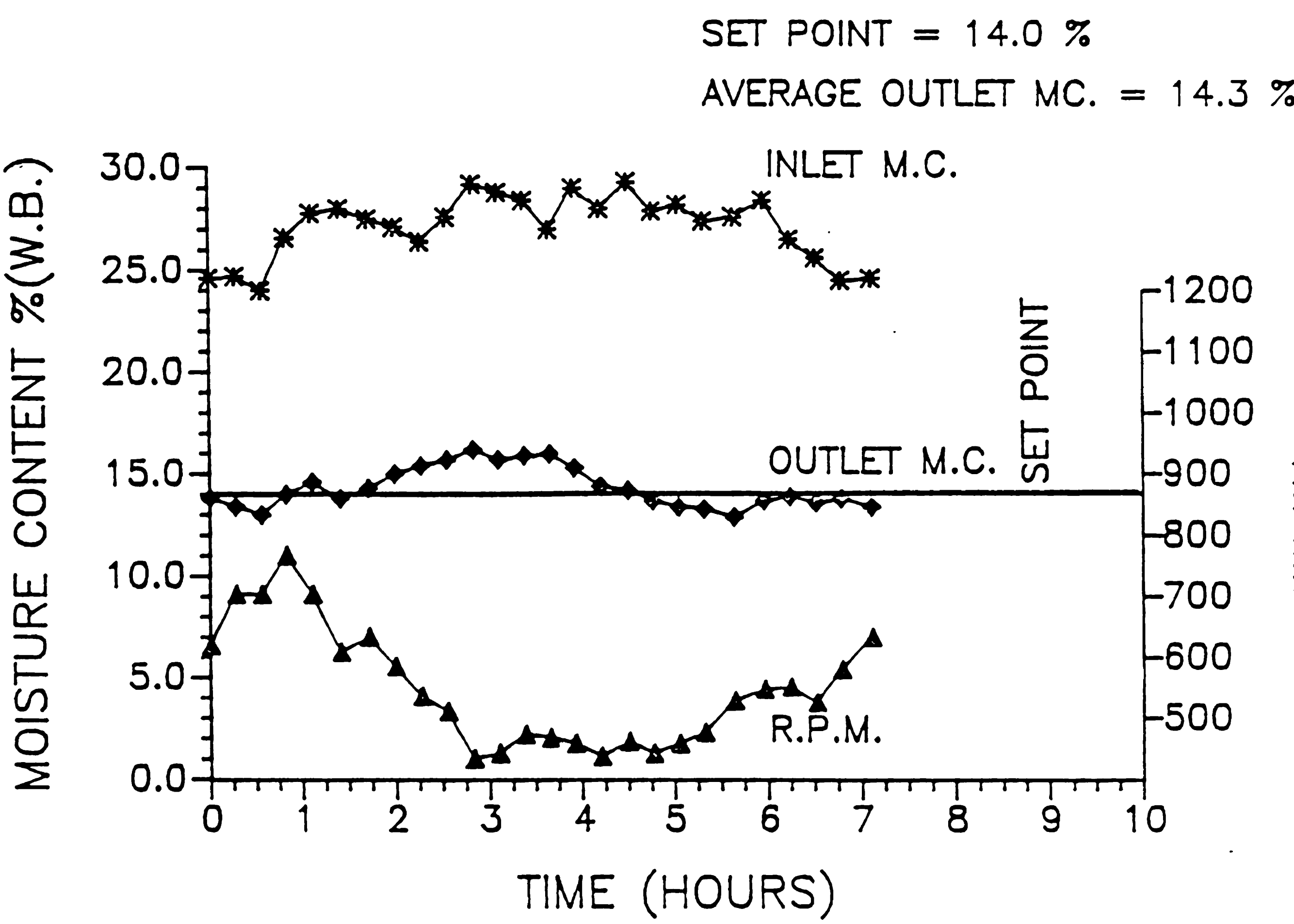

Figure 6.25 Inlet and Outlet Moisture Contents, and RPM vs Time During Automatic Control of the Meyer-Morton 850 Dryer in Test #7.

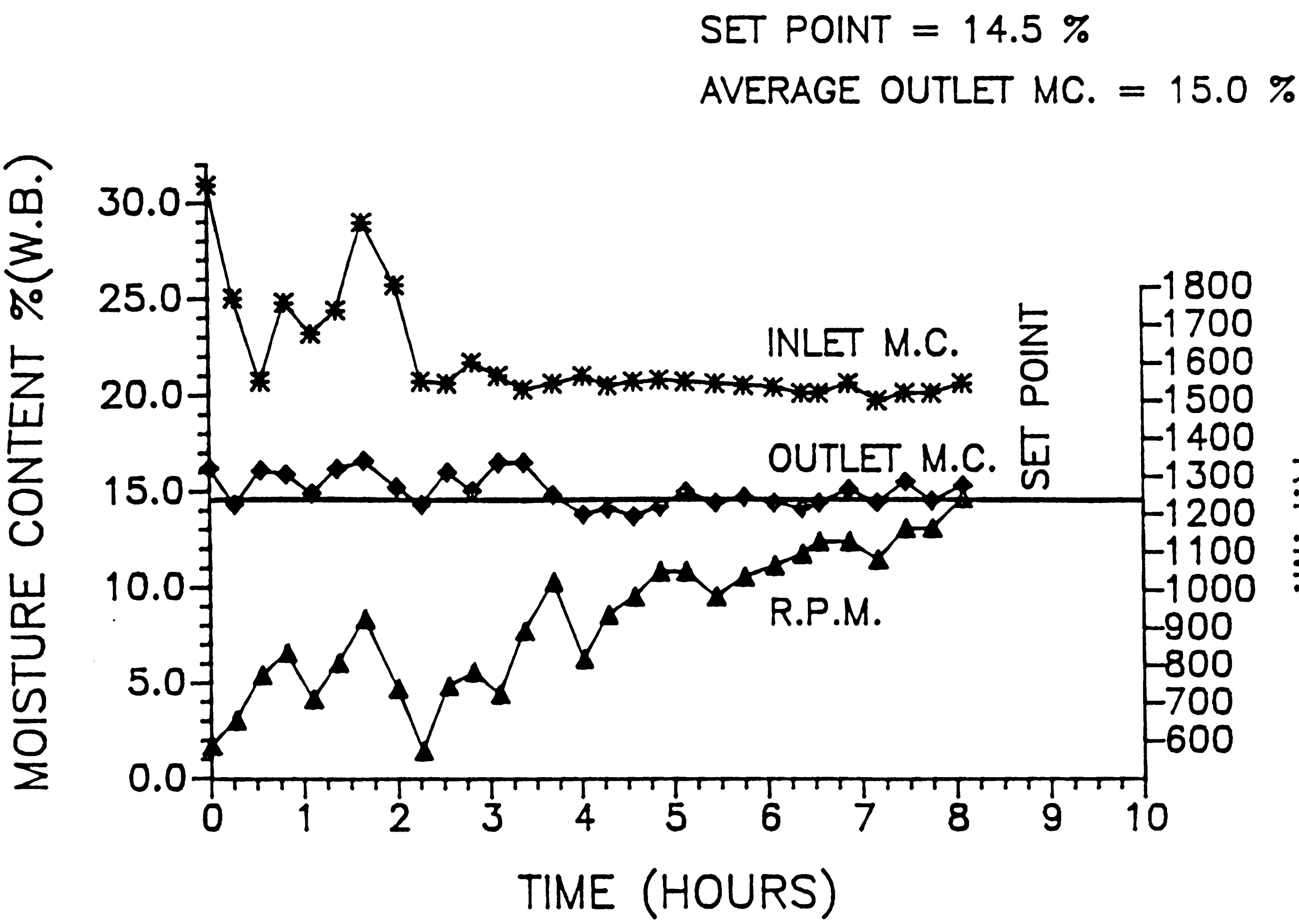

Figure 6.26 Inlet and Outlet Moisture Contents, and RPM vs Time During Automatic Control of the Meyer-Morton 850 Dryer in Test #8.

moisture content. Test #9 demonstrates the ability of the control system to control a dryer encountering an inlet moisture pattern normally encountered in the Midwestern US (e.g. the States of Iowa, Illinois and Nebraska) to an average outlet moisture content close to the set point.

Test #10 (Figure 6.28) is a run conducted using the linear model to describe the drying process in the control algorithm (see p 63, Chapter 4). The linear model is a two parameter model in which the two parameters are estimated by the sequential least square method. The set point in test #10 was 13.5%(w.b); the average outlet moisture content over 17 hours of dryer-operation was 13.7%. The .2% value above the set point is due to slight underdrying in the early stages of the test. The inlet moisture content varied slowly during the test. The linear model reacted slowly to changes in the inlet and the outlet grain moisture contents compared to the exponential model. Therefore, the exponential model controlled the drying process closer to set point than the linear model under similar inlet moisture content conditions. A further disadvantage of the linear model is that, the dryer has to run in manual for considerable time before it can be switched to the automatic mode because of the method used in estimating the parameters of the linear model. For the above reasons, the exponential model is preferred over the linear model and is used in the control algorithm of the second crossflow dryer tested in this study, the Zimmerman crossflow dryer.

The summary of the results obtained from the tests conducted with the Meyer-Morton dryer is shown in Table 6.7.

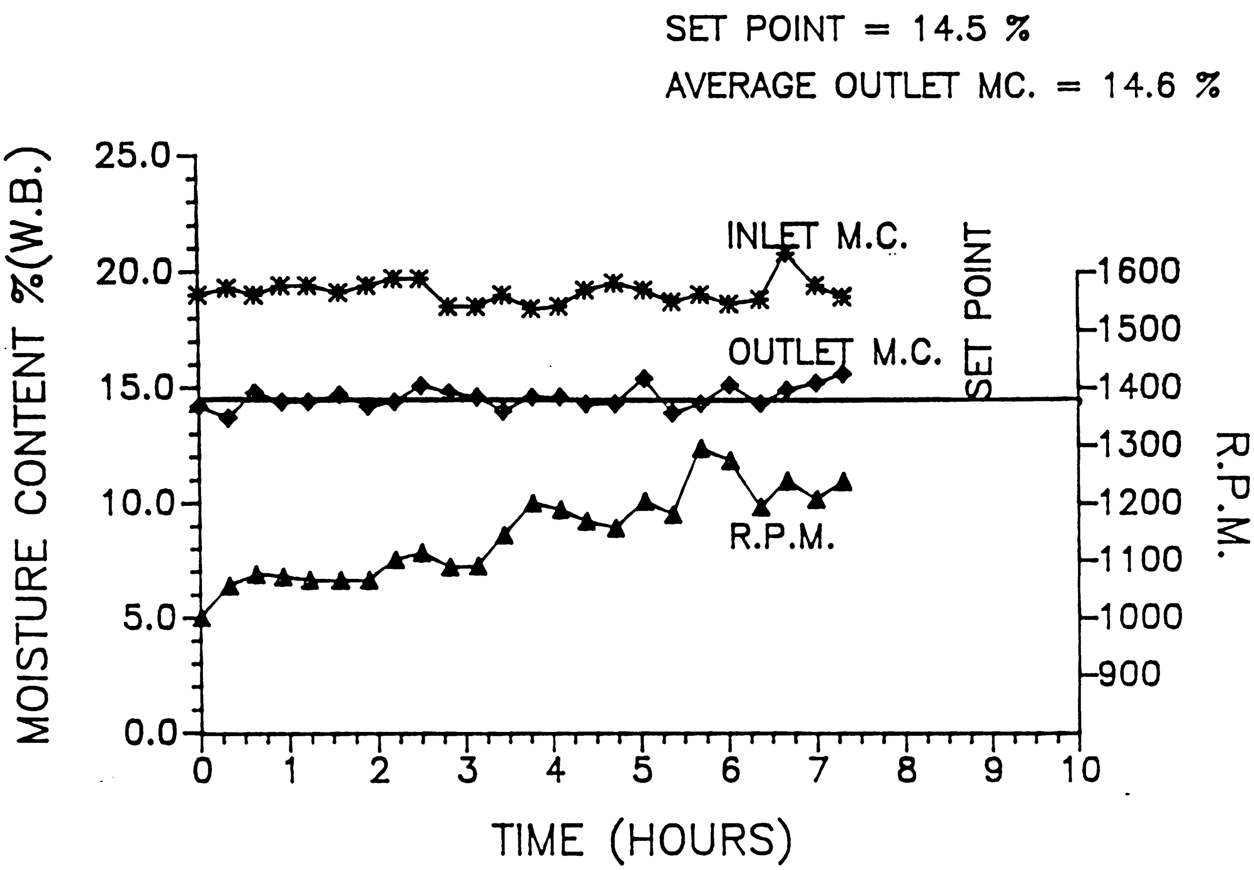

Figure 6.27 Inlet and Outlet Moisture Contents, and RPM vs Time During Automatic Control of the Meyer-Morton 850 Dryer in Test #9.

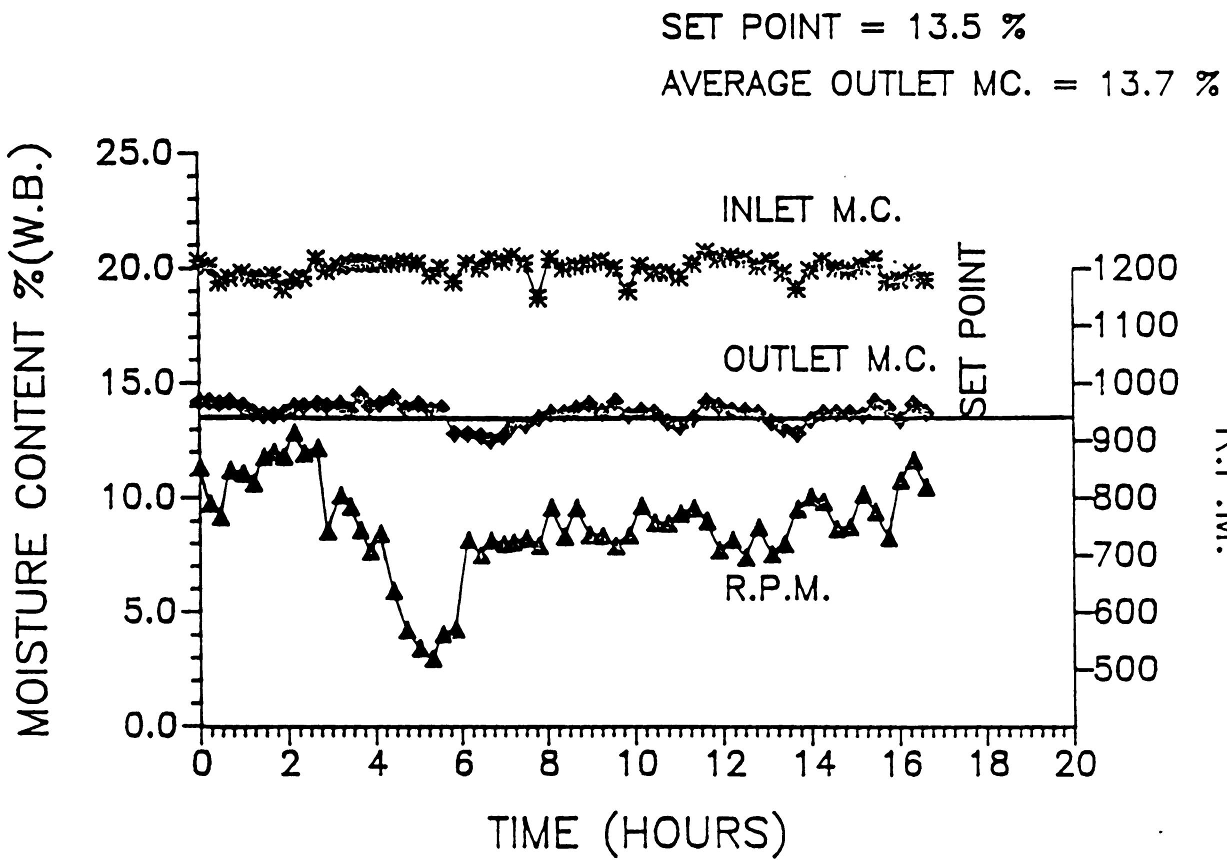

Figure 6.28 Inlet and Outlet Moisture Contents, and RPM vs Time During Automatic Control (Linear Model) of the Meyer Morton 850 Dryer in Test #10.

Table 6.7 Summary of the results obtained from the different control tests (see Tables A.1-A.10) with the Meyer-Morton 850 dryer.

	Test Number					
	1	2	3	4	5	6
Date :1985	12/9	12/13	12/14	12/15	12/19	12/20
Ave Inlet MC	22.2	23.3	21.5	23.2	20.6	21.0
Min Inlet MC	20.8	21.7	21.0	21.6	19.8	20.1
Max Inlet MC	23.6	25.2	22.0	24.6	21.3	21.9
Set Point	14.5	14.5	14.5	15.0	15.0	15.0
Ave Outlet MC	14.4	14.9	14.6	14.9	14.8	15.1
Min Outlet MC	13.0	12.5	13.4	13.9	13.1	13.8
Max Outlet MC	15.9	17.8	15.9	16.5	15.8	16.2
Ave RPM	821	717	721	695	848	775
Min RPM	698	629	673	609	752	711
Max RPM	960	893	752	817	960	914

	Test Number				
	7	8	9	10	11
Date :1986	10/9	10/29	11/14	11/28	12/3
Ave Inlet MC	26.8	23.0	19.2	19.9	19.3
Min Inlet MC	23.8	19.5	18.0	17.0	18.2
Max Inlet MC	31.0	34.3	21.0	20.9	20.9
Set Point	14.0	14.5	14.5	13.5	14.5
Ave Outlet MC	14.0	15.1	14.6	13.7	14.5
Min Outlet MC	11.1	13.4	12.5	12.2	12.0
Max Outlet MC	16.3	17.1	17.5	15.1	16.5
Ave RPM	563	882	1125	765	1034
Min RPM	426	548	936	519	873
Max RPM	768	1224	1310	980	1213

6.2.2 Zimmerman Crossflow Dryer

Figures 6.30 to 6.33 and Tables A.11 to A.14 show the experimental results of the dryer control system tests conducted on the Zimmerman dryer.

Figure 6.29 illustrates the manual control of the Zimmerman dryer. The inlet grain moisture content varied between 18% and 25% during the 17 hour duration of the test. The set point was 15% (w.b.); the average grain outlet moisture content obtained was 15.5%. The .5% above the set point is due to insufficient corrective action carried out during the manual control. The operator reacted only to the outlet moisture content. During the 17 hours of operation the dryer operator changed the auger rpm only three times; each time the outlet moisture content was above the set point. Once, with the outlet moisture above the set point, the inlet moisture content dropped substantially, but still the operator reduced the auger rpm. This resulted in overdrying at the end of the test. In general, the operator controlled the drying process reasonably well considering the variation in the inlet moisture content during the test. It must be emphasized that during this test the dryer operator had additional information about the drying process supplied by the moisture meter (inlet and outlet moisture content every 4-5 minutes), which helped him achieve the good result.

Figure 6.30 and Table A.11 show the result of the automatic control of test #11 performed with the Zimmerman dryer. The average outlet moisture content during 14.9 hours of drying was 16.9%; the set point was 17%. Based on the average outlet moisture content, the controller was successful in controlling the drying process. The unload auger rpm was changed from 481 to 1662 during the te_t; the large change was due to the large variation in the inlet moisture content which varied between 19.1% and 31.5%.

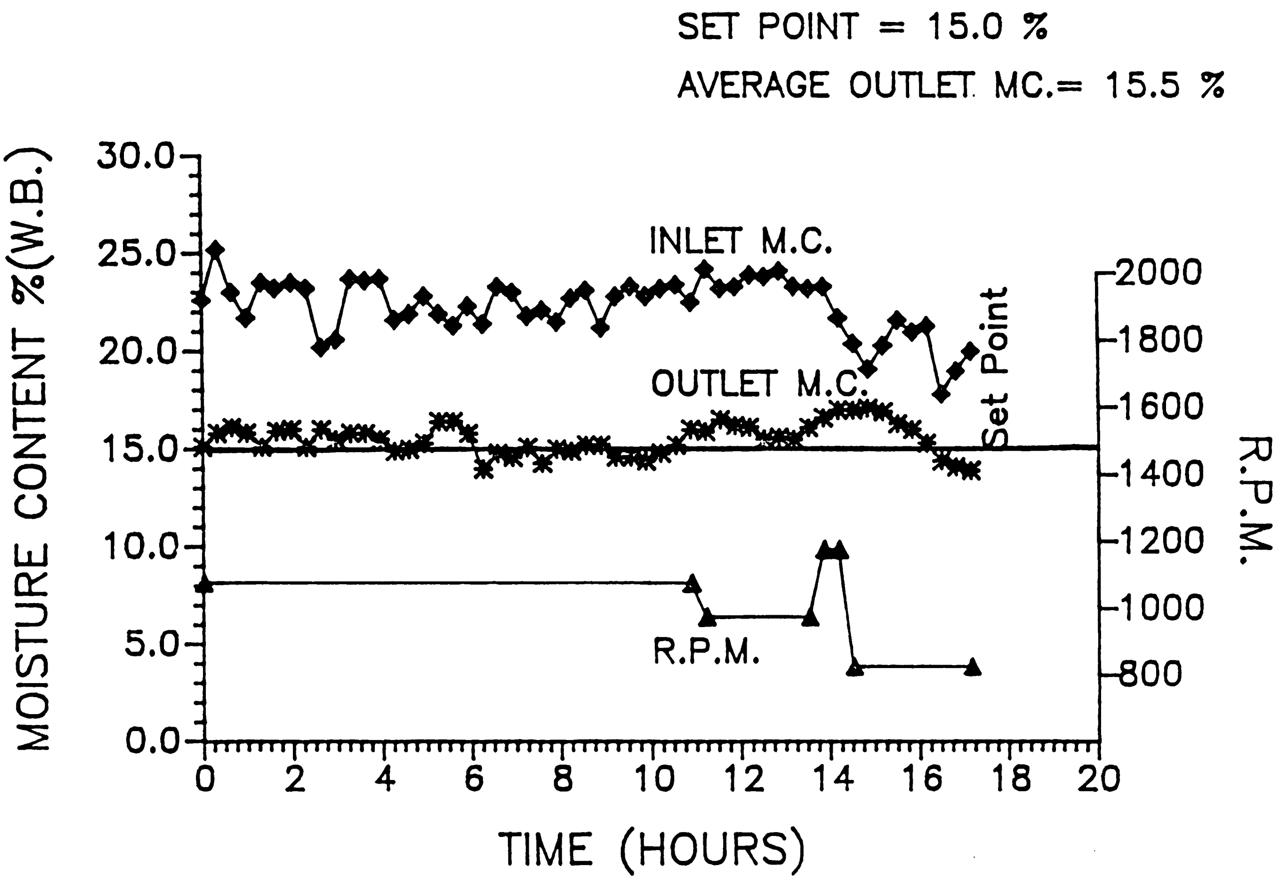

Figure 6.29 Inlet and Outlet Moisture Contents, and RPM vs Time During Manual Control of the Zimmerman ATP 5000 Dryer.

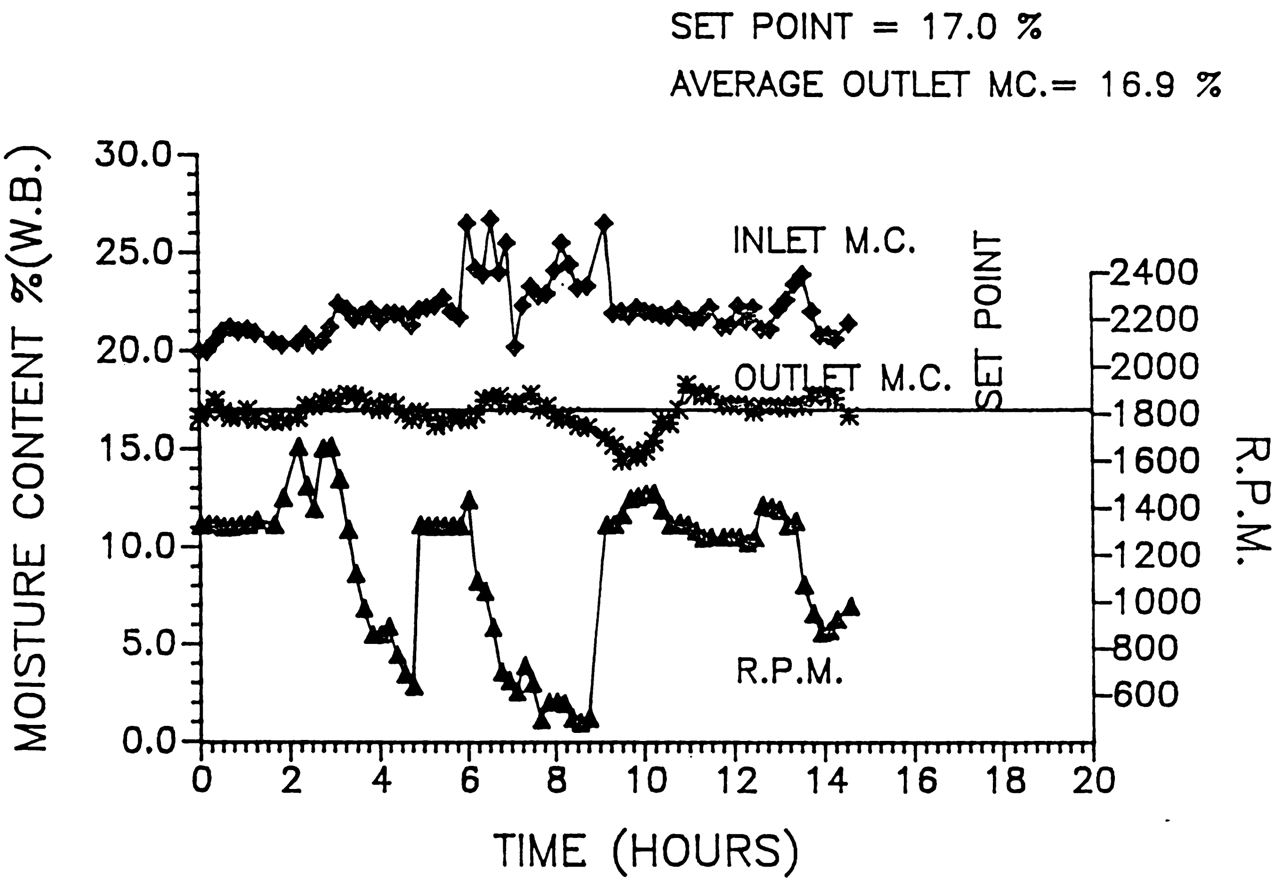

Figure 6.30 Inlet and Outlet Moisture Contents, and RPM vs Time During Automatic Control of the Zimmerman ATP 5000 Dryer of Test #11.

Figure 6.31 shows the results of test #12. The inlet moisture content ranged between 19.9% and 23.5% which differs only by 2.4% and 6% from the set point, respectively. The average grain outlet moisture content after 13 hours of drying was 17% for a set point of 17.5%; the grain was overdried by .5%. The overdrying can be attributed partially to the maximum level reached by the controller (i.e. the controller had adjusted the auger rpm to its maximum value). The maximum rpm occurred because of the small amount of moisture removed. Manual control during start up contributed to the overdrying of the grain, the average grain outlet moisture content, excluding the first two hours of start-up, is 17.24%.

Test #13 is shown in Figure 6.32. The inlet moisture content varied from 16.1% to 25.5% during the 12 hours of drying. The average grain outlet moisture content was .5% below the set point. The controller reached saturation four times for a minimum of one hour duration. The 16.1% grain inlet moisture content was 1.4% below the set point, because the controller was not allowed to speed up the rpm of the unload auger to the desired value. Overdrying of part of the grain was thus unavoidable.

The grain inlet moisture content sample in the Zimmerman dryer was taken at the wet leg conveyor at ground level and not at the dryer inlet. The location of the inlet sample port deleteriously affected the operation of the control system, because the controller reacted to an inprecise value of inlet moisture content. This had a significant effect on the controller performance when a large and sudden changes occurred in the inlet moisture content. To eliminate this time effect, a delay was introduced in the control algorithm. The main purpose of the delay is to delay the controller reaction to the measured inlet moisture content for a period equal to the time for the grain mass

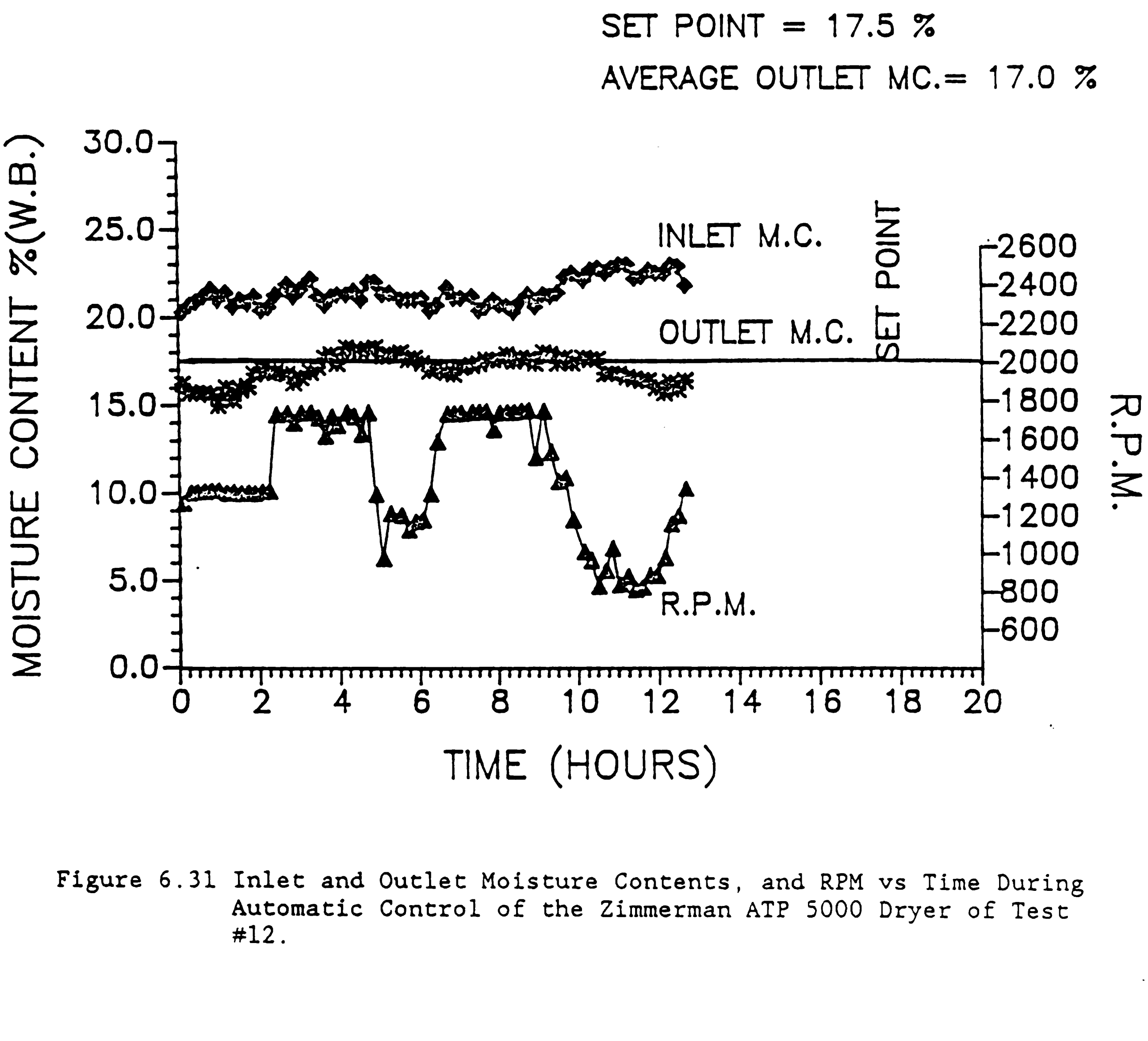

Figure 6.31 Inlet and Outlet Moisture Contents, and RPM vs Time During Automatic Control of the Zimmerman ATP 5000 Dryer of Test #12.

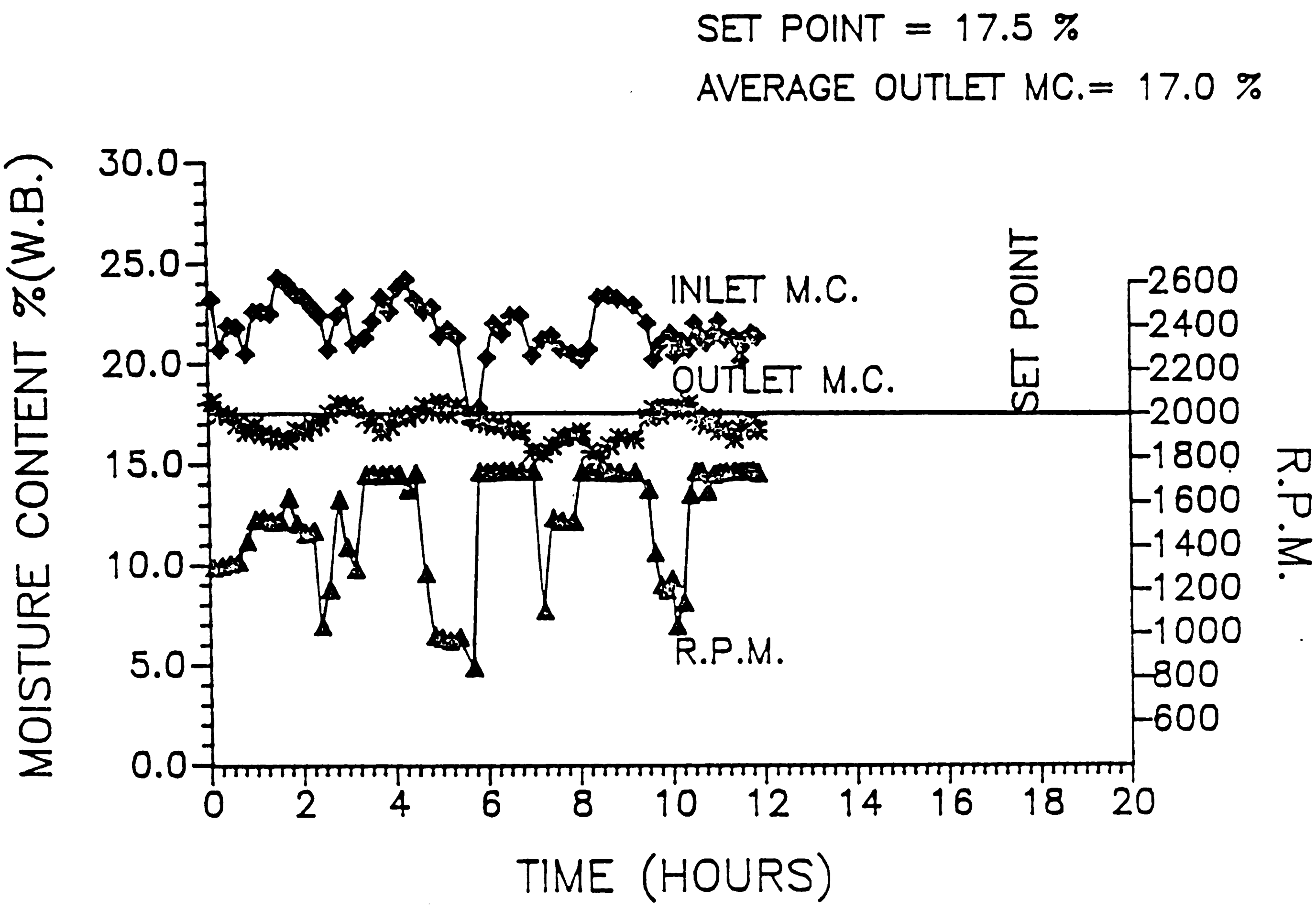

Figure 6.32 Inlet and Outlet Moisture Contents, and RPM vs Time During Automatic Control of the Zimmerman ATP 5000 Dryer of Test #13.

(represented by the present inlet moisture content sample) to reach the dryer entrance. The required time(delay) was calculated based on the current grain flow rate and the capacity of the wet leg.

Test #14 with the Zimmerman dryer is shown in Figure 6.33. The test was conducted with the above modification incorporated in the control system algorithm. The grain inlet moisture content had a minimum of 17.9% and a maximum of 26.3%. At the start of the test the grain inlet and outlet moisture contents were almost the same. The average grain outlet moisture content during 12.5 hours of drying was 16.6%, only .1% above the set point. The auger reached the maximum rpm when very low moisture content grain entered the dryer. The limitation of the auger speed resulted in overdrying two hours later. The introduction of the delay in the control algorithm improved the control system performance of the Zimmerman dryer (compared test #13 and 14).

The summary of the results obtained from the tests conducted with the Zimmerman dryer is shown in Table 6.8.

6.3 Performance Index

The objective of an automatic control system is to control the process so that the output is close to the set point. In grain drying, the objective of the control system is to control the drying process of the grain entering a dryer to a set moisture content, regardless of the variation in the inlet moisture content or the drying conditions.

To compare results obtained using different control system strategies or different tests for the same control strategy, a performance index needs to be established. The performance index should account for overdrying or underdrying, and for the rate of drying or the rate of inlet moisture content changes.

Thus, it is reasonable to incorporate the deviation of the grain outlet moisture content from the set point,the change in the grain

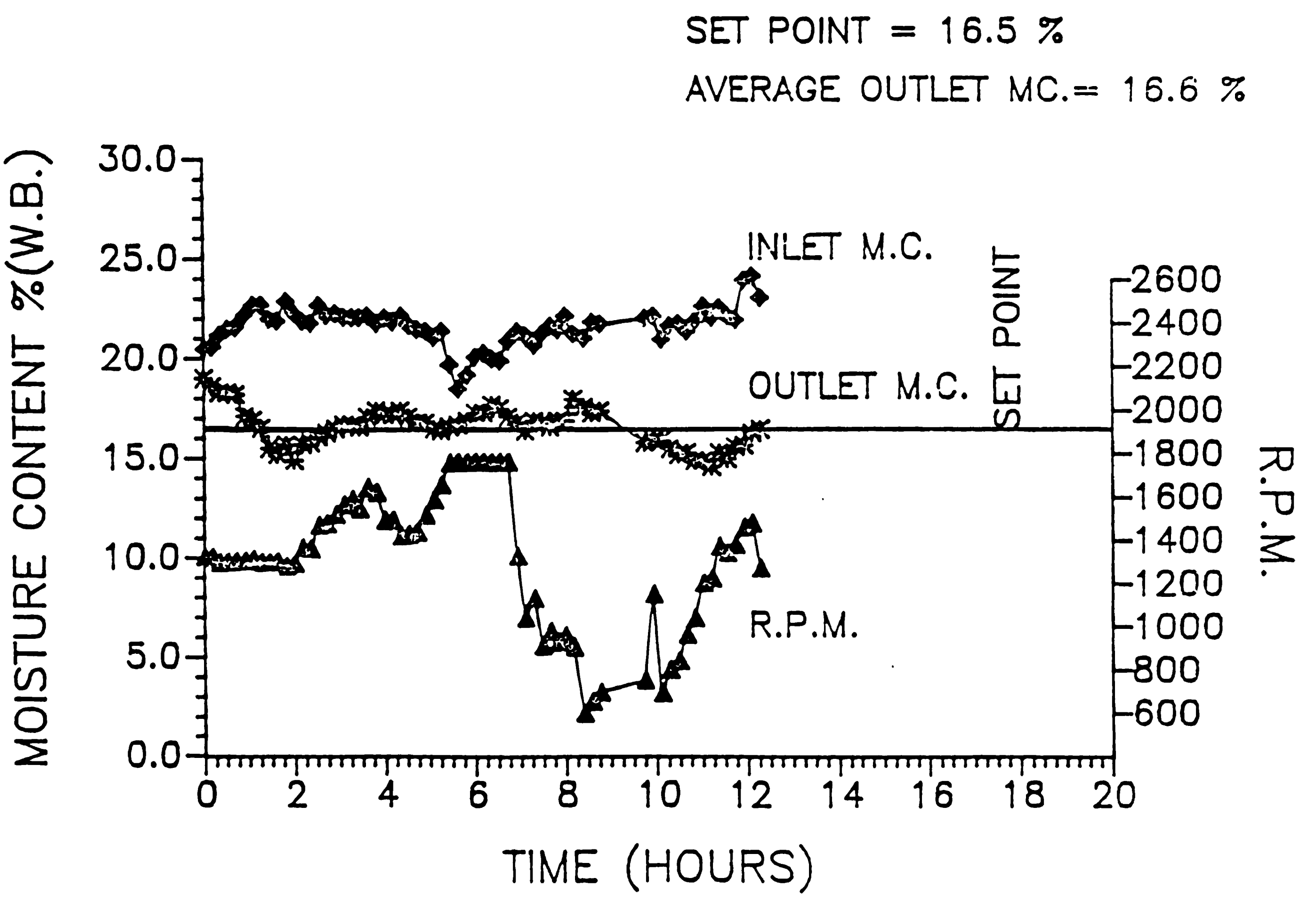

Figure 6.33 Inlet and Outlet Moisture Contents, and RPM vs Time During Automatic Control of the Zimmerman ATP 5000 Dryer of Test #14.

Table 6.8 Summary of the results obtained from the different control tests (see Tables A.11-A.14) with the Zimmerman ATP 5000 dryer.

	Test Number			
	11	12	13	14
Date :	12/15/86	12/16/86	12/19/86	01/15/87
Ave Inlet MC	22.1	21.4	21.7	21.6
Min Inlet MC	19.1	19.9	16.1	17.9
Max Inlet MC	31.5	23.5	25.5	26.3
Set Point	17.0	17.5	17.5	16.5
Ave Outlet MC	16.9	17.0	17.0	16.6
Min Outlet MC	14.3	14.9	14.6	14.4
Max Outlet MC	18.6	18.5	20.0	19.1
Ave RPM	1148	1390	1513	1294
Min RPM	481	811	848	554
Max RPM	1662	1749	1746	1765

inlet moisture content, and the grain flow rate into the performance index. Different performance indices are investigated in this section to evaluate the control strategies of certain automatic control systems. The performance indices are:

$$PI1 = \int_0^T e^2 \, (Gp/1000)dt = \sum_{i=2}^{n} e_i^2 \, (Gp_i/1000) \, (t_i - t_{i-1}) \qquad (6.1)$$

$$PI2 = \int_0^T e^2 \, (Gp/1000)(Min-Mina)^{-2}dt$$

$$= \sum_{i=2}^{n} e_i^2 (Gp_i/1000)(Min_i-Mina)^{-2}(t_i-t_{i-1}) \qquad (6.2)$$

$$PI3 = \int_0^T e^2(Gp/1000)(Min_+ - Min)^{-2}dt$$

$$= \sum_{i=2}^{n} e_i^2(Gp_i/1000)(Min_i - Min_{i-1})^{-2}(t_i-t_{i-1}) \qquad (6.3)$$

$$PI4 = \int_0^T e^2(Gp/100)dt / \int_0^T (Min-Mina)^2dt$$

$$= \sum_{i=2}^{n} e_i^2(Gp_i/100)(t_i-t_{i-1}) / \sum_{i=2}^{n} (Min_i - Mina)^2(t_i-t_{i-1}) \qquad (6.4)$$

$$PI5 = \int_0^T e^2(Gp/100)dt / \int_0^T (Min_+ - Min)^2dt$$

$$= \sum_{i=2}^{n} e_i^2 (Gp_i/100)(t_i - t_{i-1}) / (\sum_{i=2}^{n} (Min_i - Min_{i-1})^2 (t_i - t_{i-1}) \quad (6.5)$$

$$PI6 = \text{STD of grain outlet m.c./STD of grain inlet m.c.} \quad (6.6)$$

$$PI7 = \int_0^V e^2 dv = \int_0^V e^2 Gp\ dt \quad (6.7)$$

$$PI8 = \int_0^V e^2 (Min - Mina)^{-2} dv \quad (6.8)$$

where

- e = outlet m.c. - set point
- Gp = grain flow rate bushels/hr
- Min = inlet moisture content (%,W.B.)
- Mina = average inlet moisture content (%,W.B.)
- Min_+ = inlet moisture content at time t+dt
- PI = performance index
- t = time, hours.
- STD = standard deviation

Equations 6.1 through 6.8 have been evaluated for several tests conducted with the Meyer-Morton 850 dryer; the summary of the results is shown in Table 6.7. Table 6.9 gives the results of evaluating the performance indices of the tests in Table 6.7.

A ranking of the different tests according to the different performance indices is shown in Table 6.10. PI4 to PI6 rank test #8 as the best, whereas PI1 ranks test #8 as the worst. This is expected since the inlet moisture content of the grain is not included in PI1, and test #8 has the largest variation in the inlet moisture content of the eleven experimentally conducted tests. The large change in the grain inlet moisture content contributes to the overdrying and underdrying and results in the larger value of PI1 for test #8. PI3 ranks test #8 near the bottom due to the constant inlet moisture encountered after two hours of drying (see Section 6.2.1).

The grain inlet moisture content is included in PI2 and PI3 by dividing the square of the error (outlet m.c. - set point) by the square of the difference between the present grain inlet moisture content and the average inlet moisture content or the previous inlet moisture content. Dividing by the square of the inlet moisture content difference, creates a problem when the difference is zero or very close to zero. When division by zero takes place, the result is an indefinite value. Dividing by a small number results in over-penalizing the control system when there is no variation in the inlet moisture content or (PI3 for test #8) the variation is very small. Therefore, PI2 and PI3 are inappropriate as performance indices.

PI4 and PI5 are modifications of PI2 and PI3, respectively. In PI4 and PI5 the square of the present difference in the inlet moisture content is replaced by the overall sum of the square of the difference in the inlet moisture content either, the average inlet moisture content or the previous inlet moisture content. The ranking of the tests is similar.

PI6 is simple and useful as a quick check of control system performance. The index indicates how the control system performs in reducing the variation in the grain inlet moisture.

PI7 and PI8 are not evaluated numerically because of their similarity to PI1 and PI2. The drawback of PI1 and PI2 is also applicable to PI7 and PI8.

PI4, PI5, and PI6 were used to compare tests #2 and #8 from the dryer control tests with the exponential drying model (see Table 6.11a and b); tests #10 and 11 were obtained using the control algorithm with the linear drying model. Using PI4, PI5, PI6, the rankings of the above tests is shown in Table 6.11b. Test #8 is ranks at the top while test #11 is ranked at the bottom. Test #10 ranks second followed by test #2. The three performance indices are consistent in their ranking due to their similarity.

Test #11 is expected to be ranked low since the dryer was running for a shorter period of time compared to other tests. Thus, some consideration must also be given to the length of the test since tests with a longer running time have a better chance to be ranked high.

It must be stressed that control systems of grain dryers should be grouped according to the similarity of conditions faced during the operations.

In conclusion, the idea of using a performance index to evaluate a control system has merit. However, it must be emphasized that a performance index must be closely examined so that a control system is not penalized when it encounters a difficult to control drying operation. Finally, PI4, PI5, and PI6 are recommended for measuring the performance of a dryer control system.

6.4 CONCLUSIONS

In order to develop an automatic dryer controller, a dryer process-model is required. For this purpose, a basic heat and mass transfer differential equation crossflow-drying model has been developed, and validated with experimental data collected from a commercial crossflow

Table 6.9 Performance indices for the different control tests in Table 6.7.

Test No.	PI1	PI2	PI3	PI4	PI5	PI6
1	2.3	103.1	33.3	.6	.8	.9
2	6.9	205.9	150.6	1.5	.4	1.4
3	1.4	291.8	46.2	3.9	2.3	2.5
4	1.4	76.0	51.5	.4	.8	.8
5	1.7	175.9	60.0	1.4	2.4	1.4
6	4.1	77.0	122.3	4.8	3.7	1.7
7	4.3	21.6	31.4	.2	.3	.7
8	7.6	36.1	151.8	.1	.2	.2
9	6.9	314.9	147.6	3.3	2.7	1.5
10	3.1	117.4	82.2	.9	.6	1.0
11	6.2	115.4	159.2	6.1	5.9	2.1

Table 6.10 Ranking of different control tests according to the different PIs.

PI1	PI2	PI3	PI4	PI5	PI6
3	7	7	8	8	8
4	8	1	7	7	7
5	4	3	10	10	4
1	6	4	1	1	1
10	1	5	4	4	10
6	11	10	3	3	5
7	10	6	5	5	2
11	5	9	9	9	9
2	2	2	6	6	6
9	3	8	2	2	11
8	9	11	11	11	3

Table 6.11a Performance indices for tests 2,8,10, and 11.

Test No.	PI4	PI5	PI6
2	1.5	3.8	1.4
8	.1	.2	.2
10	.9	.6	1.0
11	6.1	5.9	2.1

Table 6.11b Ranking of tests 2,8,10, and 11.

PI4	PI5	PI6
8	8	8
10	10	10
2	2	2
11	11	11

dryer. The new model requires excessive computer time but played a fundamental role in the development of two empirical process models. Both empirical models were employed, in conjunction with a dryer control algorithm, as essential components in the automatic control system.

A series of successful tests were conducted with the feedforward moisture content-based controller on two commercial dryers over a period of two drying seasons. The controller controlled the outlet moisture content well even for large and rapid inlet grain moisture changes. The new automatic controller appears to be stable, durable and accurate. Commercial application of the controller by the grain-processing industry will only be a matter of time. Adoption of the unit will result in improved grain quality, decreased energy consumption, and better record-keeping.

CHAPTER 7

7. SUMMARY

1. An unsteady state differential-equation simulation model for crossflow grain drying has been developed.

2. Two simplified empirical drying models for the automatic control of crossflow dryers have been developed.

3. A control algorithm has been developed for crossflow grain drying using a simplified empirical drying model and a feedforward with feedback trim control algorithm.

4. The control algorithm has been incorporated into a commercial on-line moisture-measuring system to form an automatic control system for crossflow grain dryers.

5. The control system has been implemented and successfully tested on several commercial crossflow grain dryers; the control system consists of a microcomputer, a semi-continuous moisture meter, a tachometer, and the control/dryer-model software.

6. The average outlet moisture content in the commercial dryers was controlled to ±0.6% of the set point during two drying seasons; the inlet grain moisture content variation in one hour was much as 9%.

7. The newly developed crossflow dryer automatic control system was found to be stable during all experimental and simulated tests.

CHAPTER 8

SUGGESTIONS FOR FUTURE STUDY

1. Test the control system on different dryer types (i.e. mixed-flow, concurrent-flow, fluidized bed dryers).
2. Test the control system on multi-stage grain dryers.
3. Test the control system for different grain types (i.e. wheat, soybeans, rice, etc.).
4. Develop a control strategy which modulates the drying air temperature, and possibly the airflow rate, in addition to the grainflow rate.
5. Analyze the advantage of a control strategy based on the rate of change of the inlet grain moisture content.
6. Develop auxiliary software programs to complement the basic control software (i.e. plot the data, calculate and print summary of tests results, etc.).
7. Evaluate the effect of different pseudo inlet moisture contents on the performance of the control system.
8. Analyze the employment of different numerical techniques to reduce the CPU time of the control system simulation model.
9. Study the effect of variations in air and grain parameters on the simulation results of the unsteady state crossflow drying model.
10. Study the effect of MC valve location and the importance of the inlet MC measurement accuracy on the control system performance.
11. Evaluate the economical feasibility of use of the control system.

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10. APPENDICES

A. Experimental Results

B. Simulation Results

C. Specifications for the Data Acquisition Components

APPENDIX A :Experimental Results

Table A.1 Experimental results of an automatic control test on a crossflow grain dryer.
Test Number : 1
Date : 12/9/1985
Dryer Type : Meyer-Morton Model 850
Set Point : 14.5%(w.b.)

Sample #	Time hr	Inlet MC % w.b.	Outlet MC % w.b.	R.P.M.
1	0.00	21.7	13.9	817
2	0.14	21.1	14.3	834
3	0.27	21.2	14.3	834
4	0.39	21.2	14.3	817
5	0.52	21.5	13.7	817
6	0.65	21.3	13.5	834
7	0.80	21.5	13.5	817
8	0.92	21.8	13.9	834
9	1.04	21.6	14.5	834
10	1.17	21.5	13.9	872
11	1.32	22.1	13.8	872
12	1.45	21.7	13.7	834
13	1.59	22.4	14.1	834
14	1.70	22.4	13.6	834
15	1.85	21.9	14.3	872
16	1.99	22.1	13.0	914
17	2.12	22.1	13.8	914
18	2.24	21.7	14.6	893
19	2.37	21.5	14.6	914
20	2.50	22.0	15.0	872
21	2.64	22.8	14.7	893
22	2.80	22.5	13.7	893
23	2.94	22.1	15.2	834
24	3.07	22.4	15.3	834
25	3.20	23.0	15.4	853
26	3.34	22.0	15.7	872
27	3.47	22.1	14.9	800
28	3.59	21.8	15.5	783
29	3.72	22.6	15.5	817
30	3.84	23.5	13.9	783
31	3.97	22.3	15.6	738
32	4.10	23.5	14.7	738
33	4.22	22.5	15.9	724
34	4.35	22.4	14.7	724
35	4.49	22.8	14.6	738
36	4.62	23.1	14.4	752
37	4.74	23.4	14.7	724
38	4.87	23.2	15.3	724
39	5.04	23.1	14.0	711
40	5.17	23.5	14.2	738
41	5.29	22.9	15.0	711
42	5.40	22.3	14.2	698
43	5.55	21.9	15.2	724
44	5.69	20.8	14.1	711

45	5.82	22.9	13.6	738
46	5.94	23.6	14.6	738
47	6.09	23.5	14.8	724
48	6.20	22.1	13.7	738
49	6.34	23.0	14.7	724
50	6.47	22.5	13.8	711
51	6.60	23.0	13.5	768
52	6.72	22.6	13.7	752
53	6.85	22.5	13.6	800
54	6.97	22.3	13.3	800
55	7.10	23.0	14.3	834
56	7.24	22.8	14.1	872
57	7.37	22.4	15.6	872
58	7.50	22.6	14.7	834
59	7.64	22.3	14.5	834
60	7.75	23.3	14.6	834
61	7.90	22.4	14.1	817
62	8.04	22.3	14.3	800
63	8.17	22.6	15.0	834
64	8.30	23.1	15.2	853
65	8.44	22.3	15.3	834
66	8.57	21.7	14.7	834
67	8.70	22.2	14.5	834
68	8.82	21.9	14.7	834
69	8.97	21.6	14.0	834
70	9.10	21.0	13.8	834
71	9.25	21.1	14.5	893
72	9.39	21.2	14.7	893
73	9.52	21.6	14.1	914
74	9.65	22.1	15.2	914
75	9.79	21.2	14.4	893
76	9.92	21.6	14.3	914
77	10.05	22.3	14.4	914
78	10.19	21.9	13.7	914
79	10.32	22.1	15.1	960
80	10.45	21.8	14.8	936
81	10.60	22.2	14.7	914
Ave		22.2	14.4	821
Std		0.7	0.6	67
Min		20.8	13.0	698
Max		23.6	15.9	960

Table A.2 Experimental results of an automatic control test on a crossflow grain dryer

Test Number : 2
Date : 12/13/1985
Dryer Type : Meyer-Morton Model 850
Set Point : 14.5%(w.b.)

Sample #	Time hr	Inlet MC % w.b.	Outlet MC % w.b.	R.P.M.
1	0.00	25.2	12.8	783
2	0.13	24.2	13.2	783
3	0.28	24.4	12.8	834
4	0.43	24.6	12.5	783
5	0.56	25.2	12.6	800
6	0.71	24.7	13.4	817
7	0.83	25.0	14.2	817
8	0.98	24.8	14.5	853
9	1.11	24.3	16.6	872
10	1.25	23.9	15.5	834
11	1.38	24.3	16.6	872
12	1.55	23.6	15.8	872
13	1.66	23.7	16.9	834
14	1.80	23.7	17.8	834
15	1.95	23.8	16.7	893
16	2.08	24.3	17.8	752
17	2.21	24.0	16.8	673
18	2.35	24.8	16.2	711
19	2.48	23.8	16.8	662
20	2.60	24.1	17.0	662
21	2.78	23.7	16.0	650
22	2.86	23.6	15.6	662
23	2.98	23.7	15.8	650
24	3.13	23.4	15.3	662
25	3.25	23.7	15.2	673
26	3.38	23.9	14.9	685
27	3.51	23.1	16.3	673
28	3.65	23.7	15.0	673
29	3.80	23.5	15.3	685
30	3.91	23.3	14.9	650
31	4.05	22.5	15.9	640
32	4.20	22.9	14.7	629
33	4.31	23.4	14.3	650
34	4.46	23.0	14.9	650
35	4.58	23.4	15.3	673
36	4.73	22.9	13.9	662
37	4.85	23.2	15.8	673
38	5.00	23.0	14.2	673
39	5.15	22.4	14.5	698
40	5.28	23.2	14.6	662
41	5.41	23.1	14.9	685
42	5.56	23.2	14.2	685
43	5.71	23.2	14.6	711
44	5.85	23.1	13.3	673
45	6.00	23.1	14.8	698
46	6.13	23.3	13.8	698
47	6.26	23.0	15.3	711

48	6.40	22.9	13.5	698
49	6.55	22.5	13.9	698
50	6.70	22.1	14.9	724
51	6.83	23.6	13.9	724
52	6.96	22.5	14.9	724
53	7.15	22.1	14.1	711
54	7.30	22.1	14.8	711
55	7.45	22.6	15.9	711
56	7.56	23.1	14.8	711
57	7.73	22.6	15.3	662
58	7.86	22.4	13.7	662
59	8.00	22.3	15.3	673
60	8.15	21.9	14.5	673
61	8.28	22.1	14.4	711
62	8.41	22.0	14.1	698
63	8.56	23.0	16.0	711
64	8.70	21.7	14.3	724
65	8.85	22.6	14.7	698
66	8.98	22.7	14.9	711
67	9.13	22.4	14.4	673
68	9.26	22.3	14.1	698
Ave		23.3	14.9	717
Std		0.8	1.2	67
Var		0.7	1.4	4509
Min		21.7	12.5	629
Max		25.2	17.8	893

Table A.3 Experimental results of an automatic control test on a crossflow grain dryer
Test Number : 3
Date : 12/14/1985
Dryer Type : Meyer-Morton Model 850
Set Point : 14.5%(w.b.)

Sample #	Time hr	Inlet MC % w.b.	Outlet MC % w.b.	R.P.M.
1	0.00	21.6	15.4	724
2	0.13	21.4	14.1	724
3	0.27	21.7	14.6	738
4	0.42	22.0	15.3	752
5	0.55	21.9	14.9	724
6	0.70	22.0	14.6	738
7	0.83	21.7	15.4	738
8	0.97	21.4	14.0	724
9	1.12	21.8	14.9	724
10	1.25	21.6	14.8	724
11	1.40	21.8	13.4	698
12	1.53	21.6	15.9	698
13	1.68	21.4	15.3	698
14	1.82	21.7	14.6	711
15	1.95	21.6	14.5	711
16	2.08	21.5	15.7	673
17	2.22	21.3	14.3	673
18	2.37	21.5	15.0	698
19	2.50	21.4	14.4	673
20	2.65	21.5	14.0	724
21	2.78	21.9	13.7	711
22	2.92	21.1	15.2	711
23	3.07	21.5	14.6	724
24	3.20	21.1	13.7	738
25	3.35	21.6	13.9	724
26	3.50	21.5	14.8	724
27	3.65	21.0	14.2	738
28	3.78	21.5	13.9	738
29	3.92	21.7	15.3	738
30	4.07	21.4	14.7	738
31	4.22	21.7	14.5	711
32	4.35	21.3	14.4	724
33	4.50	21.5	15.6	752
34	4.63	21.6	14.1	711
35	4.77	21.5	14.4	698
36	4.90	21.1	14.3	698
37	5.05	21.4	14.2	711
38	5.22	21.0	14.2	711
39	5.37	21.7	14.3	724
40	5.50	21.4	15.0	752
41	5.63	21.5	13.7	724
42	5.77	21.6	14.9	711
43	5.92	21.4	15.0	711
44	6.07	21.0	13.8	711
45	6.22	21.5	14.5	711
46	6.35	21.1	13.6	752
47	6.50	21.3	14.5	738
48	6.65	21.3	14.4	752

49	6.80	21.4	13.4	752
50	6.93	21.6	15.9	752
51	7.07	21.0	14.8	724
52	7.22	21.4	13.8	738
53	7.37	21.3	14.5	711
54	7.50	21.2	15.3	724
55	7.65	21.5	14.5	724
56	7.78	21.0	13.9	724
57	7.93	21.4	15.6	724
Ave		21.5	14.6	722
Std		0.2	0.6	19
Var		0.1	0.4	371
Min		21.0	13.4	673
Max		22.0	15.9	752

Table A.4 Experimental results of an automatic control test on a crossflow grain dryer
Test Number : 4
Date : 12/15/1985
Dryer Type : Meyer-Morton Model 850
Set Point : 15.%(w.b.)

Sample #	Time hr	Inlet MC % w.b.	Outlet MC % w.b.	R.P.M.
1	0.00	21.6	14.5	783
2	0.14	21.9	15.3	800
3	0.30	22.0	15.2	800
4	0.45	22.1	14.9	783
5	0.59	22.0	15.2	800
6	0.72	22.4	15.4	817
7	0.85	22.7	15.1	817
8	0.99	22.6	14.7	783
9	1.12	22.6	14.4	783
10	1.25	22.7	15.9	738
11	1.40	22.2	14.7	738
12	1.52	22.3	15.7	738
13	1.65	22.4	15.7	711
14	1.79	22.3	16.3	711
15	1.92	22.5	15.1	673
16	2.10	22.2	14.9	673
17	2.22	22.5	15.4	685
18	2.37	22.4	14.0	673
19	2.52	22.1	15.4	724
20	2.65	22.2	14.8	711
21	2.77	24.0	14.5	724
22	2.89	24.6	14.3	724
23	3.07	24.2	14.7	698
24	3.20	23.7	14.8	685
25	3.32	24.1	14.8	698
26	3.44	22.1	14.2	698
27	3.57	23.6	13.9	724
28	3.77	23.8	15.3	685
29	4.44	23.5	14.9	640
30	4.57	23.1	16.2	650
31	4.69	23.3	15.9	650
32	4.80	23.8	15.1	650
33	4.94	23.9	16.0	619
34	5.05	23.2	15.6	609
35	5.20	23.7	14.9	629
36	5.32	24.0	14.4	629
37	5.44	23.8	14.5	673
38	5.57	23.9	15.0	673
39	5.70	23.7	14.4	662
40	5.82	23.7	15.0	662
41	6.07	23.4	14.9	650
42	6.22	24.6	14.5	650
43	6.35	24.2	14.8	650
44	6.49	23.7	15.4	650
45	6.60	23.2	14.4	640
46	6.74	23.4	14.3	640
47	6.87	23.8	14.5	662
48	6.99	23.6	14.4	650

49	7.12	24.0	15.0	673
50	7.25	24.1	14.0	673
51	7.39	23.8	14.1	698
52	7.50	24.0	14.0	673
53	7.64	23.5	15.3	711
54	7.75	23.9	14.2	711
55	7.90	23.4	15.4	724
56	8.02	23.8	16.2	698
57	8.20	23.3	14.0	662
58	8.29	23.9	15.0	698
59	8.44	23.3	14.6	673
60	8.57	23.9	14.7	698
61	8.70	24.1	16.5	685
62	8.82	23.4	14.7	685
63	8.97	23.2	14.6	698
64	9.09	23.0	15.9	662
65	9.24	22.7	14.5	685
66	9.37	23.0	15.0	685
67	9.50	22.9	14.7	698
Ave		23.2	14.9	696
Std		0.7	0.6	49
Var		0.6	0.4	2426
Min		21.6	13.9	609
Max		24.6	16.5	817

Table A.5 Experimental results of an automatic control test on a crossflow grain dryer
Test Number : 5
Date : 12/19/1985
Dryer Type : Meyer-Morton Model 850
Set Point : 15%(w.b.)

Sample #	Time hr	Inlet MC % w.b.	Outlet MC % w.b.	R.P.M.
1	0.00	21.1	13.2	752
2	0.11	21.1	14.0	768
3	0.25	21.1	13.5	768
4	0.38	21.3	13.4	768
5	0.51	20.9	14.7	783
6	0.65	21.0	13.5	783
7	0.76	20.6	14.5	783
8	0.93	21.0	14.3	768
9	1.05	21.3	14.4	783
10	1.16	21.2	14.2	783
11	1.30	20.6	14.7	783
12	1.41	21.3	14.0	783
13	1.53	21.3	14.5	768
14	1.65	21.1	15.1	783
15	1.78	21.1	14.6	768
16	1.93	21.0	15.2	783
17	2.06	21.2	13.7	768
18	2.18	20.6	14.3	783
19	2.30	20.7	13.1	800
20	2.41	20.7	15.0	817
21	2.53	21.3	14.4	872
22	2.66	21.3	14.9	872
23	2.78	21.3	14.9	817
24	2.90	21.2	14.5	872
25	3.01	20.8	13.9	817
26	3.15	20.7	15.4	817
27	3.26	21.1	14.5	893
28	3.38	21.3	14.6	893
29	3.51	21.2	14.9	893
30	3.63	20.7	14.9	893
31	3.75	20.9	14.9	872
32	3.88	20.0	14.6	893
33	4.01	21.0	15.1	893
34	4.13	20.9	15.0	893
35	4.30	20.5	14.8	893
36	4.41	20.7	14.2	872
37	4.53	20.3	14.6	914
38	4.66	20.2	14.5	914
39	4.83	20.6	15.5	960
40	4.96	20.5	15.0	960
41	5.08	20.5	15.5	914
42	5.21	20.6	15.2	936
43	5.33	20.4	15.2	893
44	5.45	20.1	14.3	872
45	5.58	20.2	15.0	914
46	5.70	20.2	15.2	914
47	5.83	20.2	15.2	914
48	5.95	20.3	15.1	914

49	6.06	20.5	15.1	914
50	6.20	20.2	15.0	914
51	6.31	20.1	15.1	893
52	6.45	19.8	15.6	893
53	6.56	20.3	15.2	893
54	6.68	20.3	15.7	936
55	6.81	20.4	15.2	853
56	6.93	20.4	15.1	853
57	7.06	20.2	14.9	853
58	7.20	20.6	15.8	834
59	7.33	20.8	14.9	893
60	7.45	20.2	14.9	872
61	7.58	20.5	15.0	834
62	7.71	20.5	14.9	817
63	7.90	20.4	14.8	834
64	8.01	20.2	15.1	834
65	8.15	20.2	14.9	872
66	8.26	20.1	14.8	817
67	8.40	20.4	15.0	834
68	8.53	20.4	15.3	872
69	8.66	20.4	15.7	872
70	8.80	20.4	14.8	834
71	8.91	20.4	14.8	800
72	9.05	20.4	15.4	800
73	9.18	20.3	15.0	834
74	9.35	20.0	15.0	834
75	9.55	20.2	14.7	800
Ave		20.6	14.8	849
Std		0.4	0.6	55
Var		0.2	0.3	2996
Min		19.8	13.1	752
Max		21.3	15.8	960

Table A.6 Experimental results of an automatic control test
on a crossflow grain dryer.
Test Number : 6
Date : 12/20/1985
Dryer Type : Meyer-Morton Model 850
Set Point : 14.5%(w.b.)

Sample #	Time hr	Inlet Mc % w.b.	Outlet MC % w.b.	R.P.M.
1	0.00	21.1	14.5	872
2	0.14	20.2	15.0	872
3	0.30	20.6	15.0	872
4	0.52	20.1	14.5	872
5	0.69	21.0	15.3	872
6	0.87	20.8	15.2	914
7	1.00	20.7	16.2	872
8	1.14	20.4	15.6	893
9	1.92	20.7	15.8	872
10	2.04	21.2	14.9	853
11	2.15	21.1	15.9	853
12	2.30	21.2	15.3	834
13	2.44	20.8	15.7	817
14	2.59	21.0	15.7	817
15	2.70	20.9	16.0	817
16	2.95	21.6	15.4	853
17	3.09	20.6	16.2	783
18	3.22	20.8	15.6	783
19	3.34	20.8	15.7	768
20	3.49	20.6	16.2	800
21	3.60	20.7	15.0	738
22	3.74	20.5	16.0	738
23	3.87	20.8	14.4	724
24	4.00	21.0	15.9	738
25	4.14	20.8	14.6	738
26	4.25	21.2	15.5	738
27	4.37	20.8	14.8	738
28	4.50	21.1	15.3	738
29	4.64	21.1	14.8	738
30	4.75	21.0	14.5	752
31	4.89	21.2	15.2	724
32	5.05	20.5	14.5	738
33	5.17	21.2	14.5	768
34	5.29	21.1	14.8	738
35	5.42	21.1	14.2	738
36	5.54	21.2	14.5	738
37	5.67	21.5	16.0	752
38	5.80	21.1	14.6	768
39	5.92	21.3	15.6	724
40	6.05	21.2	13.8	724
41	6.17	20.8	14.9	711
42	6.32	20.9	15.3	724
43	6.47	20.8	16.0	752
44	6.59	21.0	14.6	752
45	6.74	21.0	14.7	724
46	6.87	21.0	15.3	724
47	7.00	21.1	14.5	768
48	7.17	20.7	15.0	724

	49	7.30	20.8	15.0	738
	50	7.44	21.4	14.6	783
	51	7.57	21.9	14.1	752
	52	7.70	21.2	15.3	752
	53	7.84	21.1	14.2	800
	54	7.95	21.4	15.2	752
	55	8.07	21.6	14.4	752
	56	8.20	21.3	15.1	752
	57	8.32	21.3	14.6	738
	58	8.45	21.2	14.2	768
	59	8.57	21.7	15.5	738
	60	8.69	21.6	14.2	752
	61	8.82	21.0	15.2	738
	62	8.97	20.7	14.9	738
	63	9.09	20.7	15.6	752
	64	9.24	20.7	15.3	783
	65	9.37	21.3	14.9	752
	66	9.50	20.5	15.6	752
	67	9.62	20.8	14.4	768
	68	9.75	21.4	15.5	752
	69	9.89	21.1	14.5	783
	70	10.00	21.2	15.3	752
	71	10.14	20.9	14.3	800
	72	10.25	20.7	15.4	768
	73	10.40	21.3	15.5	817
	74	10.59	21.2	14.5	783
	75	10.72	21.2	14.8	752
	76	10.84	21.0	14.5	752
	77	10.97	20.7	14.9	768
	78	11.12	21.3	15.0	768
Ave			21.0	15.1	775
Std			0.3	0.6	49
Var			0.1	0.3	2407
Min			20.1	13.8	711
Max			21.9	16.2	914

Table A.7 Experimental results of an automatic control test
on a crossflow grain dryer
Test Number : 7
Date : 10/9/1986
Dryer Type : Meyer-Morton Model 850
Set Point : 14%(w.b.)

Sample #	Time hr	Inlet MC % w.b.	Outlet MC % w.b.	R.P.M.
1	0.00	25.9	12.4	518
2	0.15	25.2	13.1	533
3	0.28	25.1	13.0	640
4	0.41	24.9	11.1	650
5	0.55	24.5	11.6	711
6	0.70	25.0	12.3	752
7	1.23	24.4	12.9	619
8	1.38	24.8	14.6	619
9	1.51	24.4	13.1	724
10	1.65	25.0	13.7	685
11	1.80	23.8	13.2	711
12	1.93	24.2	12.8	698
13	2.08	27.0	14.0	768
14	2.21	26.2	13.9	768
15	2.35	27.3	14.8	698
16	2.50	28.2	14.4	711
17	2.65	27.9	14.1	619
18	2.80	28.1	13.5	600
19	2.95	26.3	15.0	619
20	3.10	28.7	13.5	650
21	3.23	27.0	15.0	581
22	3.36	27.1	14.9	590
23	3.51	26.7	15.8	540
24	3.65	26.0	14.9	533
25	3.80	27.7	15.8	511
26	3.93	27.5	15.6	511
27	4.08	31.0	16.1	441
28	4.21	28.4	16.3	426
29	4.63	29.4	15.7	498
30	4.78	27.3	16.0	451
31	4.91	27.7	15.6	474
32	5.20	26.3	16.3	462
33	5.35	31.0	14.8	462
34	5.48	27.0	15.8	457
35	5.61	27.1	13.8	436
36	5.76	28.9	14.9	441
37	5.91	28.7	14.5	457
38	6.05	29.9	13.9	468
39	6.20	28.9	13.7	446
40	6.33	26.9	13.6	441
41	6.48	26.1	13.2	457
42	6.63	30.2	13.5	462
43	6.75	27.1	13.5	468
44	6.90	27.6	13.0	486
45	7.03	25.9	13.2	511
46	7.20	29.2	12.5	548
47	7.38	29.6	13.6	548
48	7.51	27.1	13.7	548

	49	7.66	25.4	13.5	556
	50	7.80	27.5	14.2	548
	51	7.93	26.7	13.5	526
	52	8.08	24.5	13.7	526
	53	8.21	24.7	14.3	581
	54	8.36	24.3	13.3	581
	55	8.50	24.9	12.1	650
	56	8.66	24.2	14.6	619
Ave			26.8	14.0	563
Std			1.8	1.2	98
Var			3.4	1.4	9509
Min			23.8	11.1	426
Max			31.0	16.3	768

Table A.8 Experimental results of an automatic control test on a crossflow grain dryer.
Test Number : 8
Date : 10/29/1986
Dryer Type : Meyer-Morton Model 850
Set Point : 14.5%(w.b.)

Sample #	Time hr	Inlet MC % w.b.	Outlet MC % w.b.	R.P.M.
1	0.00	34.3	14.0	724
2	0.13	32.8	14.4	650
3	0.26	31.8	14.6	564
4	0.41	23.7	14.8	548
5	0.56	23.3	14.9	548
6	0.70	29.0	15.1	548
7	0.85	30.8	15.3	548
8	0.98	31.5	16.2	548
9	1.11	32.0	16.6	556
10	1.26	31.2	15.7	548
11	1.40	31.2	16.4	556
12	1.53	30.6	16.0	619
13	1.68	24.4	14.7	600
14	1.81	25.6	13.8	711
15	1.95	20.9	16.3	768
16	2.08	20.5	15.8	783
17	2.23	20.6	15.6	834
18	2.36	29.0	16.2	834
19	2.50	23.4	15.6	711
20	2.63	23.0	14.2	711
21	2.78	21.2	15.7	817
22	2.91	27.6	16.6	800
23	3.05	28.5	16.6	936
24	3.18	29.5	15.7	914
25	3.36	28.5	14.7	752
26	3.53	22.9	15.7	724
27	3.68	20.8	14.1	573
28	3.81	20.5	14.5	573
29	3.95	20.6	14.9	738
30	4.08	20.5	17.1	752
31	4.23	20.7	14.6	783
32	4.36	22.6	15.4	783
33	4.50	21.3	16.3	724
34	4.65	20.6	16.7	724
35	4.78	20.2	16.8	893
36	4.91	20.3	16.1	893
37	5.05	20.6	13.8	1037
38	5.23	20.6	14.2	1010
39	5.38	20.5	13.9	834
40	5.55	21.4	13.6	800
41	5.70	20.7	14.3	936
42	5.83	20.3	13.9	936
43	5.96	20.8	15.3	984
44	6.11	20.6	13.4	984
45	6.25	21.1	14.1	1066
46	6.38	20.5	15.0	1037
47	6.53	20.5	15.4	1037
48	6.66	20.9	14.9	1066

49	6.81	20.8	14.3	984
50	6.98	20.4	14.4	984
51	7.15	20.5	15.7	1037
52	7.28	20.4	15.0	1037
53	7.43	20.5	14.4	1066
54	7.60	20.3	15.8	1066
55	7.76	20.1	14.1	1097
56	7.90	20.1	14.1	1097
57	8.03	19.9	14.1	1129
58	8.18	20.3	14.7	1129
59	8.35	20.5	15.1	1129
60	8.50	20.7	15.6	1129
61	8.63	19.8	15.7	1066
62	8.80	19.5	13.7	1097
63	8.96	20.1	15.6	1200
64	9.10	20.1	15.3	1129
65	9.23	20.0	14.8	1200
66	9.38	20.2	14.1	1129
67	9.55	20.6	14.9	1224
68	9.70	20.6	15.7	1163
69	9.86	20.6	16.3	1200
70	10.00	20.7	15.8	1200
71	10.16	20.7	16.3	1129
Ave		23.0	15.1	882
Std		4.1	0.9	213
Var		17.1	0.8	45200
Min		19.5	13.4	548
Max		34.3	17.1	1224

Table A.9 Experimental results of an automatic control test on a crossflow dryer.
Test Number : 9
Date : 11/14/1986
Dryer Type : Meyer-Morton Model 850
Set Point : 14.5%(w.b.)

Sample #	Time hr	Inlet MC % w.b.	Outlet Mc % w.b.	R.P.M.
1	0.00	19.6	12.5	936
2	0.16	19.3	12.8	960
3	0.36	19.3	13.4	936
4	0.53	19.4	14.0	952
5	0.73	19.4	14.6	960
6	0.90	19.1	14.4	1022
7	1.08	18.9	13.8	992
8	1.21	19.1	14.5	1010
9	1.38	19.2	13.5	1087
10	1.53	19.4	13.9	1028
11	1.70	19.0	14.5	1086
12	1.83	18.9	15.0	1066
13	1.98	19.5	14.4	1037
14	2.15	19.3	14.3	1107
15	2.28	19.5	15.2	1066
16	2.45	19.3	13.5	1066
17	2.58	19.1	13.7	1066
18	2.78	19.1	15.7	1066
19	2.95	19.4	13.7	1076
20	3.11	19.4	14.7	1056
21	3.25	19.4	14.9	1086
22	3.41	19.9	13.8	1119
23	3.58	19.5	14.8	1142
24	3.71	19.9	15.4	1086
25	3.85	18.9	15.4	1101
26	4.01	18.1	14.1	1077
27	4.18	18.2	15.1	1097
28	4.35	18.8	14.0	1086
29	4.48	19.7	13.9	1140
30	4.65	18.2	14.0	1151
31	4.81	18.7	14.4	1239
32	4.96	18.0	14.7	1163
33	5.13	18.6	15.3	1227
34	5.30	18.4	14.3	1151
35	5.45	18.7	14.1	1175
36	5.60	19.7	14.4	1163
37	5.76	19.4	14.8	1151
38	5.91	19.5	13.7	1163
39	6.06	18.9	14.7	1244
40	6.26	19.5	16.0	1164
41	6.41	18.6	13.8	1187
42	6.56	18.7	13.9	1175
43	6.73	19.5	13.7	1280
44	6.90	18.4	14.8	1310
45	7.05	18.6	16.0	1268
46	7.21	18.6	14.2	1280
47	7.41	19.0	14.3	1187
48	7.58	18.6	14.3	1200

	49	7.73	20.5	14.5	1253
	50	7.88	21.0	15.3	1225
	51	8.05	19.0	15.4	1200
	52	8.20	19.8	14.9	1214
	53	8.36	19.0	14.4	1238
	54	8.50	18.7	16.7	1238
	55	8.65	18.6	16.4	1200
	56	8.81	20.4	17.5	1187
	57	8.95	20.6	16.6	992
Ave			19.2	14.6	1125
Std			0.6	0.9	95
Var			0.4	0.9	8951
Min			18.0	12.5	936
Max			21.0	17.5	1310

Table A.10 Experimental results of an automatic control test on a crossflow grain dryer.
Test Number : 10
Date : 11/28/1986
Dryer Type : Meyer-Morton Model 850
Set Point : 13.5%(w.b.)

Sample #	Time hr	Inlet Mc % w.b.	Outlet MC % w.b.	R.P.M.
1	0.00	20.3	14.4	956
2	0.13	19.9	13.7	940
3	0.28	20.1	14.8	936
4	0.41	20.2	14.3	980
5	0.56	20.8	15.1	949
6	0.69	20.5	14.0	879
7	0.84	20.0	14.5	869
8	0.98	20.3	14.5	856
9	1.13	20.5	14.2	856
10	1.26	20.1	14.2	853
11	1.41	20.4	14.2	798
12	1.56	19.7	14.1	783
13	1.69	19.4	14.0	770
14	1.84	19.3	14.1	765
15	2.00	19.7	14.1	856
16	2.13	19.5	14.3	843
17	2.28	19.2	14.3	837
18	2.41	20.4	13.6	850
19	2.56	19.6	13.9	819
20	2.69	19.5	13.4	833
21	2.84	19.4	13.5	863
22	3.00	19.5	13.6	882
23	3.13	19.2	13.4	891
24	3.28	20.1	13.8	872
25	3.41	19.3	14.2	878
26	3.56	18.9	13.2	866
27	3.69	19.5	14.1	934
28	3.84	19.5	13.8	897
29	3.98	19.6	14.1	875
30	4.13	19.5	13.9	882
31	4.28	20.4	14.2	900
32	4.41	20.3	13.9	876
33	4.56	19.6	13.9	876
34	4.71	20.2	14.0	669
35	4.84	20.2	14.0	805
36	5.00	20.0	14.1	805
37	5.15	20.2	13.3	766
38	5.30	20.1	14.2	805
39	5.43	20.3	14.4	755
40	5.58	20.2	14.6	733
41	5.73	20.3	13.8	695
42	5.88	20.1	14.2	720
43	6.02	20.2	14.6	689
44	6.17	20.1	13.6	788
45	6.32	20.3	14.6	622
46	6.47	20.1	14.1	652
47	6.60	20.1	14.0	567
48	6.73	20.0	13.8	571

49	6.90	20.2	14.0	537
50	7.05	20.1	14.1	538
51	7.20	19.7	13.9	519
52	7.35	19.7	13.7	519
53	7.50	19.7	13.9	554
54	7.65	20.3	13.8	571
55	7.80	19.2	12.9	554
56	7.97	19.6	12.7	587
57	8.12	19.9	13.0	681
58	8.25	20.5	12.5	774
59	8.40	20.2	13.1	712
60	8.55	19.8	12.2	687
61	8.70	20.2	12.5	726
62	8.85	20.6	12.5	727
63	8.98	19.8	12.4	695
64	9.13	20.7	13.0	746
65	9.28	20.6	13.4	731
66	9.43	20.4	13.0	715
67	9.58	20.2	13.1	735
68	9.73	20.1	13.2	725
69	9.86	17.0	13.4	713
70	10.00	20.4	13.6	722
71	10.15	20.4	13.7	794
72	10.30	20.3	13.7	775
73	10.45	20.3	13.6	728
74	10.58	19.7	13.7	738
75	10.73	19.8	13.5	822
76	10.88	20.4	14.2	745
77	11.03	20.3	14.2	742
78	11.18	20.1	13.9	731
79	11.33	20.3	13.3	713
80	11.48	20.2	14.1	755
81	11.63	20.3	14.3	715
82	11.76	19.6	14.0	717
83	11.92	18.7	13.2	715
84	12.07	19.3	13.9	755
85	12.22	19.9	13.4	797
86	12.37	20.3	14.1	775
87	12.52	19.6	14.0	765
88	12.65	19.9	13.4	749
89	12.80	19.9	13.4	754
90	12.95	19.6	13.2	759
91	13.10	19.2	13.0	768
92	13.25	20.0	13.1	778
93	13.40	19.8	13.5	785
94	13.53	20.5	13.5	780
95	13.68	20.9	14.2	778
96	13.83	20.5	14.1	742
97	13.98	20.5	14.4	704
98	14.13	20.2	13.6	715
99	14.28	20.5	14.0	726
100	14.43	20.4	13.5	728
101	14.58	20.2	13.6	691
102	14.71	20.5	14.0	702
103	14.86	20.4	14.2	681
104	15.02	19.8	13.2	818
105	15.17	20.6	13.4	717
106	15.32	19.9	13.1	687

107	15.47	19.8	13.0	743
108	15.62	19.7	13.0	698
109	15.77	18.6	12.8	715
110	15.90	19.5	12.7	848
111	16.05	19.4	13.5	802
112	16.20	20.3	13.3	802
113	16.35	20.5	13.7	800
114	16.50	20.0	13.7	786
115	16.65	19.9	13.7	745
116	16.80	20.1	13.7	747
117	16.95	19.9	13.7	752
118	17.08	19.8	13.7	749
119	17.23	20.0	13.4	762
120	17.38	20.2	13.8	852
121	17.53	20.2	14.3	817
122	17.68	20.6	14.1	735
123	17.83	20.0	13.9	741
124	17.98	18.8	13.9	721
125	18.13	19.7	13.2	754
126	18.41	19.2	13.6	757
127	18.57	20.0	14.1	863
128	18.72	19.5	14.1	870
129	18.87	19.5	13.7	894
130	19.02	19.5	13.7	819
131	19.17	19.6	14.3	843
Ave		19.9	13.7	766
Std		0.5	0.5	93
Var		0.3	0.3	8727
Min		17.0	12.2	519
Max		20.9	15.1	980

Table A.11 Experimental results of an automatic control test on a crossflow grain dryer.
Test Number : 11
Date : 12/15/1986
Dryer Type : Zimmerman Model ATP 5000
Set Point : 17%(w.b.)

SAMPLE#	Time hr	Inlet MC % w.b.	Outlet MC % w.b.	R.P.M.
1	0.00	20.6	16.7	1326
2	0.11	21.2	16.4	1326
3	0.19	20.2	17.9	1330
4	0.29	19.8	17.2	1330
5	0.37	20.5	17.6	1329
6	0.47	20.5	17.3	1329
7	0.55	21.0	17.3	1320
8	0.63	20.9	16.5	1320
9	0.73	20.9	16.6	1321
10	0.81	21.4	16.6	1321
11	0.92	20.9	16.8	1328
12	1.00	21.1	16.6	1328
13	1.11	21.2	17.0	1330
14	1.19	21.0	16.9	1330
15	1.27	20.6	16.3	1349
16	1.37	21.1	16.6	1349
17	1.69	20.9	16.2	1330
18	1.77	20.1	16.6	1330
19	1.87	20.1	16.4	1445
20	1.97	20.5	16.3	1445
21	2.07	20.5	16.6	1662
22	2.32	20.3	16.5	1662
23	2.42	20.7	17.2	1494
24	2.50	20.8	17.2	1494
25	2.58	20.5	17.1	1397
26	2.66	20.1	17.2	1397
27	2.79	20.1	17.6	1654
28	2.87	20.9	17.2	1654
29	2.95	20.7	17.5	1661
30	3.05	20.2	17.7	1661
31	3.13	22.4	17.2	1523
32	3.23	22.3	17.3	1523
33	3.32	22.5	17.5	1309
34	3.42	21.6	18.1	1309
35	3.50	22.1	17.6	1120
36	3.58	21.0	17.7	1120
37	3.68	21.8	17.5	973
38	3.76	21.7	17.5	973
39	3.87	21.9	17.2	860
40	3.95	22.3	17.2	860
41	4.06	22.2	17.0	860
42	4.14	20.7	17.0	860
43	4.24	22.3	17.2	895
44	4.32	21.5	17.5	895
45	4.40	21.6	17.1	773
46	4.50	22.1	17.3	773
47	4.58	21.2	17.0	690
48	4.68	22.3	16.6	690

49	4.77	21.1	16.5	639
50	4.87	21.5	16.5	639
51	4.95	21.5	17.0	1331
52	5.04	22.6	16.8	1331
53	5.14	22.1	16.6	1325
54	5.22	22.3	16.6	1325
55	5.32	21.8	16.3	1325
56	5.40	22.8	16.0	1325
57	5.50	22.6	16.4	1325
58	5.58	22.7	16.3	1325
59	5.68	21.9	16.6	1326
60	5.77	22.1	16.5	1326
61	5.87	21.2	16.5	1326
62	5.95	22.2	16.6	1326
63	6.04	26.1	16.5	1438
64	6.14	26.8	16.4	1438
65	6.22	25.1	16.5	1089
66	6.32	23.3	17.1	1089
67	6.42	21.6	17.1	1045
68	6.50	26.2	17.8	1045
69	6.60	25.7	17.5	891
70	6.68	27.7	17.7	891
71	6.77	24.3	17.4	699
72	6.87	23.7	17.9	699
73	6.95	26.4	17.2	662
74	7.04	24.5	17.2	662
75	7.12	19.1	17.3	615
76	7.22	21.3	17.5	615
77	7.30	21.3	17.1	726
78	7.40	23.3	17.5	726
79	7.48	23.1	17.7	650
80	7.58	23.5	17.9	650
81	7.66	22.6	17.1	495
82	7.77	22.9	16.9	495
83	7.87	24.1	17.4	569
84	7.95	21.6	16.9	569
85	8.04	21.0	16.3	569
86	8.14	27.2	16.8	569
87	8.22	24.5	16.8	563
88	8.30	26.5	16.2	563
89	8.40	24.6	16.6	501
90	8.48	24.1	16.7	501
91	8.58	22.6	16.4	481
92	8.66	23.8	16.0	481
93	8.77	24.7	16.7	501
94	8.87	21.9	15.5	501
95	9.19	31.5	15.6	1330
96	9.27	21.5	15.5	1330
97	9.35	21.7	15.2	1333
98	9.45	22.1	15.1	1333
99	9.53	22.6	14.4	1374
100	9.63	21.4	14.3	1374
101	9.71	21.8	14.5	1441
102	9.81	21.7	14.8	1441
103	9.90	21.4	14.6	1450
104	9.98	22.9	14.6	1450
105	10.08	22.5	14.7	1460
106	10.16	21.4	15.0	1460

107	10.26	22.7	15.2	1462
108	10.34	21.0	15.5	1462
109	10.44	22.1	17.0	1393
110	10.52	21.4	15.8	1393
111	10.62	21.6	16.1	1329
112	10.70	21.7	16.5	1329
113	10.78	22.4	16.3	1335
114	10.90	21.8	17.6	1335
115	10.98	21.5	17.9	1328
116	11.08	21.9	18.6	1328
117	11.16	21.9	17.8	1303
118	11.26	21.1	17.9	1303
119	11.34	22.0	17.9	1273
120	11.42	21.4	17.5	1273
121	11.52	21.9	18.1	1277
122	11.60	22.4	17.5	1277
123	11.77	21.3	17.3	1277
124	11.87	21.0	17.3	1277
125	11.95	21.5	17.3	1277
126	12.05	21.0	17.1	1277
127	12.13	21.9	17.3	1277
128	12.23	20.6	17.2	1277
129	12.31	21.4	17.5	1253
130	12.41	21.5	16.9	1253
131	12.49	21.3	16.6	1276
132	12.57	23.0	17.2	1276
133	12.67	21.5	17.3	1414
134	12.75	20.6	17.0	1414
135	12.87	20.7	17.3	1404
136	12.95	21.5	17.1	1404
137	13.05	22.0	17.3	1393
138	13.13	22.2	17.1	1393
139	13.21	22.3	16.9	1327
140	13.31	22.8	17.2	1327
141	13.39	23.3	17.4	1346
142	13.49	23.4	17.2	1346
143	13.57	24.1	17.5	1074
144	13.67	23.6	16.9	1074
145	13.75	23.2	18.0	951
146	13.87	20.7	17.3	951
147	13.95	20.8	17.8	868
148	14.05	20.8	17.7	868
149	14.13	20.9	17.9	878
150	14.23	20.7	17.4	878
151	14.31	20.4	17.4	927
152	14.39	20.7	17.8	927
153	14.61	21.5	16.7	984
154	14.69	21.3	16.6	984
155	14.90	22.0	17.1	984
Ave		22.1	16.9	1148
Std		1.7	0.8	321
Var		2.9	0.7	103054
Min		19.1	14.3	481
Max		31.5	18.6	1662

Table A.12 Experimental results of an automatic control test on a crossflow grain dryer.
Test Number : 12
Date : 12/16/1986
Dryer Type : Zimmerman ATP 5000
Set Point : 17.5%(w.b.)

SAMPLE#	Time hr	Inlet MC % w.b.	Outlet MC % w.b.	R.P.M.
1	0.00	20.1	16.2	1265
2	0.10	20.5	16.2	1265
3	0.18	20.5	15.7	1320
4	0.28	20.9	15.7	1320
5	0.36	20.8	15.8	1323
6	0.44	20.9	15.5	1323
7	0.54	21.0	15.7	1328
8	0.62	21.4	15.6	1328
9	0.72	21.8	15.6	1331
10	0.80	21.4	15.5	1331
11	0.90	21.8	14.9	1334
12	0.98	20.2	15.0	1334
13	1.06	21.4	15.8	1319
14	1.18	21.3	16.1	1319
15	1.26	20.1	15.4	1326
16	1.36	21.1	15.2	1326
17	1.44	21.2	15.6	1318
18	1.54	20.8	16.1	1318
19	1.62	21.4	16.2	1323
20	1.72	20.2	15.9	1323
21	1.80	20.8	16.9	1318
22	1.88	21.5	16.7	1318
23	1.98	19.9	17.2	1326
24	2.06	20.9	16.9	1326
25	2.16	20.2	16.9	1329
26	2.24	21.0	16.8	1329
27	2.34	21.4	17.1	1729
28	2.42	21.1	16.6	1729
29	2.60	21.9	16.6	1736
30	2.70	21.8	16.9	1736
31	2.78	20.9	16.3	1686
32	2.86	21.4	16.3	1686
33	2.94	22.1	16.5	1738
34	3.04	21.1	16.7	1738
35	3.18	22.4	16.8	1740
36	3.28	22.0	16.9	1740
37	3.36	21.3	17.2	1712
38	3.46	21.0	17.2	1712
39	3.54	20.6	17.3	1620
40	3.64	20.8	18.0	1620
41	3.72	21.2	18.2	1717
42	3.80	21.1	17.5	1717
43	3.87	21.0	17.4	1673
44	3.95	21.5	17.4	1673
45	4.05	21.3	18.2	1739
46	4.18	21.2	18.3	1739
47	4.28	21.6	18.4	1718
48	4.36	21.3	17.8	1718

49	4.46	21.0	17.9	1630
50	4.54	21.0	18.2	1630
51	4.62	21.5	18.2	1739
52	4.72	22.4	18.2	1739
53	4.80	22.1	18.5	1312
54	4.90	21.8	18.0	1312
55	4.98	21.2	18.0	977
56	5.08	21.4	17.6	977
57	5.18	21.2	17.9	1214
58	5.26	21.5	17.8	1214
59	5.36	21.2	18.3	1203
60	5.54	20.8	17.7	1203
61	5.64	20.9	17.6	1129
62	5.72	21.0	17.5	1129
63	5.82	21.1	17.7	1171
64	5.90	20.9	17.6	1171
65	5.98	21.1	17.5	1182
66	6.08	21.0	17.2	1182
67	6.17	20.5	16.9	1317
68	6.27	20.2	17.0	1317
69	6.35	20.4	17.1	1590
70	6.45	20.9	17.0	1590
71	6.53	22.0	16.7	1734
72	6.70	21.3	17.0	1734
73	6.80	21.1	16.6	1734
74	6.88	21.1	16.9	1734
75	6.98	21.2	16.8	1737
76	7.06	21.0	17.6	1737
77	7.17	21.2	17.4	1742
78	7.34	21.2	17.2	1742
79	7.42	20.3	16.5	1743
80	7.52	20.4	18.0	1743
81	7.60	20.3	17.8	1745
82	7.70	20.8	17.4	1745
83	7.78	21.1	17.7	1653
84	7.88	20.9	17.5	1653
85	7.96	20.4	17.7	1737
86	8.04	20.9	17.4	1737
87	8.15	20.7	18.1	1741
88	8.23	20.5	17.7	1741
89	8.33	20.2	17.8	1740
90	8.40	20.4	17.1	1740
91	8.50	20.9	17.9	1747
92	8.58	20.9	17.5	1747
93	8.68	21.2	17.5	1749
94	8.76	21.3	17.7	1749
95	8.84	20.8	17.4	1506
96	8.94	20.4	17.4	1506
97	9.12	21.3	17.9	1746
98	9.15	21.2	18.1	1746
99	9.23	21.0	17.6	1532
100	9.33	21.3	18.1	1532
101	9.41	21.3	17.6	1379
102	9.51	21.4	17.2	1379
103	9.59	22.0	17.5	1398
104	9.69	22.5	17.8	1398
105	9.77	22.4	17.6	1178
106	9.87	22.5	17.2	1178

107	9.95	22.0	17.5	1011
108	10.15	22.1	17.9	1011
109	10.23	23.0	17.4	965
110	10.33	22.4	17.7	965
111	10.41	22.9	17.3	829
112	10.51	22.7	17.8	829
113	10.59	22.6	16.6	912
114	10.69	22.3	17.0	912
115	10.77	22.7	16.9	1029
116	10.85	22.9	16.6	1029
117	10.95	23.2	16.6	838
118	11.03	22.7	17.0	838
119	11.15	23.5	16.4	880
120	11.23	22.4	16.8	880
121	11.33	22.6	16.6	811
122	11.41	21.8	16.3	811
123	11.49	22.4	16.5	824
124	11.59	22.2	16.2	824
125	11.67	22.7	16.2	889
126	11.77	22.7	16.6	889
127	11.85	22.7	16.0	885
128	11.95	22.2	16.0	885
129	12.03	22.5	15.7	981
130	12.15	22.5	15.7	981
131	12.23	23.2	15.9	1157
132	12.31	22.7	16.7	1157
133	12.41	23.4	15.9	1200
134	12.49	22.3	15.9	1200
135	12.59	21.9	16.4	1342
136	12.67	21.6	16.3	1342
137	12.77	21.9	16.3	1342
Ave		21.4	17.0	1390
Std		0.8	0.8	308
Var		0.6	0.7	94790
Min		19.9	14.9	811
Max		23.5	18.5	1749

Table A.13 Experimental result of an automatic control test on a crossflow grain dryer.
Test Number : 13
Date : 12/19/1986
Dryer Type : Zimmerman Model ATP 5000
Set Point : 17.5%(w.b.)

SAMPLE#	Time hr	Inlet MC % w.b.	Outlet MC % w.b.	R.P.M.
2	0.00	23.2	18.1	1307
3	0.08	23.1	18.1	1307
4	0.18	20.4	17.9	1316
5	0.26	20.9	17.1	1316
6	0.36	21.6	17.3	1325
7	0.44	22.2	17.5	1325
8	0.52	22.2	17.1	1334
9	0.62	21.4	16.9	1334
10	0.71	20.6	16.6	1428
11	0.81	20.4	16.6	1428
12	0.89	22.9	16.9	1526
13	0.99	22.2	16.8	1526
14	1.07	21.8	17.0	1532
15	1.16	23.3	16.0	1532
16	1.26	21.9	16.9	1516
17	1.34	23.1	15.9	1516
18	1.44	24.2	15.8	1520
19	1.52	24.3	16.6	1520
20	1.62	25.1	16.1	1627
21	1.71	22.8	16.3	1627
22	1.79	23.2	16.1	1506
23	1.89	23.7	17.3	1506
24	1.97	23.3	16.4	1463
25	2.07	23.3	16.8	1463
26	2.16	23.5	17.5	1474
27	2.26	22.1	16.3	1474
28	2.34	23.0	17.3	1037
29	2.42	21.7	16.9	1037
30	2.52	21.2	17.6	1205
31	2.60	20.2	17.3	1205
32	2.71	21.1	18.2	1617
33	2.81	23.6	17.8	1617
34	2.89	24.9	17.7	1399
35	2.97	21.1	20.0	1399
36	3.07	21.1	18.0	1298
37	3.16	20.8	17.8	1298
38	3.29	20.8	17.2	1728
39	3.39	20.7	17.4	1728
40	3.47	22.2	17.5	1730
41	3.55	22.0	16.4	1730
42	3.66	23.7	16.7	1727
43	3.74	22.8	16.5	1727
44	3.84	22.9	16.8	1730
45	3.92	22.2	17.0	1730
46	4.02	23.2	17.0	1729
47	4.10	24.4	17.7	1729
48	4.20	22.9	17.7	1664
49	4.28	25.5	16.9	1664

50	4.36	24.4	17.3	1734
51	4.46	22.0	17.7	1734
52	4.54	22.3	18.1	1278
53	4.66	22.9	17.6	1278
54	4.74	23.2	17.7	993
55	4.84	22.3	17.4	993
56	4.92	21.4	18.2	982
57	5.00	21.3	17.9	982
58	5.10	21.7	17.8	970
59	5.18	21.7	17.2	970
60	5.28	22.3	18.0	988
61	5.38	20.2	17.8	988
62	5.46	17.1	18.1	848
63	5.68	16.1	17.7	848
64	5.76	17.2	17.2	1742
65	5.84	18.4	17.2	1742
66	5.94	21.1	16.9	1739
67	6.02	19.2	17.1	1739
68	6.10	21.8	16.7	1744
69	6.18	22.2	17.1	1744
70	6.28	21.2	16.8	1745
71	6.36	21.8	17.0	1745
72	6.44	22.5	16.3	1746
73	6.54	22.3	17.0	1746
74	6.66	22.4	17.2	1744
75	6.76	22.3	16.0	1744
76	6.84	20.1	16.5	1744
77	7.01	20.6	14.6	1744
78	7.11	21.0	16.3	1107
79	7.23	21.3	14.6	1107
80	7.33	21.6	15.4	1532
81	7.43	21.1	16.3	1532
82	7.53	20.6	16.9	1517
83	7.63	20.8	15.6	1517
84	7.78	21.3	16.2	1517
85	7.88	19.7	16.6	1517
86	7.96	20.1	16.5	1741
87	8.06	20.3	16.7	1741
88	8.16	20.9	16.0	1741
89	8.24	20.4	15.2	1741
90	8.34	23.0	14.8	1740
91	8.46	23.5	15.7	1740
92	8.58	22.7	16.2	1738
93	8.68	24.0	15.5	1738
94	8.76	24.0	16.6	1736
95	8.88	22.4	15.9	1736
96	8.98	22.9	15.9	1737
97	9.21	22.8	16.5	1737
98	9.31	23.6	17.3	1661
99	9.50	20.4	17.3	1661
100	9.58	20.2	17.5	1372
101	9.63	20.2	17.8	1372
102	9.69	21.2	17.5	1223
103	9.76	20.6	17.3	1223
104	9.83	20.9	17.5	1199
105	9.88	21.4	18.0	1199
106	9.95	21.4	17.8	1253
107	10.00	21.5	17.8	1253

108	10.05	20.0	17.6	1036
109	10.10	20.7	17.8	1036
110	10.17	20.5	17.4	1144
111	10.26	21.6	17.8	1144
112	10.34	20.3	17.6	1638
113	10.41	21.1	18.4	1638
114	10.48	21.5	17.5	1741
115	10.53	22.4	17.3	1741
116	10.59	21.4	16.8	1739
117	10.66	21.2	17.3	1739
118	10.73	20.8	17.0	1652
119	10.79	21.1	16.7	1652
120	10.86	21.5	17.6	1727
121	10.93	21.3	17.0	1727
122	11.00	20.6	16.8	1736
123	11.05	23.6	16.3	1736
124	11.12	21.5	17.1	1739
125	11.19	20.9	16.2	1739
126	11.33	20.7	16.3	1743
127	11.38	21.8	16.2	1743
128	11.45	19.7	16.5	1741
129	11.52	20.5	16.8	1741
130	11.59	20.5	17.1	1742
131	11.64	21.5	16.7	1742
132	11.69	21.8	17.0	1743
133	11.76	21.1	17.1	1743
134	11.83	21.5	16.3	1733
135	11.88	21.0	16.9	1733
Ave		21.7	17.0	1513
Std		1.5	0.8	260
Var		2.2	0.6	67638
Min		16.1	14.6	848
Max		25.5	20.0	1746

Table A.14 Experimental results of an automatic control test on a crossflow grain dryer.
Test Number : 14
Date : 1/15/1987
Dryer Type : Zimmerman Model ATP 50000
Set Point : 16.5%(w.b.)

SAMPLE #	Time hr	Inlet MC % w.b.	Outlet Mc % w.b.	R.P.M.
1	0.00	19.5	18.9	1322
2	0.10	21.4	19.1	1324
3	0.18	21.1	18.8	1317
4	0.28	20.1	18.3	1320
5	0.36	20.9	18.9	1308
6	0.44	21.4	17.7	1297
7	0.52	21.4	18.2	1299
8	0.62	21.6	18.3	1300
9	0.70	21.5	18.0	1306
10	0.80	21.7	18.3	1303
11	0.92	22.4	16.9	1298
12	1.00	21.9	17.2	1304
13	1.10	22.1	17.2	1303
14	1.18	23.2	16.6	1312
15	1.28	23.2	16.5	1299
16	1.36	22.1	16.4	1297
17	1.46	21.7	15.9	1293
18	1.54	22.2	15.1	1297
19	1.64	22.1	15.1	1303
20	1.72	21.7	15.3	1302
21	1.80	22.7	15.6	1280
22	1.92	23.0	15.7	1279
23	2.02	22.4	14.7	1295
24	2.10	22.2	15.0	1293
25	2.20	22.4	15.9	1365
26	2.28	21.4	15.4	1366
27	2.38	22.3	15.4	1363
28	2.46	21.3	16.1	1361
29	2.54	22.9	16.5	1469
30	2.64	22.4	15.7	1470
31	2.72	21.9	16.5	1478
32	2.82	22.4	16.0	1478
33	2.92	22.1	16.7	1520
34	3.02	22.5	16.3	1520
35	3.10	21.9	16.6	1566
36	3.20	22.2	16.7	1564
37	3.28	22.3	16.7	1587
38	3.38	21.9	16.6	1588
39	3.46	22.1	16.6	1547
40	3.54	22.1	16.6	1546
41	3.64	21.9	16.8	1642
42	3.72	22.4	17.3	1643
43	3.82	21.7	17.4	1620
44	3.92	21.8	17.3	1620
45	4.02	22.1	16.9	1494
46	4.10	22.1	17.5	1493
47	4.20	21.5	17.4	1490
48	4.28	22.3	17.0	1491

49	4.36	22.0	17.6	1421
50	4.46	22.3	17.1	1422
51	4.54	21.3	17.1	1427
52	4.64	22.1	17.0	1428
53	4.72	21.3	16.8	1440
54	4.82	21.6	16.8	1440
55	4.92	21.4	16.4	1519
56	5.02	21.4	17.2	1517
57	5.10	21.1	16.6	1589
58	5.20	21.0	16.4	1588
59	5.28	21.2	16.7	1656
60	5.36	21.5	16.1	1656
61	5.46	20.4	16.4	1758
62	5.54	18.9	16.8	1759
63	5.64	19.1	16.5	1760
64	5.72	17.9	16.8	1759
65	5.82	18.8	17.1	1760
66	5.92	19.5	16.6	1760
67	6.02	19.5	16.9	1760
68	6.10	20.7	17.7	1761
69	6.20	20.6	17.3	1753
70	6.28	20.0	17.3	1762
71	6.36	20.2	18.0	1761
72	6.46	19.7	17.4	1760
73	6.54	19.8	17.3	1764
74	6.64	20.0	17.7	1763
75	6.72	20.7	17.3	1762
76	6.82	21.1	16.9	1762
77	6.92	21.5	17.1	1765
78	7.02	21.3	16.5	1329
79	7.10	20.9	16.5	554
80	7.20	21.5	16.2	1041
81	7.30	21.1	16.9	1132
82	7.40	20.2	16.9	1132
83	7.50	21.2	16.8	914
84	7.58	21.4	16.8	914
85	7.66	21.6	16.4	981
86	7.76	21.7	16.8	979
87	7.84	21.8	17.1	930
88	7.93	21.1	16.7	930
89	8.01	22.1	17.1	961
90	8.09	22.2	16.7	958
91	8.19	21.1	17.7	909
92	8.27	21.4	18.3	907
93	8.40	21.1	17.3	604
94	8.50	21.1	17.9	601
95	8.58	21.7	17.4	651
96	8.68	22.0	17.2	657
97	8.76	21.3	17.5	702
98	8.86	22.2	17.2	699
99	8.97	21.9	16.8	724
100	9.37	21.8	16.2	935
101	9.47	22.1	16.3	935
102	9.55	20.8	16.2	728
103	9.65	22.6	15.7	728
104	9.73	21.3	15.9	749
105	9.83	22.8	15.6	755
106	9.92	22.5	16.2	1150

107	10.02	21.8	15.5	1152
108	10.12	20.6	15.8	692
109	10.20	21.4	15.9	696
110	10.30	22.1	15.5	802
111	10.38	21.3	15.4	805
112	10.47	21.4	15.3	848
113	10.57	22.1	15.0	845
114	10.65	20.3	15.0	967
115	10.75	22.4	15.5	965
116	10.83	21.9	14.6	1044
117	10.93	21.9	15.1	1043
118	11.02	23.6	15.2	1205
119	11.12	21.7	14.6	1205
120	11.20	22.1	14.4	1227
121	11.30	22.0	14.7	1227
122	11.38	22.7	15.6	1374
123	11.47	22.5	14.9	1374
124	11.57	22.1	14.9	1344
125	11.65	22.3	15.0	1344
126	11.75	21.4	15.4	1382
127	11.83	22.6	15.8	1382
128	11.93	25.8	15.8	1462
129	12.02	22.1	15.6	1462
130	12.12	22.1	16.5	1481
131	12.20	26.3	16.0	1481
132	12.28	23.7	16.3	1272
133	12.38	22.5	16.6	1273
Ave		21.6	16.6	1294
Std		1.1	1.0	325
Var		1.2	1.0	105707
Min		17.9	14.4	554
Max		26.3	19.1	1765

APPENDIX B : Simulation Results

Table B.1 Simulation results of an automatic control test on a crossflow grain dryer.
Set Number : 1 (Test #7)
Dryer Type : Meyer-Morton Model 850
Set Point : 14.0%(w.b.)

Sample #	Time (hrs)	Inlet MC (%,w.b.)	Outlet MC (%,w.b)	RPM
1	0.14	25.9	14.3	716
2	0.28	25.2	14.3	716
3	0.41	25.1	14.3	708
4	0.55	24.9	14.3	708
5	0.69	24.5	14.3	729
6	0.83	25.0	14.4	729
7	0.97	24.4	14.4	739
8	1.10	24.8	14.4	739
9	1.24	24.4	14.5	746
10	1.38	25.0	14.5	746
11	1.52	23.8	14.6	741
12	1.66	24.2	14.1	741
13	1.79	27.0	14.1	773
14	1.93	26.2	14.0	773
15	2.07	27.3	13.6	676
16	2.21	28.2	13.9	676
17	2.35	27.9	13.3	641
18	2.48	28.1	13.5	641
19	2.62	26.3	13.0	636
20	2.76	28.7	13.3	636
21	2.90	27.0	12.3	652
22	3.04	27.1	12.4	652
23	3.17	26.7	14.6	673
24	3.31	26.0	13.8	673
25	3.45	27.7	14.6	684
26	3.59	27.5	15.3	684
27	3.73	31.0	15.0	626
28	3.86	28.4	15.1	626
29	4.00	29.4	13.5	553
30	4.14	27.3	15.4	553
31	4.28	27.7	13.9	591
32	4.42	26.3	13.9	591
33	4.55	31.0	13.5	639
34	4.69	27.0	12.9	639
35	4.83	27.1	14.2	580
36	4.97	28.9	13.9	580
37	5.11	28.7	16.8	607
38	5.24	29.9	14.4	607
39	5.38	28.9	15.1	554
40	5.52	26.9	13.3	554
41	5.66	26.1	13.6	598
42	5.80	30.2	12.5	598

43	5.93	27.1	16.6	597
44	6.07	27.6	13.1	597
45	6.21	25.9	13.3	618
46	6.35	29.2	14.7	618
47	6.49	29.6	14.5	610
48	6.62	27.1	15.6	610
49	6.76	25.4	14.7	577
50	6.90	27.5	13.0	577
51	7.04	26.7	12.5	647
52	7.18	24.5	16.0	647
53	7.31	24.7	13.6	677
54	7.45	24.3	14.1	677
55	7.59	24.9	12.9	728
56	7.73	24.2	15.9	728
Ave		26.8	14.1	654
Std		1.8	1.0	62
Min		23.8	12.3	553
Max		31.0	16.8	773

Table B.2 Simulation results of an automatic control test on a crossflow grain dryer.
Set Number : 2 (Test #1)
Dryer Type : Meyer-Morton Model 850
Set Point : 14.5

Sample #	Time (hrs)	Inlet MC (%,w.b.)	Outlet MC (%,w.b.)	RPM
1	0.14	21.7	14.5	963
2	0.28	21.1	14.5	963
3	0.41	21.2	14.5	978
4	0.55	21.2	14.6	978
5	0.69	21.5	14.6	989
6	0.83	21.3	14.7	989
7	0.97	21.5	14.2	977
8	1.10	21.8	14.3	977
9	1.24	21.6	14.3	967
10	1.38	21.5	14.5	967
11	1.52	22.1	14.3	973
12	1.66	21.7	14.5	973
13	1.79	22.4	14.7	954
14	1.93	22.4	14.5	954
15	2.07	21.9	14.3	927
16	2.21	22.1	14.7	927
17	2.35	22.1	14.3	946
18	2.48	21.7	14.9	946
19	2.62	21.5	14.8	949
20	2.76	22.0	14.4	949
21	2.90	22.8	14.6	956
22	3.04	22.5	14.6	956
23	3.17	22.1	14.2	909
24	3.31	22.4	14.0	909
25	3.45	23.0	14.4	932
26	3.59	22.0	15.1	932
27	3.73	22.1	14.7	916
28	3.86	21.8	14.3	916
29	4.00	22.6	14.6	943
30	4.14	23.5	15.1	943
31	4.28	22.3	14.2	885
32	4.42	23.5	14.2	885
33	4.55	22.5	13.9	895
34	4.69	22.4	14.5	895
35	4.83	22.8	15.3	917
36	4.97	23.1	14.2	917
37	5.11	23.4	15.2	890
38	5.24	23.2	14.3	890
39	5.38	23.1	14.2	871
40	5.52	23.5	14.5	871
41	5.66	22.9	14.7	872
42	5.80	22.3	14.9	872
43	5.93	21.9	14.7	902
44	6.07	20.8	14.6	902
45	6.21	22.9	15.1	967
46	6.35	23.6	14.8	967
47	6.49	23.5	14.3	869
48	6.62	22.1	13.9	869
49	6.76	23.0	13.0	897

50	6.90	22.5	14.8	897
51	7.04	23.0	15.5	902
52	7.18	22.6	15.2	902
53	7.31	22.5	13.8	893
54	7.45	22.3	14.6	893
55	7.59	23.0	14.3	914
56	7.73	22.8	14.8	914
57	7.87	22.4	14.4	890
58	8.00	22.6	14.3	890
59	8.14	22.3	14.1	911
60	8.28	23.3	14.8	911
61	8.42	22.4	14.6	895
62	8.56	22.3	14.2	895
63	8.69	22.6	14.4	919
64	8.83	23.1	14.2	919
65	8.97	22.3	15.1	895
66	9.11	21.7	14.3	895
67	9.25	22.2	14.3	936
68	9.38	21.9	14.6	936
69	9.52	21.6	15.1	935
70	9.66	21.0	14.4	935
71	9.80	21.1	14.1	974
72	9.94	21.2	14.7	974
73	10.07	21.6	14.6	986
74	10.21	22.1	14.5	986
75	10.35	21.2	13.9	951
76	10.49	21.6	14.1	951
77	10.63	22.3	14.2	980
78	10.76	21.9	14.5	980
79	10.90	22.1	14.9	943
80	11.04	21.8	14.0	943
81	11.18	22.2	14.3	950
Ave		22.2	14.5	929
Std		0.7	0.4	35
Min		20.8	13.0	869
Max		23.6	15.5	989

Table B.3 Simulation results of an automatic control test on a crossflow grain dryer.
Set Number : 3
Dryer Type : Zimmerman ATP 5000
Set Point : 17.5%(w.b.)

Sample #	Time (hrs)	Inlet MC (%,w.b.)	Outlet MC (%,w.b.)	RPM
1	0.07	20.1	16.8	1750
2	0.14	20.5	16.8	1750
3	0.22	20.5	16.8	1750
4	0.29	20.9	16.7	1750
5	0.36	20.8	16.6	1750
6	0.43	20.9	16.6	1750
7	0.50	21.0	16.5	1750
8	0.58	21.4	16.5	1750
9	0.65	21.8	16.4	1750
10	0.72	21.4	16.3	1750
11	0.79	21.8	16.7	1750
12	0.86	20.2	16.6	1750
13	0.94	21.4	16.9	1750
14	1.01	21.3	16.7	1750
15	1.08	20.1	16.8	1750
16	1.15	21.1	16.9	1750
17	1.22	21.2	17.3	1750
18	1.30	20.8	17.7	1750
19	1.37	21.4	17.3	1750
20	1.44	20.2	17.7	1750
21	1.51	20.8	16.2	1750
22	1.58	21.5	17.3	1750
23	1.66	19.9	17.2	1750
24	1.73	20.9	16.1	1750
25	1.80	20.2	17.0	1750
26	1.87	21.0	17.1	1750
27	1.94	21.4	16.7	1750
28	2.02	21.1	17.3	1750
29	2.09	21.9	16.2	1750
30	2.16	21.8	16.7	1750
31	2.23	20.9	17.4	1679
32	2.30	21.4	15.9	1679
33	2.38	22.1	16.8	1750
34	2.45	21.1	16.2	1750
35	2.52	22.4	16.9	1750
36	2.59	22.0	17.3	1750
37	2.66	21.3	17.0	1549
38	2.74	21.0	17.7	1549
39	2.81	20.6	17.6	1750
40	2.88	20.8	16.8	1750
41	2.95	21.2	17.2	1750
42	3.02	21.1	17.9	1750
43	3.10	21.0	16.9	1750
44	3.17	21.5	18.2	1750
45	3.24	21.3	17.8	1750
46	3.31	21.2	17.2	1750
47	3.38	21.6	16.9	1750
48	3.46	21.3	16.5	1750
49	3.53	21.0	16.7	1750

50	3.60	21.0	17.1	1750
51	3.67	21.5	17.0	1750
52	3.74	22.4	16.9	1750
53	3.82	22.1	17.4	1632
54	3.89	21.8	17.2	1632
55	3.96	21.2	17.1	1628
56	4.03	21.4	17.4	1628
57	4.10	21.2	17.1	1750
58	4.18	21.5	16.9	1750
59	4.25	21.2	16.9	1750
60	4.32	20.8	17.3	1750
61	4.39	20.9	18.1	1750
62	4.46	21.0	17.9	1750
63	4.54	21.1	17.6	1750
64	4.61	20.9	17.0	1750
65	4.68	21.1	17.2	1750
66	4.75	21.0	17.1	1750
67	4.82	20.5	17.4	1750
68	4.90	20.2	17.1	1750
69	4.97	20.4	16.7	1750
70	5.04	20.9	16.8	1750
71	5.11	22.0	16.9	1750
72	5.18	21.3	17.0	1750
73	5.26	21.1	16.8	1750
74	5.33	21.1	17.0	1750
75	5.40	21.2	16.9	1750
76	5.47	21.0	16.5	1750
77	5.54	21.2	16.2	1750
78	5.62	21.2	16.4	1750
79	5.69	20.3	16.8	1750
80	5.76	20.4	17.8	1750
81	5.83	20.3	17.2	1750
82	5.90	20.8	17.0	1750
83	5.98	21.1	17.0	1750
84	6.05	20.9	17.1	1750
85	6.12	20.4	16.9	1750
86	6.19	20.9	17.1	1750
87	6.26	20.7	17.1	1750
88	6.34	20.5	16.3	1750
89	6.41	20.2	16.4	1750
90	6.48	20.4	16.3	1750
91	6.55	20.9	16.7	1750
92	6.62	20.9	17.0	1750
93	6.70	21.2	16.8	1750
94	6.77	21.3	16.4	1750
95	6.84	20.8	16.8	1750
96	6.91	20.4	16.7	1750
97	6.98	21.3	16.5	1750
98	7.06	21.2	16.2	1750
99	7.13	21.0	16.4	1750
100	7.20	21.3	16.8	1750
101	7.27	21.3	16.8	1750
102	7.34	21.4	17.1	1750
103	7.42	22.0	17.2	1750
104	7.49	22.5	16.7	1750
105	7.56	22.4	16.4	1534
106	7.63	22.5	17.1	1534
107	7.70	22.0	17.0	1470

108	7.78	22.1	16.8	1470
109	7.85	23.0	17.0	1594
110	7.92	22.4	17.0	1594
111	7.99	22.9	17.1	1388
112	8.06	22.7	17.5	1388
113	8.14	22.6	18.0	1350
114	8.21	22.3	17.8	1350
115	8.28	22.7	17.8	1427
116	8.35	22.9	17.3	1427
117	8.42	23.2	17.4	1325
118	8.50	22.7	18.1	1325
119	8.57	23.5	17.5	1277
120	8.64	22.4	18.0	1277
121	8.71	22.6	17.7	1267
122	8.78	21.8	17.6	1267
123	8.86	22.4	17.3	1463
124	8.93	22.2	17.7	1463
125	9.00	22.7	17.8	1430
126	9.07	22.7	18.1	1430
127	9.14	22.7	17.6	1311
128	9.22	22.2	18.4	1311
129	9.29	22.5	17.4	1372
130	9.36	22.5	17.5	1372
131	9.43	23.2	16.8	1363
132	9.50	22.7	17.4	1363
133	9.58	23.4	17.2	1256
134	9.65	22.3	17.6	1256
135	9.72	21.9	17.6	1277
136	9.79	21.6	17.6	1277
137	9.86	21.9	17.2	1607
Ave		21.4	17.1	1655
Std		0.8	0.5	162
Min		19.9	15.9	1256
Max		23.5	18.4	1750

Table B.4 Simulation results of an automatic control test on a crossflow grain dryer.
Set Number : 4
Dryer Type : Meyer-Morton Model 850
Set Point : 14.5%(w.b.)

Sample #	Time (hrs)	Inlet MC (%,w.b.)	Outlet MC (%,w.b.)	RPM
1	0.14	21.0	13.2	911
2	0.28	21.3	13.2	911
3	0.41	21.5	13.4	1001
4	0.55	21.8	13.6	1001
5	0.69	22.0	13.7	973
6	0.83	22.1	13.9	973
7	0.97	22.2	14.0	952
8	1.10	22.3	14.3	952
9	1.24	22.2	14.4	941
10	1.38	22.2	14.5	941
11	1.52	22.0	14.6	939
12	1.66	21.9	14.7	939
13	1.79	21.7	14.7	948
14	1.93	21.4	14.7	948
15	2.07	21.1	14.8	968
16	2.21	20.9	14.7	968
17	2.35	20.6	14.8	996
18	2.48	20.3	14.7	996
19	2.62	20.1	14.8	1028
20	2.76	19.9	14.8	1028
21	2.90	19.8	14.8	1057
22	3.04	19.7	14.7	1057
23	3.17	19.7	14.7	1076
24	3.31	19.8	14.6	1076
25	3.45	19.9	14.6	1082
26	3.59	20.0	14.5	1082
27	3.73	20.2	14.4	1073
28	3.86	20.5	14.3	1073
29	4.00	20.7	14.2	1052
30	4.14	21.0	14.2	1052
31	4.28	21.3	14.1	1024
32	4.42	21.5	14.2	1024
33	4.55	21.8	14.2	994
34	4.69	22.0	14.2	994
35	4.83	22.1	14.3	968
36	4.97	22.2	14.3	968
37	5.11	22.3	14.4	950
38	5.24	22.2	14.5	950
39	5.38	22.2	14.6	941
40	5.52	22.0	14.7	941
41	5.66	21.9	14.7	943
42	5.80	21.7	14.7	943
43	5.93	21.4	14.7	957
44	6.07	21.1	14.8	957
45	6.21	20.9	14.8	982
46	6.35	20.6	14.8	982
47	6.49	20.3	14.8	1012
48	6.62	20.1	14.8	1012
49	6.76	19.9	14.8	1043

	50	6.90	19.8	14.7	1043
	51	7.04	19.7	14.7	1068
	52	7.18	19.7	14.7	1068
	53	7.31	19.8	14.6	1081
	54	7.45	19.9	14.5	1081
	55	7.59	20.0	14.5	1079
	56	7.73	20.2	14.4	1079
	57	7.87	20.5	14.3	1063
	58	8.00	20.7	14.2	1063
Ave			21.0	14.4	1004
Std			0.9	0.4	53
Min			19.7	13.2	911
Max			22.3	14.8	1082

Table B.5 Simulation results of an automatic control test on a crossflow grain dryer.
Set Number : 5
Dryer Type : Meyer-Morton Model 850
Set Point : 14.5%(w.b.)

Sample #	Time (hrs)	Inlet MC (%,w.b.)	Outlet MC (%,w.b.)	RPM
1	0.14	21.0	13.2	911
2	0.28	21.5	13.2	911
3	0.41	22.0	13.3	993
4	0.55	22.2	13.6	993
5	0.69	22.2	13.6	950
6	0.83	22.0	13.7	950
7	0.97	21.7	13.8	947
8	1.10	21.1	14.4	947
9	1.24	20.6	14.7	984
10	1.38	20.1	15.0	984
11	1.52	19.8	15.2	1038
12	1.66	19.7	15.3	1038
13	1.79	19.9	15.3	1072
14	1.93	20.2	15.1	1072
15	2.07	20.7	14.8	1056
16	2.21	21.3	14.4	1056
17	2.35	21.8	14.0	1006
18	2.48	22.1	13.8	1006
19	2.62	22.3	13.7	963
20	2.76	22.2	13.8	963
21	2.90	21.9	14.0	951
22	3.04	21.4	14.3	951
23	3.17	20.9	14.7	976
24	3.31	20.3	14.9	976
25	3.45	19.9	15.2	1027
26	3.59	19.7	15.3	1027
27	3.73	19.8	15.3	1069
28	3.86	20.0	15.2	1069
29	4.00	20.5	15.0	1065
30	4.14	21.0	14.6	1065
31	4.28	21.5	14.2	1019
32	4.42	22.0	13.9	1019
33	4.55	22.2	13.7	971
34	4.69	22.2	13.8	971
35	4.83	22.0	13.9	950
36	4.97	21.6	14.2	950
37	5.11	21.1	14.5	967
38	5.24	20.6	14.8	967
39	5.38	20.1	15.0	1013
40	5.52	19.8	15.2	1013
41	5.66	19.7	15.3	1062
42	5.80	19.9	15.3	1062
43	5.93	20.2	15.1	1071
44	6.07	20.7	14.8	1071
45	6.21	21.3	14.4	1032
46	6.35	21.8	14.0	1032
47	6.49	22.1	13.8	981
48	6.62	22.3	13.7	981
49	6.76	22.2	13.8	952

50	6.90	21.9	14.0	952
51	7.04	21.4	14.4	959
52	7.18	20.9	14.6	959
53	7.31	20.3	15.0	1000
54	7.45	19.9	15.1	1000
55	7.59	19.7	15.3	1052
56	7.73	19.8	15.3	1052
57	7.87	20.0	15.2	1074
58	8.00	20.5	14.9	1074
Ave		21.0	14.5	1004
Std		0.9	0.6	47
Min		19.7	13.2	911
Max		22.3	15.3	1074

Table B.6 Simulation results of an automatic control test on a crossflow dryer.
Set Number : 6
Dryer Type : Meyer-Morton Model 850
Set Point : 14.5%(w.b.)

Sample #	Time (hrs)	Inlet MC (%,w.b.)	Outlet MC (%,w.b.)	RPM
1	0.14	25.0	13.6	716
2	0.28	25.5	13.6	716
3	0.41	26.0	13.7	761
4	0.55	26.4	13.7	761
5	0.69	26.8	13.8	725
6	0.83	27.0	13.8	725
7	0.97	27.2	13.7	699
8	1.10	27.3	13.7	699
9	1.24	27.2	13.7	687
10	1.38	27.1	13.6	687
11	1.52	26.9	13.6	689
12	1.66	26.6	14.0	689
13	1.79	26.2	14.3	703
14	1.93	25.7	14.6	703
15	2.07	25.3	14.8	725
16	2.21	24.7	15.1	725
17	2.35	24.2	15.3	756
18	2.48	23.8	15.5	756
19	2.62	23.4	15.6	794
20	2.76	23.0	15.7	794
21	2.90	22.8	15.8	830
22	3.04	22.6	15.8	830
23	3.17	22.6	15.8	856
24	3.31	22.7	15.7	856
25	3.45	22.9	15.5	864
26	3.59	23.2	15.3	864
27	3.73	23.6	15.0	852
28	3.86	24.0	14.7	852
29	4.00	24.5	14.3	826
30	4.14	25.0	14.0	826
31	4.28	25.5	13.7	793
32	4.42	26.0	13.4	793
33	4.55	26.4	13.3	762
34	4.69	26.8	13.2	762
35	4.83	27.0	13.1	735
36	4.97	27.2	13.2	735
37	5.11	27.3	13.3	715
38	5.24	27.2	13.6	715
39	5.38	27.1	13.8	705
40	5.52	26.9	14.0	705
41	5.66	26.6	14.3	706
42	5.80	26.2	14.6	706
43	5.93	25.7	14.9	718
44	6.07	25.2	15.1	718
45	6.21	24.7	15.3	742
46	6.35	24.2	15.5	742
47	6.49	23.8	15.7	776
48	6.62	23.3	15.7	776
49	6.76	23.0	15.9	813

50	6.90	22.8	15.9	813
51	7.04	22.6	15.9	845
52	7.18	22.6	15.8	845
53	7.31	22.7	15.7	863
54	7.45	22.9	15.5	863
55	7.59	23.2	15.3	860
56	7.73	23.6	15.0	860
57	7.87	24.0	14.7	840
58	8.00	24.5	14.3	840
Ave		25.0	14.6	771
Std		1.7	0.9	61
Min		22.6	13.1	687
Max		27.3	15.9	864

Table B.7 Simulation results of an automatic control test on a crossflow dryer.
Set Number : 7
Dryer Type : Meyer-Morton Model 850
Set Point : 14.5%(w.b)

Sample #	Time (hrs)	Inlet MC (%,w.b.)	Outlet MC (%,w.b.)	RPM
1	0.14	25.0	13.6	716
2	0.28	26.0	13.6	716
3	0.41	26.8	13.6	716
4	0.55	27.2	13.6	716
5	0.69	27.2	13.6	716
6	0.83	26.9	13.6	716
7	0.97	26.2	13.6	716
8	1.10	25.3	13.6	716
9	1.24	24.2	13.6	685
10	1.38	23.4	13.5	685
11	1.52	22.8	13.9	895
12	1.66	22.6	15.1	895
13	1.79	22.9	16.1	854
14	1.93	23.6	16.8	854
15	2.07	24.5	17.0	817
16	2.21	25.5	16.9	817
17	2.35	26.4	16.4	756
18	2.48	27.0	15.6	756
19	2.62	27.3	14.6	705
20	2.76	27.1	13.5	705
21	2.90	26.6	12.8	690
22	3.04	25.7	12.4	690
23	3.17	24.7	12.5	724
24	3.31	23.8	12.8	724
25	3.45	23.0	13.5	797
26	3.59	22.6	14.4	797
27	3.73	22.7	15.3	865
28	3.86	23.2	16.2	865
29	4.00	24.0	16.7	857
30	4.14	25.0	17.0	857
31	4.28	26.0	16.6	782
32	4.42	26.8	16.0	782
33	4.55	27.2	15.0	717
34	4.69	27.2	14.1	717
35	4.83	26.9	13.2	692
36	4.97	26.2	12.7	692
37	5.11	25.2	12.5	713
38	5.24	24.2	12.7	713
39	5.38	23.3	13.3	778
40	5.52	22.8	14.0	778
41	5.66	22.6	14.9	854
42	5.80	22.9	15.8	854
43	5.93	23.6	16.5	870
44	6.07	24.5	17.0	870
45	6.21	25.5	16.9	805
46	6.35	26.4	16.4	805
47	6.49	27.0	15.5	732
48	6.62	27.3	14.6	732
49	6.76	27.1	13.6	695

50	6.90	26.6	12.9	695
51	7.04	25.7	12.6	704
52	7.18	24.7	12.6	704
53	7.31	23.8	13.0	760
54	7.45	23.0	13.6	760
55	7.59	22.6	14.5	838
56	7.73	22.7	15.4	838
57	7.87	23.2	16.2	876
58	8.00	24.0	16.8	876
Ave		25.0	14.6	770
Std		1.7	1.5	67
Min		22.6	12.4	685
Max		27.3	17.0	895

Table B.8 Simulation results of an automatic control test on a crossflow grain dryer.
Set number : 8
Dryer Type : Meyer-Morton Model 850
Set Point : 15.5%(w.b.)

Sample #	Time (hrs)	Inlet MC (%,w.b.)	Outlet MC (%,w.b.)	RPM
1	0.14	28.0	15.0	647
2	0.28	28.0	15.0	647
3	0.41	28.0	15.0	647
4	0.55	28.0	15.0	647
5	0.69	28.0	15.0	647
6	0.83	28.0	15.0	647
7	0.97	28.0	15.0	647
8	1.10	28.0	15.0	647
9	1.24	28.0	14.9	614
10	1.38	28.0	14.8	614
11	1.52	28.0	14.9	684
12	1.66	28.0	15.0	684
13	1.79	28.0	15.0	684
14	1.93	28.0	15.1	684
15	2.07	28.0	15.1	680
16	2.21	28.0	15.2	680
17	2.35	28.0	15.3	678
18	2.48	28.0	15.3	678
19	2.62	28.0	15.3	678
20	2.76	28.0	15.5	678
21	2.90	28.0	15.5	677
22	3.04	24.0	15.5	677
23	3.17	24.0	15.7	758
24	3.31	24.0	15.8	758
25	3.45	24.0	16.2	870
26	3.59	24.0	16.6	870
27	3.73	24.0	17.1	863
28	3.86	24.0	17.5	863
29	4.00	24.0	17.9	856
30	4.14	24.0	18.3	856
31	4.28	24.0	18.5	850
32	4.42	24.0	18.7	850
33	4.55	24.0	15.0	846
34	4.69	24.0	14.9	846
35	4.83	24.0	14.9	861
36	4.97	24.0	14.9	861
37	5.11	24.0	15.0	871
38	5.24	24.0	15.0	871
39	5.38	24.0	15.1	877
40	5.52	24.0	15.1	877
41	5.66	24.0	15.2	882
42	5.80	32.0	15.3	882
43	5.93	32.0	14.9	669
44	6.07	32.0	14.6	669
45	6.21	32.0	14.2	553
46	6.35	32.0	13.8	553
47	6.49	32.0	13.5	553
48	6.62	32.0	13.1	553
49	6.76	32.0	12.7	554

50	6.90	32.0	12.3	554
51	7.04	32.0	12.0	557
52	7.18	32.0	11.6	557
53	7.31	32.0	18.0	561
54	7.45	32.0	17.6	561
55	7.59	32.0	17.1	554
56	7.73	32.0	16.9	554
57	7.87	32.0	16.7	546
58	8.00	32.0	16.6	546
59	8.14	32.0	16.6	540
60	8.28	32.0	16.5	540
61	8.42	28.0	16.5	535
62	8.56	28.0	16.5	535
63	8.69	28.0	16.7	671
64	8.83	28.0	16.9	671
65	8.97	28.0	17.1	669
66	9.11	28.0	17.3	669
67	9.25	28.0	17.5	668
68	9.38	28.0	17.7	668
69	9.52	28.0	17.9	667
70	9.66	28.0	18.2	667
71	9.80	28.0	18.4	665
72	9.94	28.0	15.0	665
73	10.07	28.0	15.3	665
74	10.21	28.0	15.3	665
75	10.35	28.0	15.3	665
76	10.49	28.0	15.3	665
77	10.63	28.0	15.3	666
78	10.76	28.0	15.3	666
79	10.90	28.0	15.3	666
80	11.04	28.0	15.3	666
81	11.18	28.0	15.3	667
Ave		28.0	15.6	686
Std		2.8	1.4	108
Min		24.0	11.6	535
Max		32.0	18.7	882

APPENDIX C : Specifications for Data Acquisition Components

C.1 A/D Converter Specifications

Integrated Circuit:	Intersil 7109 dual-slope A/D converter
Resolution:	12 bits plus sign bit and over-range bit
Full Scale Voltage	±0.5V, ±1.0V, ±2.0V, or ±4,0V, jumper selectable
Maximum Conversion Time:	50 milliseconds
Minimum Conversion Rate:	20 samples per second
Maximum Input Voltage:	±12V without damage
Input Impedance:	minimum 8 megohms
Input Current:	maximum 0.5 microamperes
Temperature Coefficient:	100 ppm/degree C
Overall Accuracy:	adjustable to better than 0.1% of full scale range
Differential Nonlinearity (maximum deviation from ideal step size):	±2 counts (0.5%)
Integral Nonlinearity (maximum deviation from ideal straight line):	±4 counts (0.1%)

C.2 D/A Converter Specifications

Integrated Circuit:	Analog Devices DAC80
Resolution:	12 bits
Full Scale Voltage:	±0.5V, ±1.0V, ±2.0V, or ±4.0V, jumper selectable
Maximum Conversion Time:	20 microseconds
Minimum Conversion Rate:	up to 50,000 conversion per second, limited only by software speed.
Output Current:	sources or sink 10ma
Nonlinearity:	±1 least significant bit
Accuracy:	Adjustable to better than 0.2% of full scale range
Monotonic:	over entire 0 to 70 degree C range
Temperature Coefficient:	100 ppm/degree C
Software Interface:	via output of two data bytes; the most significant 4 bits are stored until the least significant 8 bits are output and then the 12 bits of data are presented simultaneously to the D/A converter

C.3 Digital I/O Specifications

Integrated Circuit: MOS Technology 6522 Versatile Interface Adapter

16 bidirectional lines (usually used as 8 bits in and 8 bits out)

Latching capability on input or output

Four handshaking signals accommodate positive or negative logic

Interrupt register and interrupt enable registers are available for each handshake signal

Input Characteristics:

High Voltage:	2.4 to 5.0V
Current:	-100 t0 -250 microamperes
Low Voltage:	-0.3V to +0.4V
Current:	-1.0 to -1.6 milliamperes
Leakage Current:	±1.0 to ±2.5 microamperes
Off-State Current:	±2.0 to ±10 microamperes
Capacitance:	10 pF

Output Characteristics:

High Voltage:	2.4V minimum
Current:	-0.1 to -1.0 milliamperes (PA0-PA7, CA2 -3.0 to -5.0 milliamperes (PB0-PB7, CB1, CB2)
Low Voltage:	0.4V maximum
Current:	1.6 milliamperes
Leakage Current:	1.0-10 microamperes
Capacitance :	10 pF

C.4 Real Time Clock and Counter/Timer Specifications

Integrated Circuit:	Two MOS Technology 6522 Versatile Interface Adapters
Timers 0 and 2 :	16 bit countdown timers can be used as: * one-shot interval timers with optional pulse output on PB7 * continuous frequency generator with optional square wave output on PB7
Timers 1 and 3 :	16 bit countdown timers can be used as: * one-shot interval timers * frequency counter that counts a predetermined number of pulses on PB6 * shift register rate generator
Shift Register :	Inputs or outputs 8-bit serial data with timing pulses supplied by Timers 1 or 3, the 1.023MHZ processor clock or external clock.
Interrupt Control:	Interrupt flag and interrupt enable on all functions.
Signal Characteristics:	TTL compatible signals (one TTL load or service)