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MICROWAVE - CONVECTION DRYING OF

READY-TO-EAT CEREALS

presented by

James C. Breslin

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of the requirements for

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MICROWAVE - CONVECTION DRYING OF

READY-TO-EAT CEREALS

BY

James C. Breslin

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ABSTRACT

MICROWAVE - CONVECTION DRYING OF READY-TO-EAT-CEREALS

By

JIM BRESLIN

The performance of a convection - microwave dryer is compared to a conventional conventional dryer for ready-to-eat cereals.

A pilot scale microwave - convection dryer was built. The dryer has a working length of 4.25 m, with a maximum power of 20 KW. The residence time used in this study is approximately 120 seconds. Measurements were made to quantify the gross average environment within the pilot scale microwave - convection dryer. Several assumptions were made to approximate the rate of microwave heating.

The environmental measurements were used as boundary conditions to approximate the heat and moisture transfer occurring within the microwave - convection dryer. Experiments were made to estimate the thermal and moisture diffusivity of the product.

A mathematical model of the heat and moisture transfer was developed. The model approximates the performance of the pilot scale unit over a range of operating conditions. Several new designs are evaluated with the model.

The model is used to estimate the thermal and moisture history of a cooked cereal product being dried in the production of a Ready-To-Eat cereal product in a conventional convection dryer. The time required to dry a cooked cereal product in a microwave - convection dryer is predicted by the model. The heat generated by microwave heating is based on the assumptions used to develop the model.

Best results are obtained by limiting the microwave energy to 75 v/m in the first zone of the dryer. No microwave energy is applied in the second or third zones of the microwave - convection dryer. The drying time required to reduce the moisture content from 28 to 21% wet basis is reduced by 450% compared to the conventional convection system. The reduction in residence time can be used to decrease the length of the dryer from 10.1 to 3.1 m, or to increase the capacity of the production unit by 235%.

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CHAPTER 1 INTRODUCTION

The ready-to-eat cereal industry has grown into one of the major forces in the food industry. At the current time the average American consumes 9.6 pounds of cereal per year. This adds up to a volume of 2.4 billion pounds of cereal produced each year in the United States (Level 1988). Nielsen (1987) reported that the sales in the domestic cereal industry exceeded 5.2 billion dollars in 1987. Table 1.1 details the market share of major products in the ready-to-eat cereal industry. Corn Flakes and Frosted Flakes are the major products consumed in the United States.

TABLE 1.1

DOMESTIC SALES OF MAJOR READY-TO-EAT CEREALS BY U.S. FIRMS

		1986 10^3# SHIPPED	1986 SHARE %	CURRENT 10^3# SHIPPED	CURRENT SHARE %
KELLOGG	CORN FLAKES	135494	5.96	142890	6.11
KELLOGG	FROSTED FLAKES	128761	5.66	128500	5.50
GENERAL MILLS	CHEERIOS	128761	4.48	108500	4.40
KELLOGG	RAISIN BRAN	104534	4.60	97362	4.16
KELLOGG	RICE KRISPIES	83107	3.65	85123	3.64
GENERAL MILLS	CHEERIOS H&NUT	60626	2.67	64587	2.76
GENERAL FOODS	POST RAISIN BRAN	60311	2.62	57532	2.46
GENERAL FOODS	POST GRAPE NUTS	58327	2.56	59641	2.55
KELLOGG	FRUIT LOOPS	50751	2.23	52542	2.25
KELLOGG	MINI WHEATS	49974	2.20	51259	2.19
GENERAL MILLS	TOTAL	41329	1.82	43654	1.87
GENERAL MILLS	WHEATIES	40417	1.76	39355	1.68
GENERAL MILLS	LUCKY CHARMS	36927	1.62	37699	1.61
KELLOGG	SPECIAL K	35460	1.56	38052	1.63
KELLOGG	BRAN FLAKES	38216	1.68	37136	1.59

SOURCE: NIELSEN (1987)

All of the products listed in Table 1.1 except Cheerios, Grape Nuts, and Fruit Loops, share a central processing theme. The raw material and processing conditions change for each product, but the unit operations required to produce the products are the same. The standard unit operations are shown in Figure 1.1, they are: cooking, drying, milling, and toasting.

There are two main objectives in the cooking process. The first is to gelatinize the starch granules; Englyst 1986 reported that the gelatinization step improves the pallitabilty and nutrient value of the starch product. The second objective of the cooking process is to penetrate the starch molecule with a flavor solution. This step improves the taste, and color of the final product (Hoseney 1986).

According to Hirzel (1982) the main objective of drying in cereal production is to change the particle texture in order to meet the requirements of the milling process. In general, the texture required for milling is a hard exterior and a pliable center. The removal of excess moisture from a cooked cereal product often yields the acceptable texture.

The milling process causes a physical change in the particle shape. The change in shape prevents the gelatinization reaction from reversing and undergoing

CEREAL MANUFACTURING
BASIC PROCESS OPERATIONS

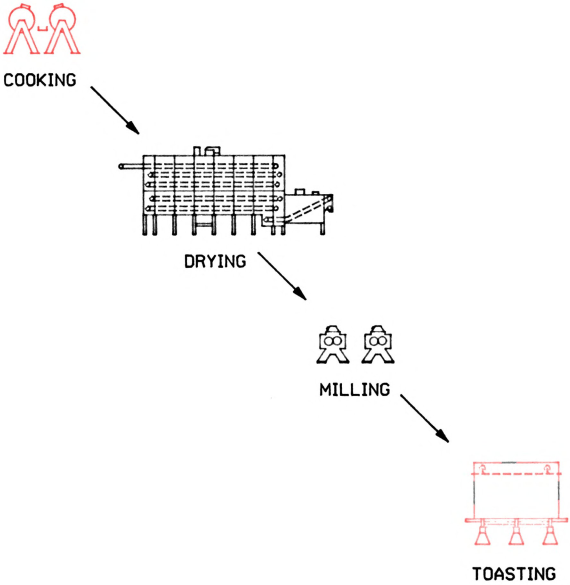


FIGURE 1.1

retrogration (Finley 1985). The net effect of the milling step is an increase in the particle surface area.

Toasting has two main objectives (Finley 1985). The first is to remove the moisture above the acceptable storage requirement of 2-3% wet basis; this step is necessary to insure a long shelf-life of the product. The second objective is to provide a suitable environment for the Mailard reactions which control the color and taste of the finished product.

This thesis is an investigation of the drying process. From the perspective of the food processor, the most important characteristics of a dryer are the product quality, the dryer capacity, and the operating and fixed drying costs.

The quality of a dried cereal product depends on the particle texture and uniformity. The texture is affected by the average moisture content and by the moisture gradient between the center and outer surface of each particle. The moisture uniformity of the dried product is critical. The drying operation needs to limit the variation in particle moisture.

The capacity of a dryer is a function of the maximum bed depth which can be obtained inside the dryer.

As the bed depth increases, the humidity of the air exiting the bed rises. When the condition of the air leaving the product bed no longer changes with bed depth, the product has reached the maximum bed depth. Using the maximum bed depth and product flow rate, the maximum capacity of the dryer can be estimated. The maximum capacity of a dryer is directly related to the size of the dryer. For a given size dryer the maximum capacity is dependent on the rate of moisture removal. The rate of moisture removal is dependent on the rate of heat transfer. Figure 1.2 illustrates the energy and moisture transfer which occur inside a conventional dryer.

The cost of the dryer can be broken into two parts: (1) the operational cost per pound of product, and (2) the fixed cost of the equipment. The unit operating costs include the energy costs required for drying one pound of product.

The floor space required is a significant characteristic of a dryer. The cost of the floor space is critical when a capacity increase is needed. The cost to construct additional floor space for a larger dryer is often higher in an existing plant than the fixed cost of the dryer.

FOOD DEHYDRATION

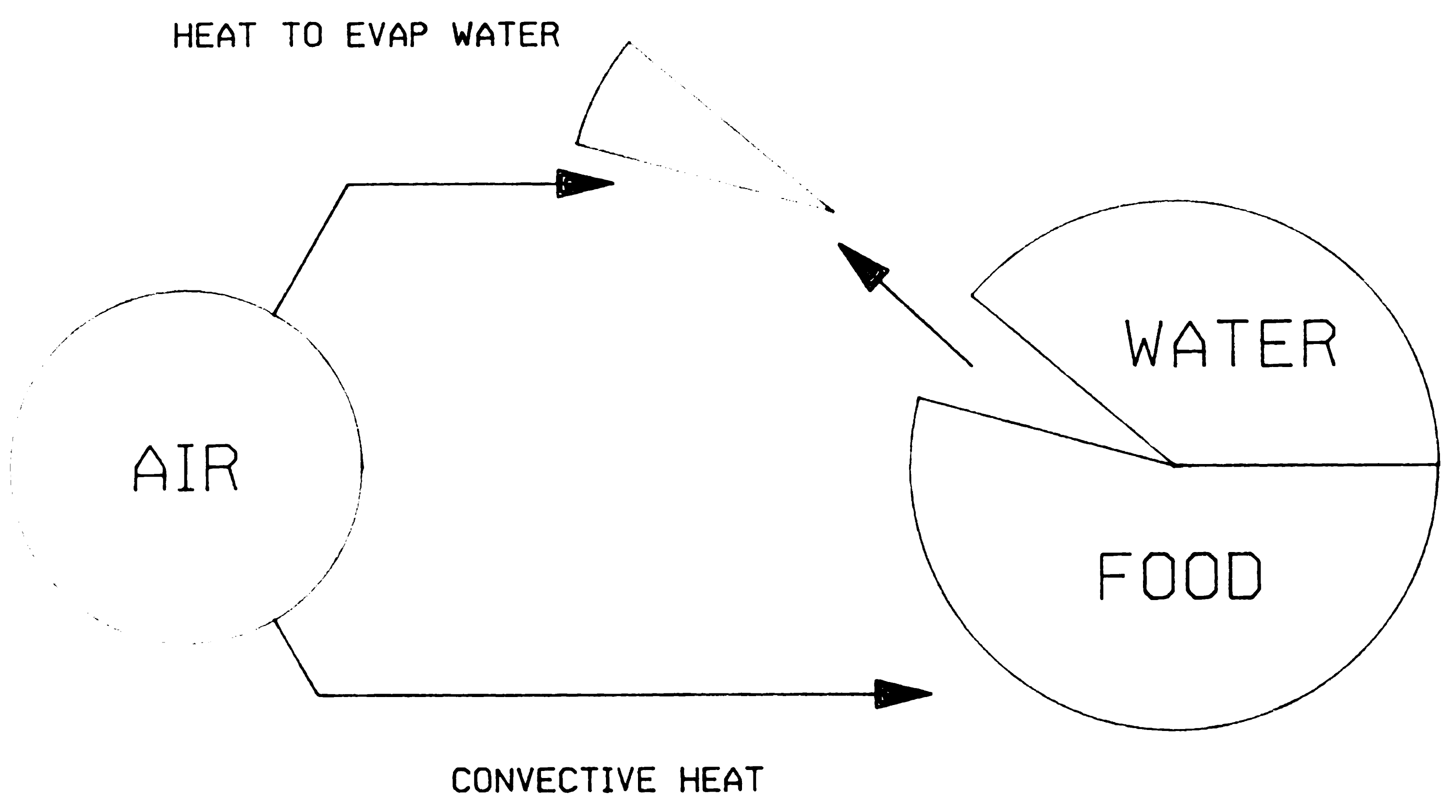


FIGURE 1.2

Oda (1987) stated that the best technique for decreasing the cost of the drying operation is to minimize the space requirements of a dryer. This can be accomplished by increasing rate of drying and therefore, minimizing the size of the dryer.

Increasing the rate of moisture removal requires an increase in the rate of heat transfer to the product being dried. When drying thick products in a conventional system, the rate of heat transfer is limited by a phenomenon known as case hardening. Van Arsdel (1980) described case hardening as the occurrence of an outer layer of very dry product encasing a high moisture interior. The dry surface acts as an insulation layer around the particle retarding the flow of moisture diffusing to the surface.

The combination of microwave energy with conventional convection drying increases the heat transfer to a drying particle. Microwave energy has the ability to deliver heat directly to the center of a particle without heating the outer surfaces (Decareau and Peterson, 1986). The additional heat transfer increases the rate of drying and therefore the capacity of the dryer, without changing the dryer size.

The goal of this thesis is to evaluate the combination of convection and microwave heating. The information can be used to design a next generation of dryers for the cereal industry.

CHAPTER 2 OBJECTIVES

The main objective of this study is to determine the increase in capacity of a conventional cereal dryer with the addition of microwave energy. The methodology used to meet the objective can be broken down into five basic parts:

1. To build a microwave - convection drying test unit.

2. To make measurements of the physical environment within the test unit.

3. To develop a mathematical model of the heat and moisture transfer occurring as the product passes through the test unit.

4. To verify the mathematical model.

5. To use the simulation model to evaluate new dryer designs, and compare the rate of drying of the new microwave - convection dryer with the drying rate of a conventional convection dryer.

CHAPTER 3 LITERATURE REVIEW

3.1 MICROWAVE ENERGY

The drying process is the highest cost unit operation in the cereal industry. The high cost of drying is due to the amount of energy required, and the large amount of floor space required for conventional dryers. Pie (1986) described the use of microwave energy to heat the interior of the product bed and force the moisture to the outer surface of the product bed. The combination of microwave energy with convection drying yielded a space savings of between 75 and 195% in the finished drying of sugar.

In the cereal industry microwave technology has not been extensively applied outside of the laboratory. The Food and Drug Administration did not approve the use of radiation in food production until 1974 (Anonymous 1974). Microwave technology has been successfully employed for the tempering of frozen meats, and the pasteurization of maraschino cherries (Appleton and Kwan 1987). However, microwave technology is not yet employed in the ready-to-eat cereal industry.

The cereal companies blame the manufacturer for not offering test units which can be used to evaluate a new process in a proprietary way. The microwave equipment manufacturers lack the technical understanding of how a product changes when exposed to the microwave system.

From the industrial manufacturers point of view, cereal processors are considered to be tentative about moving into a new technology. The proprietary nature of the food industry does not create a good environment for the equipment manufacturer to fine-tune a new system. If a microwave equipment manufacturer does make a sale, and the venture is a success, the customer usually restricts the right of the manufacturer to advertise a working unit.

Current applications of microwave energy in the drying process in the food industry center around integrating a microwave system with a convection dryer. Oda (1986) observed that pure microwave energy has a disadvantage in terms of capital cost compared to convection energy in dryers. The coupling of microwave energy with convection dryers has been employed successfully in the pasta industry to dry elbow macaroni (Decareau and Peterson 1986). Conventional drying is assisted by microwave energy to reduce the drying time. The first stage in the process is a conventional convection dryer operating at 70 - 80 C^{o} for 36 minutes. This reduces the moisture content of the pasta from 30 to 18% wet basis. The pasta is treated in the second zone of the dryer with microwave energy at 918 Mhz and hot air at 82 - 90 C^o and a relative humidity of 15 to 20 percent. A third zone cools the pasta from 74 C^o to 32 C^o. The total processing time required for process is 92 minutes. The microwave assisted process replaces a conventional system which required 8 hours. Using the three stage microwave assisted dryer, a space savings of over 400 percent is obtained.

3.1.1 MICROWAVES

Copson applies the term microwave to wave lengths between 30 cm and 1 mm. The generator used to develop radiation at these wavelengths is called a magnetron or klystron. A magnetron is a vacuum tube device which was originally developed for radar applications. It consists of a cylindrical diode containing a resonant cavity which acts as the anode. The resonant cavity is kept under a vacuum; a magnetic field is imposed parallel to the cylindrical axis. When the proper voltage is applied across the diode, electric and magnetic fields result.

Currently, there are two frequencies which are allocated for industrial use in the U.S., 915 Mhz and 2450 Mhz. The manufacturers of magnetrons have been successful at reducing the price and extending the life of magnetrons (Copson 1975). Ferrite isolators are used to protect the magnetron from reflected energy. Copson (1975) stated that magnetrons have a lifetime of 3 years. Several manufacturers guarantee magnetrons for 5 to 7 years of normal service. The cost of magnetrons has dropped from several thousand dollars to less than 100 dollars per unit (Copson 1975).

Magnetrons deliver the microwave energy into a cavity or wave guide. Inside the wave guide the microwave radiation can be absorbed by a dielectric food material. The phrase used to describe this process is "energy dissipation in a lossy medium" (Copson 1975). The term "energy dissipation" comes from the loss of energy from the microwave field to the product. The frame of reference is the microwave field. From this frame of reference come the terms -"dielectric loss factor" and "dielectric loss tangent" which will be defined in the next section.

3.1.2 MICROWAVE HEATING

The amount of microwave energy absorbed by a given volume of a food product is given by (Goldblith 1967):

$$P = E^2 \omega \varepsilon'' \varepsilon_0 \qquad 3.1.2.1$$

where,

P = energy absorbed per unit volume (watt/m)

E = Electric field strength (v/m^3)

ω = Angular frequency (rad/sec)

ε'' = Dielectric loss factor (unitless)

ε_0 = Dielectric constant of free space (farads/m).

The electric field strength E is the parameter which describes the electrical energy which has been generated by the magnetron and is transferred by the electric field inside the cavity. The field strength is a measure of the energy which is available within the cavity for absorption by the product. A detailed description of the microwave field strength can be developed from Maxwell's equations (Metexas 1974).

The angular frequency ω is a physical characteristic of the microwave radiation. The frequency is dependent on the type of magnetron used to generate the radiation.

The dielectric loss factor ε'' is a measure of the energy used by the product in reorientationn under the influence of the microwave field strength. The resistance to movement is the primary cause of heat generation (Metexas 1974).

The dielectric constant of free space ε_0 is a reference resistance for microwave propagation in free space. Free space represents the minimum resistance to propagation of microwave energy. This resistance is used as a benchmark to measure the resistance of the product to microwave propagation (Goldblith 1967).

Metaxas (1974) presented the solution to the electric field part of Maxwell's equations in the form of a plane wave (see figure 3.1.2.1) as:

$$E = E_{max} \exp -(\alpha z) \quad \exp (j(\omega\tau - \beta\tau z)) \qquad 3.1.2.2$$

where,

E = Local electric field strength (v/m)

E_{max} = Electric field strength at the surface (v/m)

$j\omega\tau$ = Phase angle of plane wave (unitless)

$j\beta tz$ = Attenuation factor of plane wave.

The first exponential term gives the attenuation of the electric field and, therefore, the power dissipated.

The attenuation of a low loss material can be expressed as (Metexas 1979):

$$\alpha = \frac{\pi \quad \varepsilon'}{\lambda \ (\varepsilon'')^{1/2}} \qquad 3.1.2.3$$

where,

α = Attenuation factor $(m)^{-1}$

λ_0 = Wave length in free space (m)

ε'' = Dielectric loss factor of product (unitless)

ε' = Dielectric constant of product (unitless).

Equations 3.1.2.2 and equation 3.1.2.3 allow the calculating of the dissipation in the microwave field strength with distance traveled.

PROPAGATION OF A PLANE WAVE IN A LOSSY MEDIUM

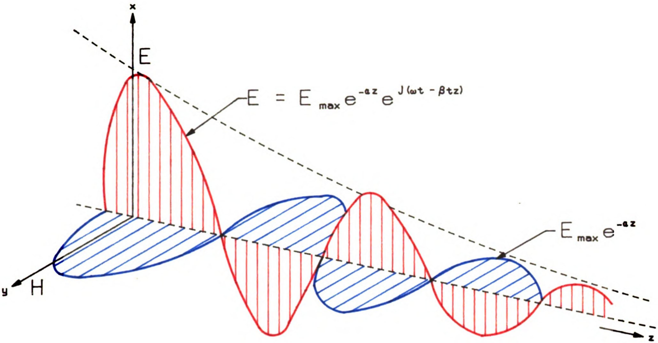


FIGURE 3.1.2.1

Von Hipple (1954) developed an expression for the penetration depth of microwave energy into a thick food product. A thick product is defined as a product over 2.5 cm in thickness, or as a packed bed of small particles over 2.5 cm in thickness. The penetration depth is the distance which a plane wave travels before it has lost 1/e of its original power. The penetration depth is expressed as:

$$D_p = \frac{\lambda^0 (\varepsilon')^{1/2}}{2 \pi \varepsilon''} \qquad 3.1.2.4$$

where,

D_p = Penetration depth of material (m).

3.1.3 DIELECTRIC PROPERTIES

Goldblith (1967) described the heat generated within an elemental volume of a particle as a function of the element field strength and the dielectric property of the particle. The dielectric property governs the amount of microwave energy which is converted into heat. The energy results from the polarization of atoms by the electric field and the physical interaction between the electric field and the atoms. Heat is generated by creating and destroying the forces used to polarize atoms, and the inability of the polarization to follow the changes in the direction of the applied microwave field.

Detailed studies of polarization have been conducted by Debye (1929) , Daniel (1967), and Hasted (1973). The interaction of an electric field with a dielectric material has its origin in the response of charged ions to the applied electric field. The movement from the equilibrium position gives rise to induced dipoles which are created by polarization. The dipoles magnify the reaction to the electric field. This is termed the interfacial polarization. Some materials contain permanent dipoles due to an asymmetric charge distribution. The dipoles tend to reorient under the influence of the electric field through so called orientation polarization described in Figure 3.1.3.1.

The average dipole consists of two charged and slightly separated particles. The configuration results in a dipole moment when the charged particles attempt to reorient to the electric field as shown in Figure 3.1.3.2. The average dipole moment is given by Metaxes (1979) as:

$$\mu = q\,X \qquad 3.1.3.1$$

where,

μ = Average dipole moment

q = The charge of the dipole

X = The distance separating the charged particles.

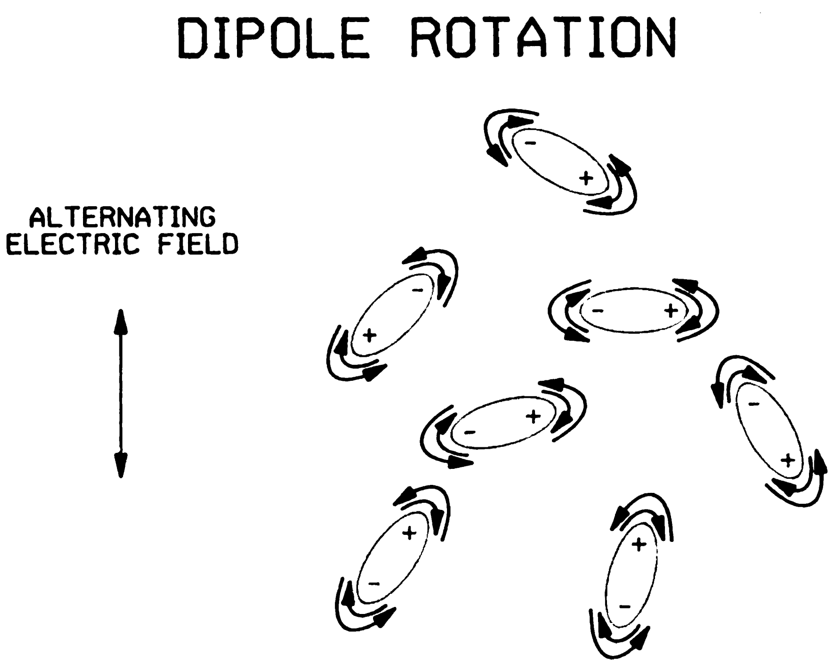


FIGURE 3.1.3.1

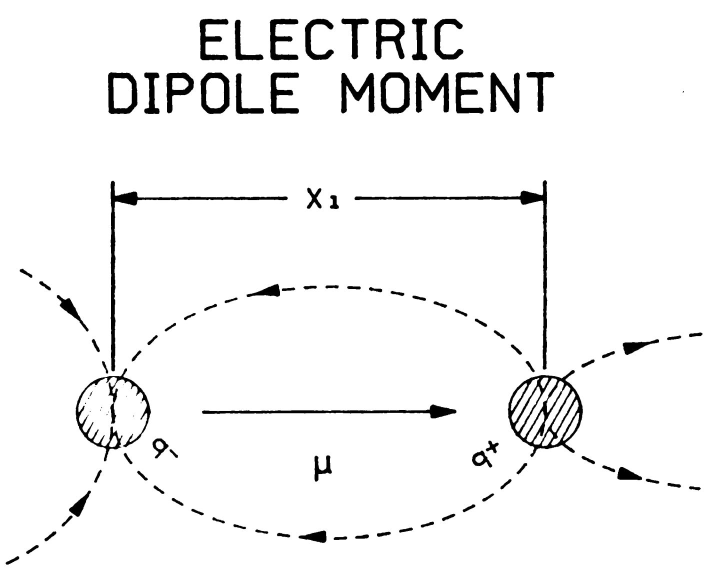


FIGURE 3.1.3.2

If the dipole moments within a given volume of N dipoles are summed, a measure of the charge density of the volume is obtained. The charge density is termed the polarization vector P, and is described by Metexas (1979) as:

$$P = \frac{\Sigma\, q\, X}{\delta\, v} \qquad 3.1.3.2$$

The polarization vector is a measure of the energy stored within a product with N′ individual dipole moments. Thus,

$$P = \mu\, N' \qquad 3.1.3.3$$

The electrical potential of a system is expressed in the electric potential vector D. The difference between the vectors P and D is equal to the electric potential not due to polarization. Thus,

$$D = \varepsilon_0\, E + P \qquad 3.1.3.4$$

and since,

$$D = \varepsilon_0\, \varepsilon'\, E \qquad 3.1.3.5$$

rearrangement yields,

$$P = \varepsilon_0\, (\, \varepsilon' - 1\,)\, E \qquad 3.1.3.6$$

in which ε' is the relative dielectric constant of the material.

If an electric field E' is applied to a single dipole the resulting dipole moment can be expressed as:

$$\mu = \alpha E' \qquad 3.1.3.7$$

in which α is the polarisability of the material and contains both the interfacial and orientation polarization affects. Combining equations (3.1.3.5),(3.1.3.6),and (3.1. 3.7) yields:

$$\varepsilon_0 (1- \varepsilon') = \alpha N' E' \qquad 3.1.3.8$$

Equation 3.1.3.8 links the macroscopic quantities e' and E to the molecular properties N' and E'.

In order to describe the dielectric constant of a material which is changing in temperature and moisture content, additional information about the dielectric property is required. The dielectric constant is divided into two parts. The complex form of the dielectric constant is given by Metexas (1979) as:

$$\varepsilon^* = \varepsilon' - j \varepsilon'' \qquad 3.1.3.9$$

where, ε' is the relative dielectric constant; and ε'' is the imaginary part which is called the dielectric loss factor. Physically, the two parts of the complex dielectric constant each describe a different process. The relative dielectric constant measures the ability of the material to store energy, and the dielectric loss factor measures the energy used by the reorientation of polarized molecules within the applied field. The loss tangent is defined as the ratio of the loss factor to the relative dielectric constant (Von Hipple 1954):

$$\tan \delta = \frac{\varepsilon''}{\varepsilon'} \qquad 3.1.3.10$$

The dielectric properties of some food materials are shown in Table 3.3.1.

TABLE 3.3.1

DIELECTRIC PROPERTIES OF SELECTED FOOD PRODUCTS

	TEMPERATURE (°C)	RELATIVE DIELECTRIC CONSTANT (unitless)	DIELECTRIC LOSS FACTOR (unitless)
BEEF STEAK			
BOTTOM ROUND	25	40.0	12.0
FROZEN LEAN	0	3.9	0.3
BACON FAT	25	2.5	0.13
POTATO RAW	25	53.7	15.7
TURKEY COOKED	25	40.0	14.0
BUTTER	0	4.05	0.39
BUTTER	35	4.15	0.44
WATER			
ICE	-12	3.2	0.003
DISTILLED	25	76.0	12.0
MILK POWDER	30	2.29	0.048
WHEY POWDER	30	2.04	0.025
NEEPAWA WHEAT	21	3.0	0.90

SOURCE: VON HIPPLE (1954)/NEILSON (1974)

3.2 DRYING

A prerequisite for improving dryer performance is an understanding of the conventional drying process. The objective of the drying process in a cereal plant is to modify the textural characteristics of the product.

Two texture characteristics are modified by the drying process. The first is the outer surface of the particle; as the temperature of the outer surface rises, the surface becomes hard. The second characteristic is the texture of the interior; as the average product moisture changes the moisture content and the texture of the interior changes little. This leaves a product with a hard, dry outer surface and a moist, pliable interior. The conventional cereal production process requires a milling step to modify the shape of the product. The product texture requirements for milling are a hard surface, and a pliable interior. Thus, the correct drying process supplies the product textures required for the milling process.

The conventional convection dryer used in cereal production is the humidity - controlled belt dryer. A physical description of the dryer type is shown in Figure 3.2.1. Typical operating specifications for the FEC belt are listed in Table 3.2.1.

TABLE 3.2.1

CONVENTIONAL BELT DRYER SPECIFICATIONS

ZONE	LENGTH (m)	SPEED (m/min)	DEPTH (m)	DRY BULB TEMPERATURE (^{o}C)	RELATIVE HUMIDITY (%)	FLOW VOLUME (m^3/min)
1	10.1	4.0	0.05	61	65	600
2	9.7	2.25	0.06	61	65	600
3	10.5	1.25	0.12	61	65	600

The belt dryer uses air at constant dry bulb and wet bulb temperatures. The dry bulb temperature of the air is controlled by the use of a steam heat exchanger. The wet bulb temperature is automatically controlled by measuring the relative humidity and changing the ratio between the volume of air removed as bleed, and the volume of air brought in the dryer as makeup.

The dryer is divided into three zones or flights. The operating conditions of a belt dryer are controlled to remove the same amount of moisture in each flight. The moisture removal from a flight is adjusted by changing the residence time of the product in the zone. As the product moisture content drops, additional time is required to remove the same amount of moisture.

BELT DRYER

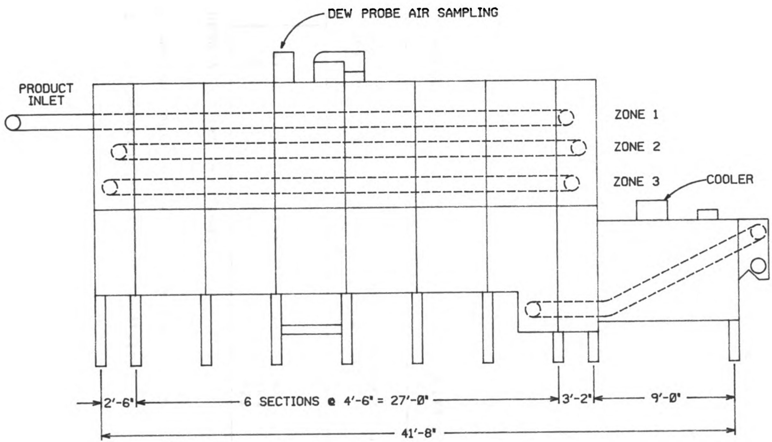


FIGURE 3.2.1

Thus, the bed depth is largest in the third zone and smallest in the first zone.

Air is supplied between the zones and is designed to move through and over the product bed, and then return to the air supply system (see Figure 3.2.2).

Typical product temperatures and moisture contents at the inlet and outlet of each zone of the dryer are shown in Table 3.2.2.

TABLE 3.2.2

CONVENTIONAL BELT DRYER OPERATING CONDITIONS

	TEMPERATURE DRY BULB (^{o}C)	R.H. (%)	RESIDENCE TIME (sec)	BED DEPTH (cm)	PRODUCT TEMP (^{o}C)	PRODUCT MOISTURE (% wb)
ZONE						
1	61	65	151	5	38*	26.3*
2	61	65	258	7	46*	23.2*
3	61	65	504	10	52*	21.5*

*** MEASURED AT OUTLET OF FLIGHT**

The measurements shown in Table 3.2.2 do not imply that the dryer is operating at optimum conditions.

PELLET DRYER AIR FLOW

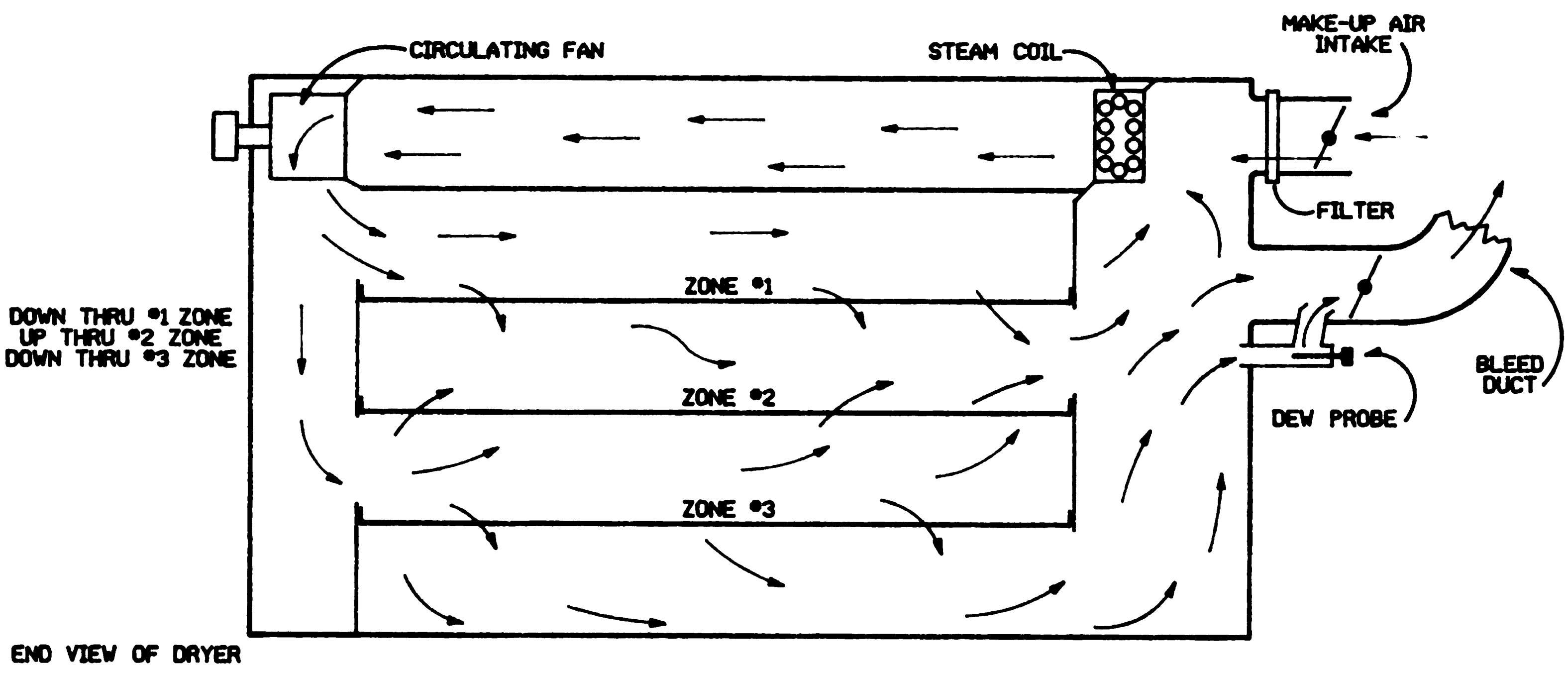


FIGURE 3.2.2

3.2.1 DRYING ANALYSIS

In order to analyze the drying process, it is necessary to understand the drying stages which the product undergoes inside the dryer. The cooked cereal product enters the dryer with a moisture content of 28% wet basis. At this moisture content the outer surface of the cooked cereal is saturated. As the temperature of the outer surface increases, the moisture evaporation rate from the particle surface increases. This stage of the drying process is called the "constant rate period". The rate of drying is constant, and is dependent on the rate of evaporation at the outer surface. In this stage of the drying process, the resistance to moisture transport at the surface is much larger than the internal resistance. The time during which a product is in the constant rate drying period depends on the rate of moisture flow from the interior of the particle to the outer surface. When the moisture concentration of the outer surface drops below saturation, the constant rate period ends.

The end of the constant rate period is characterized by a decrease in the rate of evaporation. This stage of the drying process is called the "falling rate period". In this stage the internal resistance to moisture transport is greater than the surface resistance. This causes a moisture gradient to occur within the particle, and the temperature rises above the wet bulb temperature of the air (Brooker 1978). The decrease in the evaporation rate is due to the increased resistance to moisture transport. The limiting factor is the diffusion rate of moisture from the interior of the product to the outer surface.

The point at which the moisture content of the outer surface drops below saturation is defined as the critical moisture content. This point defines the change from the constant rate period to the falling rate period.

Fortes and Okos (1981) stated that the moisture migration in the constant rate period is in the form of liquid flow. As the falling rate period begins, moisture migration is split between liquid and vapor flow. An evaporation front moves into the particle once the outer surface has reached the equilibrium moisture content. Geankoplis (1986) described the movement of moisture from the interior of the particle to the outer surface through the capillaries of a porous product. As the product dries, moisture is removed from the capillaries, and air moves in to fill the voids. As these capillaries fill with air, they block liquid flow to the surface. At this point vapor movement becomes the dominant flow mechanism.

When air pockets form in the interior of the product, the heat conduction from the outer surface to the center of the product decreases. This is due to the change in heat transfer mechanism from conduction to convection as the heat moves through the air pockets (Geankoplis 1986). The net effect is a layer of insulation in the outer surface of the product. The thickness of the insulation layer is dependent on the depth of the evaporation zone. The insulation layer slows the conduction of heat to the interior of the product and adds to the resistance of mass flow to the outer surface.

Analysis of the internal liquid and vapor transport processes which take place inside the product and control the rate of drying is beyond the scope of this work. The equations which describe the mass, heat, and total pressure transport in a porous media are given by Luikov (1966), and Perkins (1979):

$$\frac{\partial M}{\partial t} = \alpha_m \nabla^2 M + \nabla^2 k_{12} T + \nabla^2 k_{13} P \qquad 3.2.1.1$$

$$\frac{\partial T}{\partial t} = \nabla^2 k_{21} M + \alpha_t \nabla^2 T + \nabla^2 k_{23} P + \frac{q}{\rho c_p} \qquad 3.2.1.2$$

$$\frac{\partial P}{\partial t} = \nabla^2 k_{31} M + \nabla^2 k_{32} T + \alpha_p \nabla^2 P \qquad 3.2.1.3$$

where,

M = Product moisture content dry basis (kg H_2O/kg food)

T = Product Temperature (^oC)

P = Total pressure of system (Pa)

q = Microwave heat source (watt)

α_m = Mass diffusivity of product (m^2/sec)

αt = Thermal diffusivity of product (m^2/sec)

αp = Pressure diffusivity of product (m^2/sec)

k_{xx}= Coupling coefficients.

The moisture content at any point within the product is the sum of the liquid mass and the vapor mass:

$$M = M_l + M_v \qquad 3.2.1.4$$

Equations 3.2.1.1, 3.2.1.2, and 3.2.1.3 are valid for a solid which does not exhibit expansion or shrinkage, and has no internal convection.

Brooker (1978) called the thermal diffusivity, mass diffusivity, and pressure diffusivity in equations 3.2.1.1, 3.2.1.2, and 3.2.1.3, the phenomenological coefficients. The terms k_{12} and k_{21} represent the coupling coefficients known as the Dufour and Soret affects (Bird, Stewart, Lightfoot 1960).

The thermal diffusivity is not assumed to be constant. It is a combination of the thermal conductivity, specific heat, and density of the product:

$$\alpha_t = \frac{K}{\rho \, c_p} \qquad 3.2.1.5$$

The specific heat of the product is dependent on the composition and changes throughout the drying process (Heldman 1979). Fortes and Okos (1980) assumed the thermal conductivity of the product to be constant over the range of product temperature and moisture content encountered in the drying of food products. Thus,

$$\alpha_t = \frac{\kappa}{\rho(c_{pw} M_{db} + (1 - M_{db})\, c_{df})} \qquad 3.2.1.6$$

where,

α_t = Thermal diffusivity of product (m^2/sec)

κ = Thermal conductivity of product (watt/m- ^oC)

c_{px}= Specific heat of component (J/kg-^oC)

M_{db}= Moisture content of product (% dry basis).

The mass diffusivity in equation 3.2.1.1 is a combination of the terms which influence the mass transport. The diffusivity is a function of the product temperature (Fortes 1980):

$$\alpha_m = C_1 \exp(D_1\, T_p) \qquad 3.2.1.7$$

where,

α_m = Mass diffusivity of product (m^2/sec)

C_1 = Empirical coefficient (unitless)

D_1 = Empirical coefficient (unitless)

T_p = Local Product temperature (^oC).

The pressure diffusivity and therefore, equation 3.2.1.3, can be eliminated from the analysis of conventional drying systems (Brooker 1978).

3.2.2 MICROWAVE ASSISTED DRYING

Application of microwave heating to the drying process offers advantages when combined with a conventional drying system. The application of heat from a microwave source does not depend on transfer of heat through the surface. The penetration of microwave energy delivers heat directly to the interior of a thick product. This offers a unique opportunity to drying of thick products.

The application of heat to the interior of a particle has the potential of extending the constant rate drying period (Oda 1987). This can be found by analyzing the coupling between the product temperature and mass diffusivity. If energy can be delivered to the center of the product and the resistance to moisture movement is inversely proportional to temperature, the net effect is faster movement of moisture from the interior of the particle to the outer surface. The result is an extension of the constant rate drying period.

One of the potential advantages of a microwave power source is the local pressure which may be caused by a phase change of the moisture from liquid to vapor. When microwave energy is applied, the temperature of the interior is not limited to the boiling point temperature of the liquid in the product. If enough power is absorbed within a local area, the temperature of the liquid may rise above the boiling point (Fortes and Okos 1980). This will result in an increase in the contribution of the total pressure term in equation 3.2.3.1. As the local pressure rises, the driving force for moisture movement between the local area and the outer surface increases. Therefore the local rate of moisture transfer increases. This concept is valid only if the temperature of the liquid moisture trapped in the interior of the product rises above the boiling point. If the local pressure rises above the pressure of the atmosphere, a change in the transport mechanism occurring may cause the product structure to become unstable.

A mathematical model of the drying process includes equations 3.2.1.1, 3.2.1.2, 3.2.1.4, 3.2.1.6, and 3.2.1.7. A mathematical model of the heating caused by microwave radiation includes equations 3.1.2.1, 3.1.2.2, 3.1.2.3, and 3.1.2.4. The combination of these equations forms the basis of the microwave - convection drying of ready-to-eat cereals.

CHAPTER 4 EXPERIMENTAL PROCEDURES

The experimental part of this study has three objectives. The first is to obtain measurements of the environment within the microwave tunnel. This includes the air temperature, humidity, and velocity, and the microwave power to which the particles are subjected. The information is needed to describe the boundary conditions for the heat and mass transfer equations. The second step is to determine the thermal and mass diffusivity of the product. The diffusivity information is used to calculate the heat and mass transport occurring within the microwave tunnel. The third objective is to provide basic data to validate the mathematical simulation. Validation is required to check the assumptions made in developing the model.

4.1 DESCRIPTION OF THE MICROWAVE SYSTEM

The drying experiments were conducted in a Scan Pro Microwave tunnel (Skandainviska Processinsturment AB Model 40 KW, Bromma, Sweden) which has been designed for continuous flow (see Figure 4.1.1).

The Scan Pro tunnel has an operating length of 14 feet. Of this, 6 feet consist of the chokes at the inlet and outlet of the tunnel.

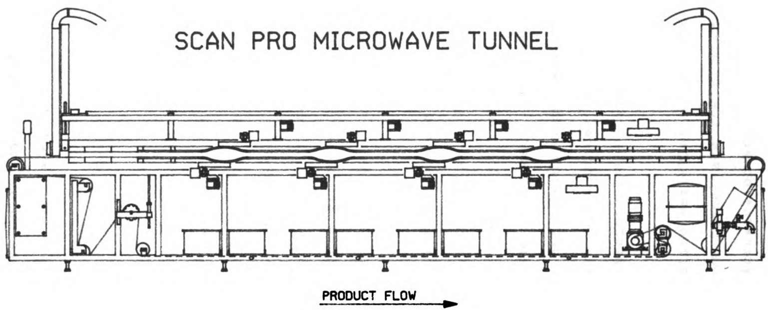


FIGURE 4.1.1

A choke is a wave guide beyond cutoff which is designed to prevent radiation from escaping through the ends of the tunnel. From the point of view of a microwave, the choke acts as a wall. Any radiation that enters the choke bounces back and forth in the choke until it is absorbed. The tunnel has 20 KW provided by 8 magnetrons of 2.5 KW each. The magnetrons are placed in pairs above and below the tunnel. The Scan Pro microwave tunnel uses surface wave guides in order to develop a uniform microwave field within the tunnel. The surface wave guides are the unique factor of the Scan Pro tunnel. Surface wave guides were designed to heat thin layers, less than 5.0 cm of material, at high field strengths. The high field strengths are obtained by guiding the microwave energy close to one of the surfaces of the wave guide. When fed with microwave power at the correct frequency, the microwave energy propagates along one of the surfaces. This design intensifies the electric field and yields high heat transfer rates. The multiple surface wave guides are designed to develop a uniform field throughout the length of the tunnel.

The operating variables which control the performance of the microwave tunnel are the product residence time and the level of microwave power.

The product residence time is adjusted by changing the speed of the conveyor. As the belt speed changes, the exposure time of the product to the microwave energy and the convective energy changes.

In order to obtain the highest mass transfer rate at the outer surface of the product, a convection source was added. The air flow system is shown in Figure 4.1.2. The sides of the oven were replaced and duct work added to provide convection heating. The modification was designed to optimize the intensity of the convection heating. Concurrent and countercurrent flow were tested by changing the location of the air inlet and outlet.

The air supply system consists of a small test oven which delivers heated air at constant temperature, humidity, and flow conditions. The test oven uses a centrifugal fan combined with a natural gas burner to supply a constant volume of air at a specified temperature.

A perforated plate is placed at the inlet to the microwave tunnel. The plate provides a pressure drop sufficient to insure a uniform air flow across the tunnel inlet. Adjustment of the air volume entering the tunnel is made by changing the pressure in the duct work at the tunnel entrance. The air velocity inside the tunnel is assumed to be uniform and a function of the inlet air volume.

SCAN PRO MICROWAVE TUNNEL
WITH CONVECTION HEATING

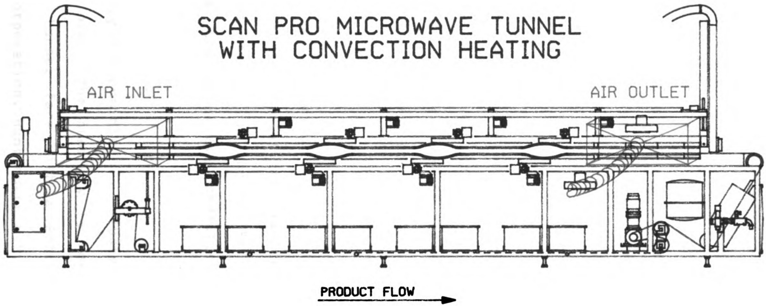


FIGURE 4.1.2

The air temperature is adjusted by using a standard natural gas burner, and is measured with a RTD type thermocouple. A PID controller maintains the temperature set point within a range of 4 ^{o}C. The supply air temperature is measured in the inlet duct at the tunnel face. The outlet air temperature is measured at the outlet duct. The air temperature inside the tunnel is not measured due to the electric field. A linear decrease in the air temperature is assumed. This assumption is based on the contact time between the product and the air stream. The residence time of the air in the tunnel is eight seconds based on the air velocity used in this study. The tunnel is divided into seven sections. The air temperature and humidity are calculated for each of the seven sections.

The field strength is adjusted by changing the electrical power to each of the magnetrons. The magnetrons have two power levels: 1.6 and 2.5 Kw (Figure 4.1.3). The frequency of the microwave radiation is fixed by the magnetron.

The supply air humidity is adjusted by using saturated steam at 30 psi. The humidity is measured in the supply duct at the tunnel face with a Rotronix probe (Rotronix Instrument Corporation, Huntington N.Y.). The instrument has a range of 0 to 150 ^{o}C.

MICROWAVE CONTROL PANEL

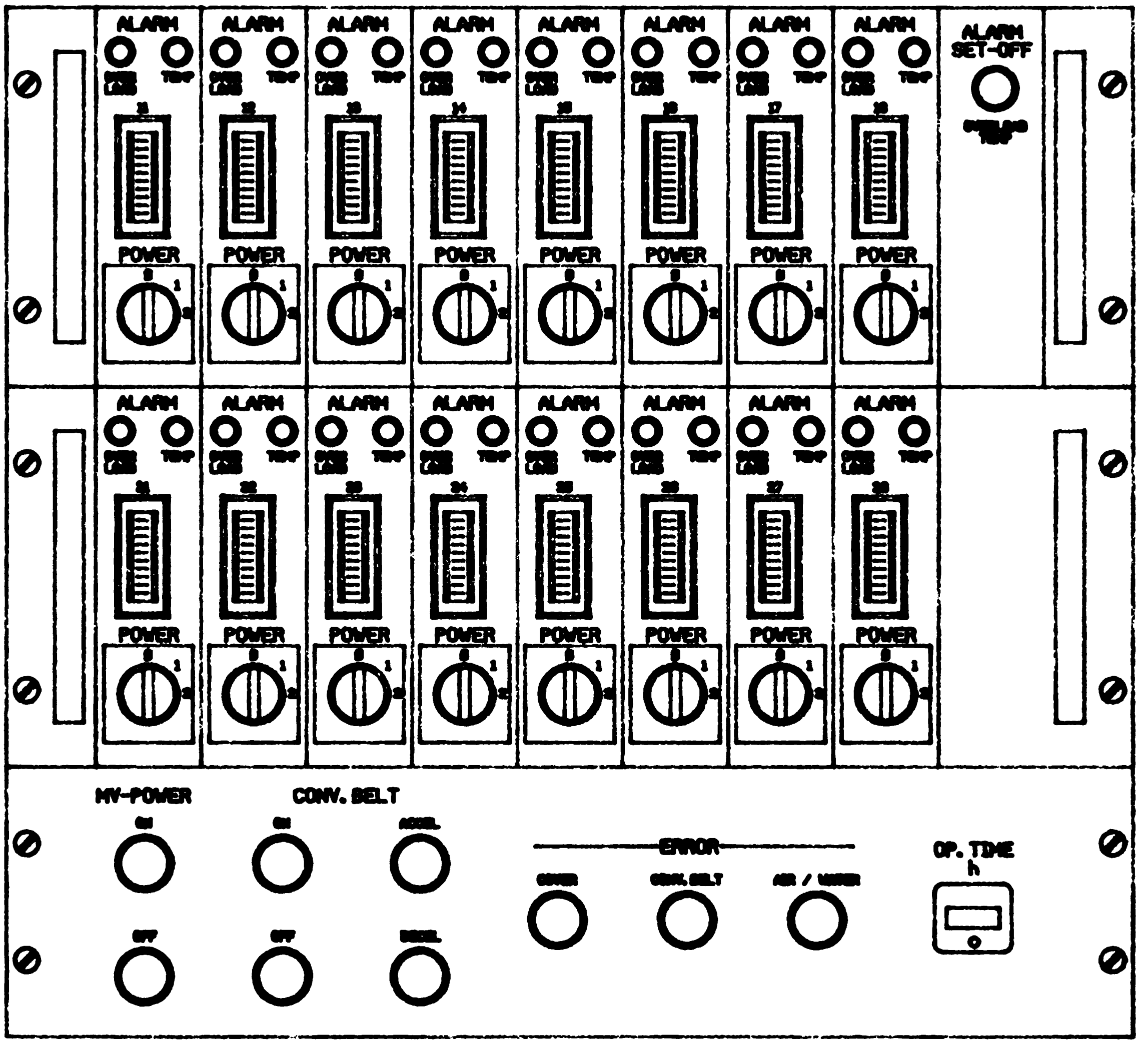


FIGURE 4.1.3

The outlet air humidity is measured in the outlet duct. The electric field prevents humidity measurement inside the tunnel. A linear relationship between the humidity change and the length of the tunnel is assumed.

4.2 MICROWAVE FIELD STRENGTH TESTS

The electric field strength determines the energy dissipated within the product. The electric field strength is a combination of the electric and magnetic fields generated by the magnetron.

It is not possible to theoretical predict the magnituide of the microwave field strength in a controlled setting with amount of technology currently available. Therefore, the electric field strength within the microwave tunnel was measured experimentally. The procedure used to measure the field strength is based on several assumptions which are used to approximate the field strength.

The experimental method consists of loading the tunnel with several containers filled with a known volume of water (see Figure 4.2.1). The temperature rise of the water was measured in discrete time segments.

MICROWAVE FIELD STRENGTH MEASUREMENTS

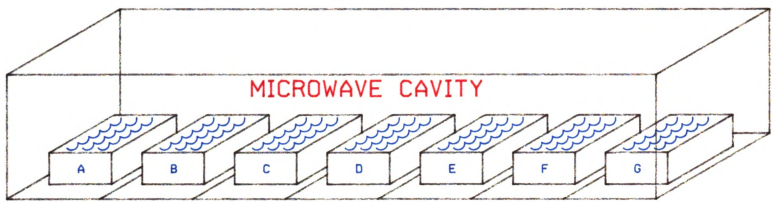


FIGURE 4.2.1

The average strength of the electric field as calculated by calorimetry, is given by Metexas (1979) as:

$$E_{avg}^2 = \frac{\rho \; c_p \; (T - T_0)}{(\varepsilon_0 \; \omega \; 2 \; \pi \; f \; \varepsilon'')t} \qquad 4.2.1$$

where,

E_{avg} = Average field strength (v/m^3).

Equation 4.2.1 is valid if the dielectric properties of the material are not a function of temperature. Between 20 and 30 C the dielectric properties do make a small change. The dielectric loss factor changes from 22 to 18, the dielectric constant changes from 82 to 78 (Von Hipple 1954). This information supports the assumption of constant dielectric properties of water.

Several approximations are made in order to use equation 4.2.1 for a 120 second experiment. First, it is assumed that the microwave field strength is uniform and constant within each of the dryer zones. This approximation is theoretically incorrect. The electric field is time dependent and changes direction at the rate of 2450 million times per second. With current technology there is no method to measure the temperature change at this high a rate. Therefore, the only pratical approch is to consider the electric field to be constant with respect to time.

Also, the variation of the field within the volume is a function of the source of the radiation and the geometry of the cavity. When more than one source is used, it is not possible to theoretically determine the electric field-strength at a given point. Therefore, the electric field strength is assumed to be constant in each dryer zone. The change in field strength with location is not as critical in a continuous drying tunnel in which the product is moving, than in a batch system in which the product is stationary. In the continuous system, the product is subject to a different rate of heating at each point. The product's movements prevent hot spots from occurring due to the microwave field strength variation. In a batch system the product maybe subjected to hot spots which may occur due to the stationary position of the microwave field.

The third assumption is that all the energy of the electric field enters the material. Under the prevous assumption of a constant microwave field in each dryer zone, it is not possible to determine the direction of incident radiation. Therefore, the ratio of energy reflected and transmitted cannot be determined. Since the main objective of this study is to find the relationship between the energy transmitted to the product and the drying rate, the assumption that all of the energy generated enters the product is justified. A quantification of the reflected energy is required to size new magnetrons for the dryer, but the absolute strength of the field and the amount of energy reflected are not critical to this study.

Seven rectangular containers of a microwave transparent material were filled with water and placed inside the microwave tunnel. The container size is 29 x 59 cm with a depth of 8 cm. The containers nearly filled the tunnel area. A closed cylinder filled with water was placed inside each container. The cylinders acted as a control volume to determine whather a phase change has occurred within the containers. The temperature of the containers and the cylinders are measured at set time periods.

Several problems were prevented by using the large containers within the tunnel. They acted as a load in the microwave tunnel. Without a load inside the tunnel the magnetrons can be damaged. The containers averaged the variation in the electric field strength over the volume of the containers, and yielded an average value (see Figure 4.2.1). Thus, the tunnel length is separated into seven sections each of which has a different field strength. The size of the containers, and the agitation received due to the moving belt, allowed a large amount of mixing to occur thereby eliminating hot spots.

The small cylinders acted as a control volume. The cylinders were closed to prevent mass evaporation. The cylinders were totally filled, thereby preventing evaporation. If a phase change occurred, the pressure inside the cylinder would have caused a rupture of the cylinder walls. This check was used to determine if energy was lost by evaporation.

The assumptions and approximations used to make a estimation of the microwave field strength available are open to question. The results of the field strength tests must be evaluated on a order of magnitude approximation.

4.3 PRODUCT DIFFUSIVITY MEASUREMENTS

The second objective of the experiments was to analyze the resistance of the product to heat and mass transfer. The terms which need to be determined experimentally are the thermal and the mass diffusivity.

The heat flow inside a solid with constant thermal properties and without internal convection, heat generation, or shrinkage is described by Geankoplis (1983) as:

$$\frac{\partial T}{\partial t} = \alpha_t \nabla^2 T \qquad 4.3.1$$

in which,

$$\alpha_t = \frac{\kappa}{\rho \, c_p} \qquad 4.3.2$$

where,

α_t = Thermal diffusivity of product (m^2/sec)

κ = Thermal conductivity of product (watt/m ^oC)

c_p = Specific heat (J/kg ^oC)

ρ = Density of product (kg/m^3)

The thermal diffusivity is a measure of the product's resistance to the flow of energy. It can be estimated by measuring the temperature change within the solid over time. Holman (1976) described the one dimensional case using a backward difference method:

$$\alpha_t = \frac{(\nabla x)^2}{\nabla t} * \frac{({}_{t+\partial t}T_n - {}_tT_n)}{({}_tT_{n-1} - {}_tT_n) - ({}_tT_n - {}_tT_{n+1})} \qquad 4.3.3$$

where,

α_t = Thermal diffusivity of product (m^2/sec)

${}_tT_m$ = Temperature at node m in time step t (C^o)

The specific heat of a product is a measure of the ability to store thermal energy. Heldman (1974) proposed the following relationship between the effective specific heat and the product moisture content as:

$$c_p = c_{pw} M_{db} + c_{pf} (1 - M_{db}) \qquad 4.3.4$$

where,

c_p = Specific heat of product (J/kg C^o)

c_{pw} = Specific heat of water (J/kg C^o)

c_{pf} = Specific heat of dry product (J/kg/C^o)

M_{db} = Moisture content of product (% dry basis).

Using equations 4.3.2 and the measurements of product temperature, the thermal conductivity of the product can be calculated.

The moisture diffusion inside a bed of product is described by Geankoplis (1983) as:

$$\frac{\partial M}{\partial t} = \alpha_m \nabla^2 M \qquad 4.3.5$$

where,

α_m = Mass diffusivity of product (m^2/sec)

M = Moisture content of product (% dry basis)

The mass diffusivity is a measure of the resistance to moisture movement within a solid. The effective mass diffusivity is an average of the resistance to mass movement in both the liquid and vapor phases.

In order to use equation 4.3.5, information describing the effective mass diffusivity α_m of the product must be determined. It is obtained using a one dimensional finite difference analysis of the moisture profile within the bed at known points at discrete time steps.

Geankoplis (1983) described the one dimensional case as:

$$\alpha_m = \frac{(\nabla x)^2}{\nabla t} * \frac{({}_{t+\partial t}M_n - {}_tM_n)}{({}_tM_{n-1} - {}_tM_n) - ({}_tM_n - {}_tM_{n+1})} \qquad 4.3.6$$

where,

${}_tM_m$ = Moisture content at node m in time step t (% dry basis)

An Arrhenius relationship based on product temperature is used to describe the mass diffusivity during the drying process as a function of product temperature (Liou 1982)(see equation 3.2.1.6).

4.4 DATA COLLECTION

The third objective is to validate the assumptions used in the model. In order to accomplish this objective, several sets of product temperature and moisture content were recorded under different experimental conditions. The data collection procedure consists of two parts. The first part provides information on the conditions inside the tunnel; the second part gives information on the change in temperature and moisture content of the product inside the tunnel.

The parameters controlled in the tunnel are the product residence time and the microwave power level. The parameters which constitute the environment inside the tunnel are a function of the product conditions. The accuracy with which the initial and boundary conditions were measured are:

1. **Supply air temperature** $\pm$ 2.0 (^{o}C)
2. **Exhaust air temperature** $\pm$ 2.0 (^{o}C)
3. **Supply air humidity** $\pm$ 1.0 (% RH)
4. **Exhaust air humidity** $\pm$ 1.0 (% RH)
5. **Product mass flow** $\pm$ 0.5 (lb/min)

The second part of the data collection centered around the determination of the rate of energy absorption and the rate of moisture loss.

Removing a sample of product from the tunnel without disrupting the system proved to be difficult. The method selected consisted of allowing the process to come to steady state, stopping the system, and removing the samples. This was the only practical method of taking samples without the risk of high levels of microwave energy escaping from the tunnel.

There is an error associated with the sampling technique. It is caused by the time required to take the measurements. The time required to make a set of measurements was about 20 seconds. In order to minimize the time, a number of people were required. The error associated with product temperature loss is larger than the moisture content loss, so three temperature measurements are made at each point. As soon as the conveyor stopped, the tunnel was opened and the product samples were removed. Measurement of the product temperature were made using an Omega (Omega Instrument Corporation, Stanford, CT.) infrared radiation detector. The average product moisture content was measured using the AOAC (Association of Analytical Chemists, 1975) two stage moisture determination method.

The system used to supply the product to the microwave dryer is outside the scope of this study and will only be described in broad terms. The product enters the microwave tunnel at the conditions shown in Table 4.4.1.

TABLE 4.4.1

PROPERTIES OF PELLETS AT INLET OF DRYER

INITIAL TEMPERATURE	98.0	(F^o)
INITIAL MOISTURE CONTENT	28.2	(% db)
INITIAL DENSITY	44.9	(lb/ft^3)
SPECIFIC HEAT DRY FOOD	0.4	(BTU/lb-F)
CRITICAL MOISTURE CONTENT	18.0	(% db)
SURFACE AREA	4.2	(ft^2/lb)
PROTEIN	0.0012	(lb/in_3)
CARBOHYDRATE	0.0093	(lb/in_3)
SODIUM	8.2 E-6	(lb/in_3)
POTASSIUM	6.9 E-6	(lb/in_3)
DIETARY FIBER	2.0 E-3	(lb/in_3)

CHAPTER 5 THEORETICAL

Describing the drying process with a mathematical model provides a method of analyzing the basic relationships of the process. In this section, the mathematical model is described for the drying of a two dimensional food product.

The heat flow in a two-dimensional solid bed without internal convection, expansion or shrinkage is described by Geankoplis (1983) as:

$$\frac{\partial T}{\partial t} = \alpha_t \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + \frac{q}{\rho c_p} \qquad 5.1.1$$

where,

α_t = Thermal diffusivity of product (m^2/sec)

T = Product temperature (^oC)

q = Microwave heat generation (watt)

c_p = Specific heat of product (J/kg ^oC).

The boundary condition for the heat transfer at the outer surface is given by Fortes and Okos (1980) as:

$$J_q = h_t(T_s - T_a) + L_v \frac{\partial M}{\partial t} \qquad 5.1.2$$

where,

J_q = Heat flux at the outer surface (watt/m^2)

h_t = Convective heat transfer coefficient (watt/m^2- C^o)

T_s = Temperature of the outer surface (C^o)

T_a = Dry bulb temperature of the air (C^o).

L_v = Latent heat of vaporization ($J/kg\ H_2O$)

The convective heat transfer coefficient is defined by Holman (1976) as:

$$h_t = \frac{N_u\ \kappa_a}{x} \qquad 5.1.3$$

where,

N_u = Nusselt Number (dimensionless)

κ_a = Thermal conductivity of the air (watt/m- ^oC)

x = Distance air has moved over bed (m).

The Nusselt number is a dimensionless number and relates the convective heat transfer coefficient h_t to the thermal conductivity of the air. The Nusselt number is a combination of two dimensionless numbers, the Prandtl number and the Reynolds number. Holman (1976) gives the following relationship for a flow over a flat plate:

$$N_u = 0.332\ P_r^{1/3}\ R_e^{1/2} \qquad 5.1.4$$

where,

P_r = Prandtl number (dimensionless)

R_e = Reynolds number (dimensionless).

The Prandtl number relates the thickness of the hydrodynamic and thermal boundary layers. The Reynolds number expresses the dimensionless flow velocity.

The initial conditions used in equation 5.1.1 are:

$$T_{n,o} = T_o \qquad 5.1.5$$

where,

T_o = Temperature of the product as it enters the tunnel (C^o).

5.2 MASS TRANSFER

The moisture transfer inside a two-dimensional solid food product is described by Geankoplis (1983) as:

$$\frac{\partial M}{\partial t} = \alpha_m \left(\frac{\partial^2 M}{\partial x^2} + \frac{\partial^2 M}{\partial y^2} \right) \qquad 5.2.1$$

where,

α_m = Mass diffusivity of product (m^2/sec)

M = Moisture content of product (% dry basis).

The boundary conditions at the outer surface of the product bed are:

$$J_m = h_m (P_s - P_a) \qquad 5.2.2$$

where,

J_m = Moisture flux at outer surface (kg/m^2).

The convective mass transfer coefficient h_m is defined by Geankoplis (1983) as:

$$h_m = \frac{S_h \; \alpha_m}{x} \qquad 5.2.3$$

where,

S_h = Sherwood number (dimensionless)

α_a = Mass diffusivity of moisture in air (m/sec).

The Sherwood number is a dimensionless relationship between the convective mass transfer coefficient and the product diffusivity. The Sherwood number is given by Holman (1976) as:

$$S_h = 0.664 \; R_e^{1/2} \; S_c^{\;1/3} \qquad 5.2.4$$

where,

S_c = Schmidt number (dimensionless).

The Schmidt number relates the thickness of the hydrodynamic and mass transfer boundary layers. The Schmidt number is defined as:

$$S_c = \frac{\nu}{\rho \; \alpha_a} \qquad 5.2.5$$

where,

μ = Viscosity of the air (kg/m sec)

ρ = Density of the air (kg/m^3)

α_a = Diffusivity of the air (m/sec).

The initial conditions used in the solution of equation 5.2.1 are stated as:

$$M_{n,o} = M_o \qquad 5.2.6$$

where,

M_o = Moisture content of the product entering the tunnel (% dry basis).

A steady state condition inside the tunnel is assumed. The product temperature rise and moisture decrease are calculated at each point in the tunnel. This procedure has the effect of tracking the change in product temperature and moisture of the food product in the tunnel.

5.3 NUMERICAL METHODS

The differential equations for the heat and mass transfer are solved using the Finite Element Method (FEM) (Segerlind 1978). The FEM is a widely used numerical procedure for solving differential equations. The method has become the standard technique to solve problems in structural mechanics, heat transfer, and fluid flow. Program Oven, a generalized FEM oven - simulation program was employed.

Figure 5.3.1 gives a description of the basic steps used by the program to estimate the change in product temperature and moisture content.

PROGRAM FLOW

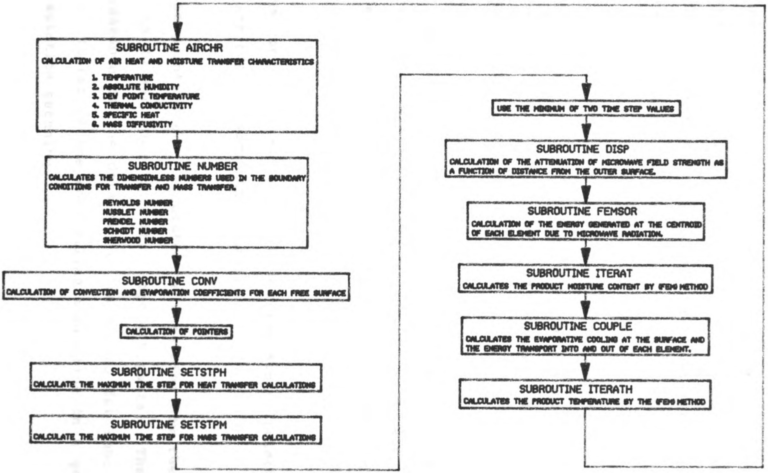


FIGURE 5.3.1

Subroutine Airchr calculates the air characteristics, at the start of each time step. The air characteristics include the temperature, absolute humidity, dewpoint temperature, thermal diffusivity, and mass diffusivity.

The free surfaces are identified and the Reynolds number, Nusselt number and Prandtl number, Schmidt number and Sherwood number are calculated for each element with a free surface by Subroutine Number.

Next the product heat and moisture transfer characteristics are calculated by subroutine Kscalc. This includes the product density, specific heat, thermal conductivity, and moisture diffusivity.

The convection and evaporation terms are calculated for each free edge in subroutine Conv.

The pointers are calculated to determine how the data vector is broken down into its component parts. The size and breakdown of the data vector is needed for subroutine Iterat. Iterat is the controlling subroutine in a general (FEM) solution technique.

Subroutine setstp calculates the maximum time step which can be used from the stiffness and capacitance matrices for the smallest element. The procedure is executed once for heat and once for moisture transfer and the minimum value is taken as the time step. This step eliminates the possibility of numerical instability.

In subroutine Disp the attenuation of the microwave field strength is calculated for each element based on the minimum distance from a free surface, and the microwave attenuation α.

The heat generated at the center of each element due to the microwave radiation is calculated in subroutine Femsor.

The product moisture content is calculated by Iterat.

The evaporate cooling at the surface and the energy transported into and out of each element by the moisture movement are calculated by the subroutine couple.

The energy transferred into and out of each element is added to the source term and the product temperature is calculated by Iterat.

The model consists of two coupled differential equations (ie 5.1.1, 5.2.1) with a microwave heat source and the associated initial and boundary conditions. A two-dimensional grid is used to describe the food product bed to be dried in both the conventional convection dryer and the microwave - convection dryer.

A listing of the computer program is contained in Appendix C. The solution technique is based on a finite difference technique in time using a central difference method. The method is inherently stable, due to dynamic adjustment in the time step based on the method described by Segerlind (1976)

A product residence time of 128 seconds requires 322 seconds of computer time on a Digital Vax 8700.

CHAPTER 6 RESULTS AND DISCUSSION

In this chapter the experimental and simulation results are presented and discussed.

The experimental results are divided into three parts:

1. Tests to determine the microwave field strength.
2. Experiments to determine the product thermal and mass diffusivity.
3. Comparison of the experimental and simulated data to evaluate the simulation model.

6.1 MICROWAVE FIELD STRENGTH MEASUREMENTS

The technique used to measure the microwave field strength is indirect in nature. The amount of energy absorbed by a material of known thermal and dielectric properties is used to calculate the intensity of the microwave field. Currently, there are no reliable instruments on the market which measure the field strength.

Table 6.1.1 presents the change in temperature of water in the containers and cylinders for zones A through G of the microwave tunnel (see Figure 4.2.1).

TABLE 6.1.1

MICROWAVE FIELD STRENGTH MEASUREMENTS

	CONTAINER A	B	C	D	E	F	G
INITIAL CONTAINER TEMPERATURE ^{o}C	19.1	19.5	19.1	19.3	19.3	19.6	19.4
INITIAL CYLINDER TEMPERATURE ^{o}C	19.1	19.5	19.1	19.3	19.3	19.5	19.4
FINAL CONTAINER TEMPERATURE ^{o}C	19.3	20.4	32.4	22.3	30.2	31.2	20.5
FINAL CYLINDER TEMPERATURE ^{o}C	19.3	20.5	31.8	22.2	30.4	31.2	20.5
TEMPERATURE RISE CONTAINER ^{o}C/sec	0.2	0.9	13.3	3.0	10.9	1.6	1.1
TEMPERATURE RISE CYLINDER ^{o}C/sec	0.2	1.0	12.7	2.8	11.3	1.7	1.0

Water has a penetration depth of 1 - 2 cm, therefore all of the energy gained by the water is absorbed at the outer surface of the container. The microwave field strength calculated will be assumed to be available at the outer surface.

The temperature of each container is measured at three locations with a RTD thermocouple after 120 seconds of exposure to the microwave field. Approximately 30 seconds after the completion of the test, the three temperature values were averaged to approximate the temperature rise of the container.

The basic assumptions made are, that the field strength is constant over the container volume and that all of the microwave energy generated enters the water bath. These approximations are necessary to estimate the field strength inside the tunnel.

The data in Table 6.1.1 shows that zones 3 and 5 exhibit an increases in water temperature of more than 10 ^{o}C. Zones 2, 4, and 6 experience an increase in water temperature between 1.0 and 2.9 ^{o}C. The two levels of water temperature indicate that there are two levels of microwave energy within the tunnel. The increase in water temperature is used to calculate the microwave field strength.

The containers function as a load inside the microwave cavity. The load eliminates the variation in field strength due to non-uniform loading. The cylinders function as the control volume to measure the rise in water temperature.

The difference between the water temperature in the cylinders and the containers is due to one of three possible reasons. The first is the variation in the microwave field. The assumption was made that the field strength is constant inside each container. The second possible source of error is that evaporation occurred only in the large containers. The third source of error is non-uniform mixing occurring inside the tunnel; the temperature inside any container may not have been uniform through out the container. In most cases, the differences are small enough to be assigned to experimental error.

TABLE 6.1.2

MICROWAVE FIELD STRENGTH CALCULATIONS

	CONTAINER						
	A	**B**	**C**	**D**	**E**	**F**	**G**
CYLINDER ENERGY GAIN Cal	0.2	0.8	10.2	2.3	8.8	1.4	0.9
POWER DISSIPATED CONTAINER Watt	2.3	11.4	145.2	33.2	126.9	19.5	12.6
MEASURED FIELD STRENGTH v/m	9.9	23.4	83.4	39.8	77.9	30.5	24.5

Table 6.1.2 presents the energy calculations used to determine the field strength. The data in Table 6.1.2 shows that zones 3 and 5 have a microwave field strength of between 83.38 to 77.95 v/m. Zones 2, 4, and 6 have a microwave field strength between 23.4 to 39.84 v/m. The range in microwave field strength and the variation in the heating seen in the zones are due to the location of the magnetrons. The magnetrons are located in zones 3 and 5 (see Figure 4.1.1). The heating in zones 2, 4, and 6 is due to microwave energy escaping from zones 3 and 5. The value of microwave field strength is calculated for each container, and constitutes an average over the volume occupied by the container. The field strength values are to

be used as a guide in determining the energy input to the product. The field strength information is used to calculate the amount of heat being added by the microwave field; therefore, the accuracy required in using the field strength data is critical. The accuracy of the data is based on the assumptions made in designing the experiments.

Appendix A contains the measured data and calculated values of the microwave field strength for each of the five test runs. The data verifies how repeatable the measurements are.

TABLE 6.1.3

COMBINED MICROWAVE FIELD STRENGTH BY POSITION

SECTION	A	B	C	D	E	F	G
AVERAGE FIELD STRENGTH	10.2	33.5	87.1	61.7	86.1	37.1	14.7
MINIMUM FIELD STRENGTH	0.0	2.4	5.9	4.5	3.1	8.4	12.0
MAXIMUM FIELD STRENGTH	21.6	37.4	93.5	67.5	89.7	52.9	35.8
STANDARD DEVIATION FIELD STRENGTH	6.9	2.4	5.9	4.6	3.1	8.4	4.4

Table 6.1.3 represents a tabulation of the calculated field strength for each of the five experiments. The

average, the range and the standard deviation values are given. The data show that the measured field strength can be replicated to within 15% of the full range value.

6.2 PRODUCT THERMAL AND MASS DIFFUSIVITY MEASUREMENTS

The second goal of the experimental investigations is to obtain the thermal and mass diffusivity of the product being dried. Table 6.2.1 contains the data of the product temperature measurements which occur inside a controlled convection dryer at discrete points inside a block of cooked cereal shown in Figure 6.2.1

TABLE 6.2.1 TRANSPORT MEASUREMENT BLOCK

PRODUCT TEMPERATURE GRADIENT DATA

	BLOCK SECTION					
TIME (sec)	A (deg F)	B (deg F)	C (deg F)	D (deg F)	E (deg F)	F (deg F)
600.	106.	87.	86.	86.	86.	86.
1200.	113.	89.	86.	86.	86.	86.
1800.	117.	92.	87.	86.	86.	86.
2400.	120.	95.	87.	86.	86.	86.
3000.	122.	98.	88.	86.	86.	86.
3600.	123.	100.	89.	87.	86.	86.
4200.	125.	102.	91.	87.	86.	86.
4800.	126.	104.	92.	87.	86.	86.
5400.	127.	106.	93.	88.	87.	86.
6000.	127.	107.	94.	88.	87.	87.
6600.	128.	108.	95.	89.	87.	87.
7200.	128.	109.	96.	90.	87.	87.
7800.	129.	111.	98.	90.	88.	87.
8400.	129.	111.	99.	91.	88.	88.
9000.	130.	112.	99.	92.	89.	88.

TRANSPORT MEASUREMENT BLOCK

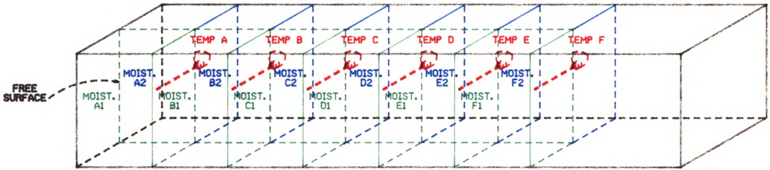


FIGURE 6.2.1

The uniform block of product in figure 6.2.1 has one free surface exposed to the controlled air stream. The product temperatures are measured and are used to calculate the product thermal diffusivity and thermal conductivity.

Table 6.2.2 presents the thermal diffusivity and thermal conductivity of the product calculated at each point at each time step.

The thermal conductivity of the cereal product is calculated from the thermal diffusivity, density and specific heat values.

The thermal conductivity of the product is not constant. Table 6.2.2 shows that a change occurs in the thermal conductivity from .356 to .789 BTU/sec-ft-F_o. This pattern is repeated for each of the tests and cannot be attributed to experimental error. The range in thermal conductivity is attributed to an evaporation front moving from the outer surface. The change in thermal conductivity cannot be separated from a density change as detailed data is not available.

The product block used to determine the thermal diffusivity and thermal conductivity is used to calculate the mass diffusivity if the product moisture profile through the block is measured at discrete points in time.

Table 6.2.3 presents the moisture profile measured within the product block.

TABLE 6.2.2 TRANSPORT MEASUREMENT BLOCK

THERMAL DIFFUSIVITY AND CONDUCTIVITY CALCULATIONS

TIME minutes	50	60	70	80	90	100	110	120
T BLOCK B deg F	98	100	102	104	106	107	108	109
α_t BLOCK B ft^2/sec	.743	.743	.752	.759	.767	.774	.781	.789
K BLOCK B B/s-ft-F	.356	.353	.351	.350	.349	.349	.349	.350
T BLOCK C deg F	88	89	91	93	94	95	96	98
α_t BLOCK C ft^2/sec	.676	.687	.697	.706	.716	.726	.736	.748
K BLOCK C B/s-ft-F	.361	.362	.362	.362	.363	.363	.363	.365
T BLOCK D deg F	86	86	87	88	88	89	90	90
α_t BLOCK D ft^2/sec	.655	.663	.674	.684	.695	.706	.717	.727
K BLOCK D B/s-ft-F	.356	.360	.363	.367	.371	.374	.377	.381

TABLE 6.2.3 TRANSPORT MEASUREMENT BLOCK

PRODUCT MOISTURE GRADIENT DATA

TIME (sec)	BLOCK SECTION					
	A (% wb)	B (% wb)	C (% wb)	D (% wb)	E (% wb)	F (% wb)
600.	18.	28.	28.	28.	28.	28.
1200.	14.	26.	28.	28.	28.	28.
1800.	12.	23.	28.	28.	28.	28.
2400.	11.	21.	27.	28.	28.	28.
3000.	10.	19.	27.	28.	28.	28.
3600.	10.	17.	25.	28.	28.	28.
4200.	9.	16.	24.	28.	28.	28.
4800.	9.	15.	23.	27.	28.	28.
5400.	9.	14.	22.	27.	28.	28.
6000.	9.	13.	21.	26.	28.	28.
6600.	8.	13.	20.	26.	28.	27.
7200.	8.	12.	19.	25.	27.	27.
7800.	8.	12.	18.	24.	27.	27.
8400.	8.	12.	18.	24.	27.	27.
9000.	8.	11.	17.	23.	26.	27.

Table 6.2.4 presents the mass diffusivity of the product in each section of the product bed at each time step. The mass diffusivity of the cereal product is calculated from the product moisture data and equation 4.3.5 (Figure 6.2.1). The mass diffusivity is calculated and then used to develop a overall mass diffusivity which is a function of product temperature.

The mass diffusivity is modified by the local product temperature in accordance with equation 3.1.6. Coefficients A and B are developed from a least square fit of the product moisture measurement and the raw mass diffusivity.

TABLE 6.2.4 TRANSPORT MEASUREMENT BLOCK

PRODUCT MASS DIFFUSIVITY CALCULATIONS

TIME minutes	50	60	70	80	90	100	110	120
M BLOCK B % wb	18.7	17.1	15.9	14.8	14.0	13.3	12.7	12.3
α_m BLOCK B ft^2/sec	.812	.779	.262	.159	.116	.091	.077	.067
BASE B	.502	.428	.130	.071	.048	.035	.028	.023
M BLOCK C % wb	26.5	25.4	24.3	23.2	22.1	21.1	20.1	19.2
α_m BLOCK C ft_2/sec	.074	.088	.102	.120	.144	.179	.237	.246
BASE C	.079	.085	.092	.102	.115	.135	.168	.232
M BLOCK D % wb	28.1	27.9	27.6	27.3	26.8	26.3	25.7	25.1
α_m BLOCK D ft^2/sec	.042	.051	.055	.060	.064	.069	.075	.082
BASE D	.053	.057	.061	.064	.067	.071	.074	.077

6.3 OPERATIONAL DATA COLLECTION

The third objective of the experimental section was to collect operational data which can be used to verify the assumptions made in the model. The operational data can be divided into two parts; the oven conditions and the product conditions. The oven conditions for run 9 are presented in Tables 6.3.1.

TABLE 6.3.1

MICROWAVE CONVECTION DRYER TUNNEL TEST RUNS

TUNNEL OPERATING CONDITIONS RUN # 9

Zone	Residence Time (sec)	Air Temp (F)	Air Humidity (lbW/lbA)	Food Width (ft)	Air Velocity (ft/s)	Field Strength (v/m)
1	17.7	115.	0.005	2.0	2.0	6.
2	17.7	120.	0.015	2.0	2.0	24.
3	17.7	126.	0.025	2.0	2.0	95.
4	17.7	132.	0.036	2.0	2.0	35.
5	17.7	138.	0.046	2.0	2.0	79.
6	17.7	144.	0.057	2.0	2.0	29.
7	17.7	150.	0.068	2.0	2.0	12.

The operational conditions shown in Table 6.3.1 contain the heat transfer supplied to the product by the microwave tunnel. The dead zone velocity represents the average velocity of the air above the product. The microwave field strength represent an average of microwave field strengths measured for each zone.

The product temperature and moisture measurements are presented in Table 6.3.2.

The data shown in Table 6.3.2 gives a history of the product temperature and moisture changes occurring inside the tunnel for run 9. The product temperatures exhibit a range which is dependent on the point at which the measurement was made. The initial temperatures for run 9 average 97 ±3 F°. The temperature measurements made in zone 6 had an average value of 170 ±23 F°.

TABLE 6.3.2

PRODUCT TEMPERATURE AND MOISTURE CONTENT MEASUREMENTS

MICROWAVE DRYING TEST RUN # 9; NO EXTERNAL CONVECTION

POSITION ft	TIME sec	TEMP 1 deg F	TEMP 2 deg F	TEMP 3 deg F	MOIST 1 % wb	MOIST 2 % wb
0.00	0.0	99.0	96.0	96.0	26.3	26.3
2.00	17.7	108.0	96.0	99.0	25.5	26.3
4.00	35.4	111.0	105.0	119.0	25.4	26.5
6.00	53.1	117.0	119.0	119.0	26.1	25.3
8.00	70.8	138.0	144.0	158.0	25.2	24.0
10.00	88.5	170.0	175.0	164.0	23.1	21.2
12.00	106.2	155.0	178.0	177.0	20.2	19.8
14.00	123.9	165.0	178.0	182.0	18.1	17.2

The range in temperatures can be attributed to two sources of error. The first source is the non-uniformity in the microwave field strength. If the field strength is more intense on one side of the tunnel, a range in product temperatures will be measured. The second source of error is the measurement technique (see section 4.3). The method used had a non-uniform time lag due to the time required to open the tunnel. This lag allows the product to cool, thereby increasing the temperature variation.

The product moisture content measurements for run 9 in Table 6.3.2 also show a range dependent on position. The minimum moisture range occurs near the inlet, and increases to a maximum of 1.9% at point 5. The range is small, but the accuracy of the moisture content data is critical. The product moisture content is used to calculate the pounds of water evaporated in the tunnel. Error in the moisture content has an influence on the calculated effectiveness of the tunnel at higher loads. The range in moisture content data can be assumed to stem from three sources. The product bed may not have been at a uniform moisture content when the measurements were made. Also, the non-uniformity in the microwave field may have induce a non-uniformity in the product bed. The second possible error in the moisture contents may be due to a change in the structure of the product. Pie (1987) theorized that moisture bound to the structure of the product changes and becomes free water. The technique used for moisture analysis does not detect bound water, therefore a transition between bound and free water is not detected. If the change in the product binding structure does occur, it will cause a range in product moisture.

The most likely cause of the range in product moisture is the range in product temperature. If a range in product temperature is caused by the non-uniformity of the microwave field, then the product moisture will also be non-uniform.

6.4 COMPARISON BETWEEN EXPERIMENTAL AND SIMULATED DATA

The objective of this section is to present a comparison between the experimental data and the simulated results.

Each of the experimental data sets were compiled, and divided into two parts. The information about the tunnel operating conditions from runs 7 - 23 was used to describe the boundary conditions inside the tunnel. The measured product temperature and moisture content values from test runs 7 -23 were used to evaluate the performance of the simulation.

Figure 6.4.1. presents the simulated product temperature, and product moisture content as a function of residence time in the tunnel for run 9. Superimposed on the curves are the experimental temperature and moisture profiles. Figure 6.4.1 shows three errors.

The first is the slope of the temperature curve in zones 3 and 5. In these sections, the model is predicting a faster rise in the product temperature than the experimental data indicates. This is due to the method used to calculate the microwave field strength.

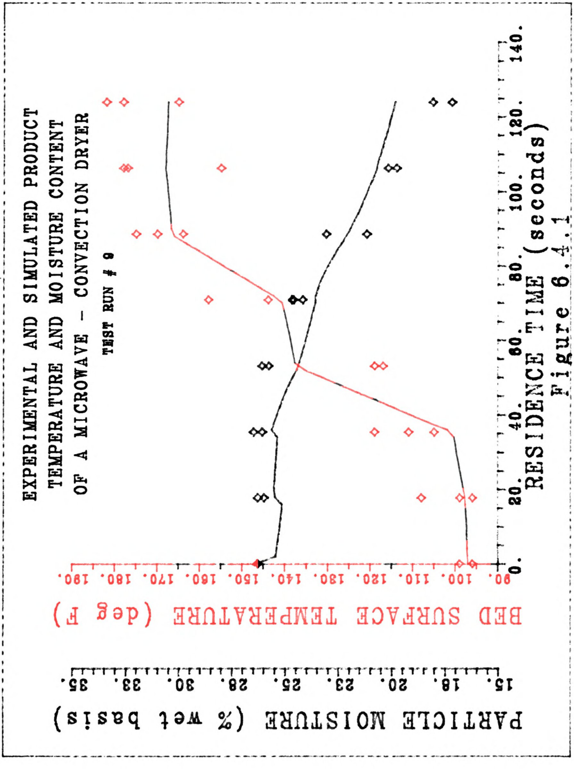

EXPERIMENTAL AND SIMULATED PRODUCT
TEMPERATURE AND MOISTURE CONTENT
OF A MICROWAVE - CONVECTION DRYER
TEST RUN # 9
PARTICLE MOISTURE (% wet basis)
15. 18. 20. 23. 25. 28. 30. 33. 35.
BED SURFACE TEMPERATURE (deg F)
90. 100. 110. 120. 130. 140. 150. 160. 170. 180. 190.
RESIDENCE TIME (seconds)
0. 20. 40. 60. 80. 100. 120. 140.

Figure 6.4.1

The field strength measured by a container may not necessarily correspond to the zones set up in the simulation. This is due to the volume inside the microwave tunnel used as a partial choke between the magnetrons. A container may be located between the high intensity field near a magnetron and low intensity field inside the choke. Therefore, a higher than actual microwave field strength may have been measured in zone 3, and a lower than actual field strength may have been measured in zone 4 (see Figure 4.1.1).

The second error occurs due to the equilibrium at the surface of the product bed. The model predicts an instantaneous drop in the moisture content of the outer node to match the vapor pressure of the air. This results in a decrease in the average moisture content of the bed. The decrease is due to oversized finite elements used at the product surface. The number of surface elements causes a large drop in the average moisture content of the product bed. The inaccuracy of the FEM grid at the surface must be balanced against the computational time of refining the model at the surface.

The third error may be caused by the values used for the product mass diffusivity and thermal conductivity. Note that the relationship between the product temperature and mass diffusivity influences the slope of the moisture content curve.

The relationship between the experimental data and the simulated values for run 9 as shown in Figure 6.4.1, are within the accuracy limits needed to evaluate the possible advantages to adding microwave energy into the drying operation, in the opinion of the author.

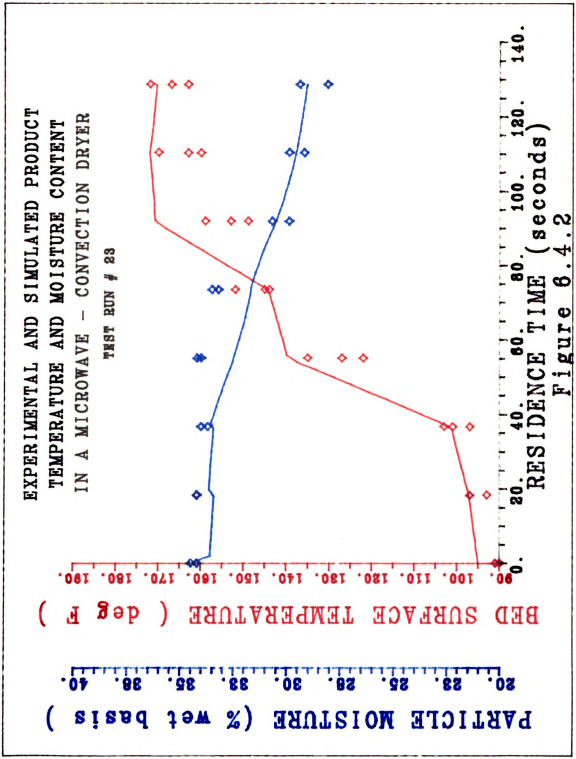
Table 6.4.1 presents the conditions in the tunnel for run 23. The product load for run 23 was more than twice that of run 9. Therefore the FEM grid for the bed depth was changed. The new grid has the same shape and number of nodes but the distance between the nodes has been increased to compensate for the larger bed depth, and new initial conditions.

TABLE 6.4.1

PRODUCT TEMPERATURE AND MOISTURE CONTENT MEASUREMENTS

MICROWAVE DRYING TEST RUN # 23: EXTERNAL CONVECTION

Zone	Residence Time (sec)	Air Temp (F)	Air Humidity (lbW/lbA)	Food Width (ft)	Air Velocity (ft/s)	Field Strength (v/m)
1	17.7	170.	0.012	2.0	5.0	6.
2	17.7	166.	0.019	2.0	5.0	24.
3	17.7	161.	0.026	2.0	5.0	95.
4	17.7	156.	0.033	2.0	5.0	35.
5	17.7	151.	0.040	2.0	5.0	79.
6	17.7	146.	0.047	2.0	5.0	29.
7	17.7	141.	0.055	2.0	5.0	12.



EXPERIMENTAL AND SIMULATED PRODUCT
TEMPERATURE AND MOISTURE CONTENT
IN A MICROWAVE - CONVECTION DRYER
TEST RUN # 23
RESIDENCE TIME (seconds)
BED SURFACE TEMPERATURE (deg F)
PARTICLE MOISTURE (% wet basis)

Figure 6.4.2

Figure 6.4.2 shows the relationship between the experimental and the simulated temperature and moisture content values for run 23.

The same errors noted in run 9 are found in run 23. Runs 9 and 23 represent two levels of loading. Run 9 had a load of 6.03 pounds of dry product per minute, run 23 had 14.03 pounds of dry product per minute.

The simulation represents the experimental adequately, considering the assumptions of microwave field strength which are used to calculate the microwave heating. The ability of the model to calculate the effect of a change in bed depth is obvious.

TABLE 6.4.2

PRODUCT TEMPERATURE AND MOISTURE CONTENT MEASUREMENTS

MICROWAVE DRYING TEST RUN # 23; EXTERNAL CONVECTION

POSITION ft	TIME sec	TEMP1 deg F	TEMP2 deg F	TEMP3 deg F	MOIST1 % wb	MOIST2 % wb
0.00	0.0	90.0	96.0	96.0	26.3	26.3
2.00	18.3	93.0	97.0	97.0	34.2	34.2
4.00	36.6	103.0	97.0	101.0	34.0	33.7
6.00	54.9	135.0	122.0	127.0	34.2	34.0
8.00	73.2	152.0	145.0	144.0	33.2	33.5
10.00	91.5	149.0	153.0	159.0	29.9	30.7
12.00	109.8	170.0	160.0	163.0	29.9	29.2
14.00	128.1	172.0	167.0	163.0	28.1	29.4

The test conditions for runs 7 - 23 are compiled in Appendix B.

Reviewing the relationship between the experimental data and the simulated values over the entire range of test runs provides an indication of the performance of the simulation. The deficiencies of the model appear to be:

1. The exact value of microwave field strength in each zone of the tunnel is unknown.

2. The accuracy of the FEM grid at the outer surface is limited.

3. The relationship between the product temperature and mass diffusivity is inaccurate.

Runs 9 and 23 represent the best fits between the experimental data and the simulated values. The other test runs represent a range in loading and initial conditions. The model is general enough to accept the variations, and produces reasonable results, in the opinion of the author. Figures 6.4.3 and 6.4.4 represent the average performance of the model.

The model is not required to perfectly describe the relationship between microwave and convection drying, but to give an indication of the trend. It can then be employed for the design the next generation of dryers.

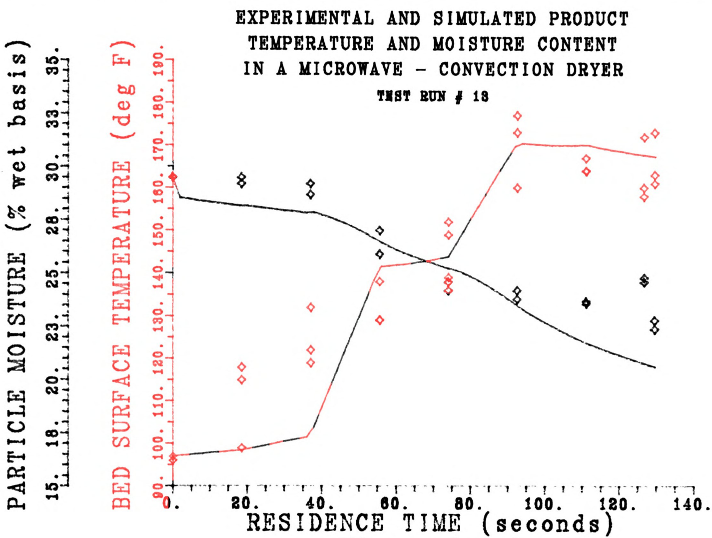

EXPERIMENTAL AND SIMULATED PRODUCT
TEMPERATURE AND MOISTURE CONTENT
IN A MICROWAVE - CONVECTION DRYER
TEST RUN # 13
PARTICLE MOISTURE (% wet basis)
15. 18. 20. 23. 25. 28. 30. 33. 35.
BED SURFACE TEMPERATURE (deg F)
90. 100. 110. 120. 130. 140. 150. 160. 170. 180. 190.
0. 20. 40. 60. 80. 100. 120. 140.
RESIDENCE TIME (seconds)

Figure 6.4.3

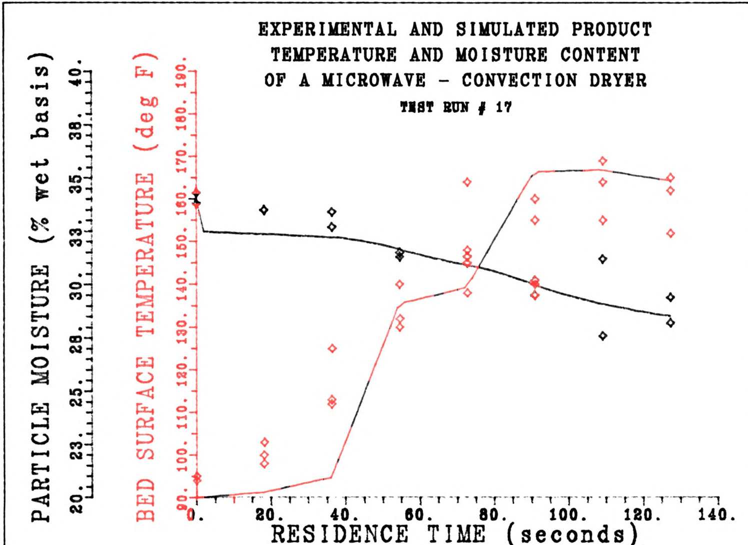

EXPERIMENTAL AND SIMULATED PRODUCT
TEMPERATURE AND MOISTURE CONTENT
OF A MICROWAVE - CONVECTION DRYER
TEST RUN # 17
PARTICLE MOISTURE (% wet basis)
20. 23. 25. 28. 30. 33. 35. 38. 40.
BED SURFACE TEMPERATURE (deg F)
90. 100. 110. 120. 130. 140. 150. 160. 170. 180. 190.
0. 20. 40. 60. 80. 100. 120. 140.
RESIDENCE TIME (seconds)

Figure 6.4.4

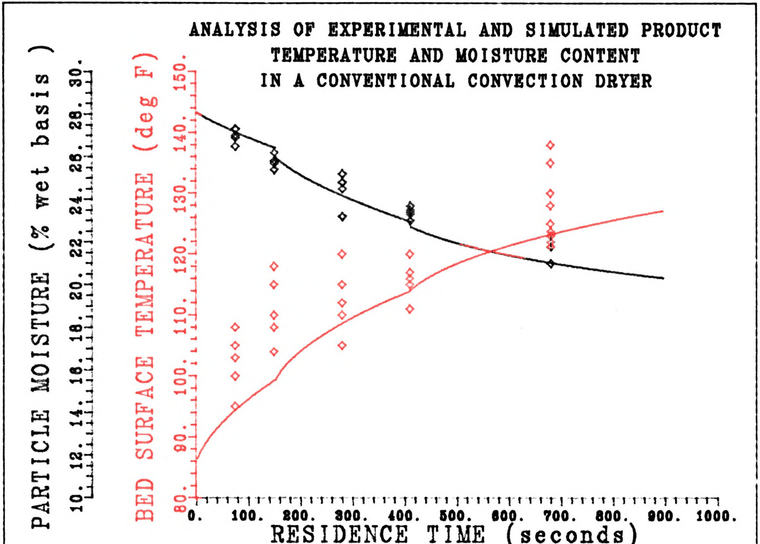
6.5 USE OF THE MODEL

The goal of this project was to determine if an accelerated drying rate can be obtained with the addition of microwave energy. The model is adequate to give an indication of the effect of microwave energy on the drying rate. The next step in this study is to remove the conditions used in the test runs, and to employ the model to fully analyze the use of microwave energy in the design of a new dryer.

6.6 ANALYSIS OF A CONVENTIONAL CONVECTION DRYER

The experimental and simulated temperature and moisture content values in the convection dryer without the addition of microwave energy is presented in Figure 6.6.1. The operating conditions are shown in Table 3.2.1. The belt dryer is designed to heat the product at the outer surface, and to dry the product from the outer surface.

Figure 6.6.1 shows how the product temperature and moisture content values change through the convection dryer. There is good agreement between the experimental and simulated values. In order to correctly model a three flight dryer, the model was subdivided into three sections.


ANALYSIS OF EXPERIMENTAL AND SIMULATED PRODUCT
TEMPERATURE AND MOISTURE CONTENT
IN A CONVENTIONAL CONVECTION DRYER
PARTICLE MOISTURE (% wet basis)
10. 12. 14. 16. 18. 20. 22. 24. 26. 28. 30.
BED SURFACE TEMPERATURE (deg F)
80. 90. 100. 110. 120. 130. 140. 150.
0. 100. 200. 300. 400. 500. 600. 700. 800. 900. 1000.
RESIDENCE TIME (seconds)
Figure 6.6.1

The product temperature and moisture content gradients which occur at the outlet of the first flight are averaged, and used as input to the second flight. The averaging of the gradients inside the product bed approximates the product blending which occurs between dryer flights. At the end of the first, zone the product drops from the belt in the first zone to the belt in the second zone. The drop between zones is treated as a mixing step which averages the temperature and moisture gradients. The mixing action results in a discontinuity of the heating and the drying curves between the flights. This procedure is repeated between the second and third flights.

The temperature and moisture gradients which occur at the end of the second and third zones are tabulated in Appendix D.

The fit between the production data and the model predictions are best for the first two flights. The predicted product temperature is low for the third flight. This may be due to a change in the product characteristics or in the bed depth. The temperature at the end of the third flight cannot be measured in production, and was estimated. The predicted product moisture content is low in the third flight of the dryer. This is due to the error in the product temperature.

The results shown in Figure 6.6.1 match the current pellet dryer performance within the accuracy needed to evaluate design changes. The results shown in Figure 6.6.1 will be used as a reference to compare new designs of a microwave convection dryer with the conventional convection dryer.

CHAPTER 7 DESIGN OF A MICROWAVE CONVECTION DRYER

In this chapter, the model discussed in chapter 6 will be used to evaluate new operating conditions of the microwave - convection dryer. Different combinations of microwave heating and convection heating are tested. The assumptions made in developing the model have been justified.

7.1 ADDITION OF MICROWAVE ENERGY IN THE FALLING RATE PERIOD

In the falling rate period of the drying process, extensive energy is required to remove water. Applying microwave energy in this section, increases the rate of drying. Table 7.1 contains the conditions used in a microwave convection dryer during the falling rate period.

TABLE 7.1

MICROWAVE CONVECTION DRYER OPERATING CONDITIONS

MICROWAVE HEATING IN THIRD ZONE

Zone	Residence Time (sec)	Air Temp (F)	Air Humidity (lbW/lbA)	Food Width (ft)	Air Velocity (ft/s)	Field Strength (v/m)
1	151.1	141.	0.085	4.0	12.0	0.0
2	260.9	141.	0.085	4.0	12.0	0.0
3	458.5	141.	0.085	4.0	12.0	25.0

The microwave - convection dryer described in Table 7.1 has the same size and product flow rate as the conventional system analyzed in section 6.6. The addition of microwave energy occurs in zone # 3. As in section 6.6, the dryer model used three simulations to approximate the mixing and the change in bed depth from 5 to 10 cm between the first and third zones.

Figure 7.1 presents the results of a simulation based on the conditions shown in Table 7.1. The product temperatures and moisture contents in the microwave - convection dryer are identical to the production system until the product enters the third zone. There, the rate of heating increases due to the application of microwave energy. This causes an increase in the rate of moisture removal. The final product moisture is 17.5% wet basis compared to 21.5% in the conventional convection dryer. Thus, the addition of microwave heating in the third zone causes a decrease in the final moisture content of 4 percent.

7.2 ADDITIONAL CONVECTION HEATING

Results shown in section 7.1 that the addition of microwave heating in the third zone of the dryer causes an increase in the drying rate. Heat can be applied from any source.

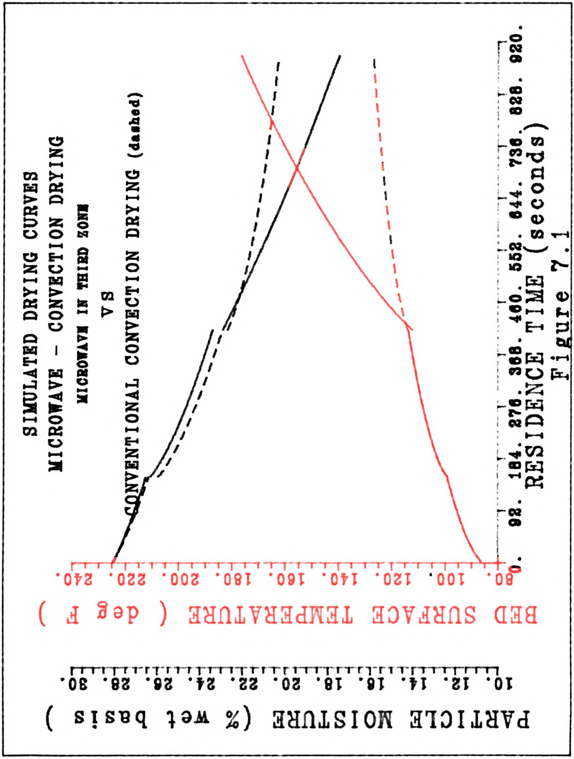

SIMULATED DRYING CURVES
MICROWAVE - CONVECTION DRYING
MICROWAVE IN THIRD ZONE
VS
CONVENTIONAL CONVECTION DRYING (dashed)
0. 92. 184. 276. 368. 460. 552. 644. 736. 828. 920.
RESIDENCE TIME (seconds)
80. 100. 120. 140. 160. 180. 200. 220. 240.
BED SURFACE TEMPERATURE (deg F)
10. 12. 14. 16. 18. 20. 22. 24. 26. 28. 30.
PARTICLE MOISTURE (% wet basis)

Figure 7.1

Thus, an increase in convection heating needs to be evaluated. The dryer conditions at higher levels of convection heating are shown in Table 7.2.

TABLE 7.2

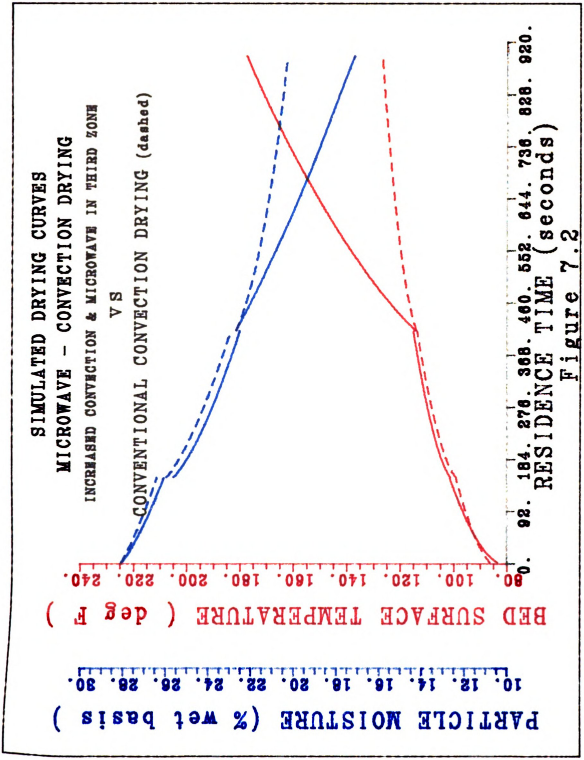
MICROWAVE CONVECTION DRYER OPERATING CONDITIONS

MICROWAVE HEATING AND HIGH CONVECTION THIRD ZONE

Zone	Residence Time (sec)	Air Temp (F)	Air Humidity (lbW/lbA)	Food Width (ft)	Air Velocity (ft/s)	Field Strength (v/m)
1	151.1	141.	0.085	4.0	25.0	0.0
2	260.9	141.	0.085	4.0	25.0	0.0
3	458.5	141.	0.085	4.0	25.0	25.0

The additional convection heating is increased by impingement from a high velocity air stream onto the top and bottom of the product bed. It is applied in all three zones. Microwave heating is again applied only in the third zone.

As Figure 7.2 and the data in Table 7.2 show, the addition of convection heating does increase the rate of heat transfer at the outer nodes. The additional thermal energy raises the temperature and lowers the moisture content of the outer nodes. However the conduction of heat into the center of the bed and the moisture migration from the center of the bed are slow relative to the initial rate of heat transfer.



SIMULATED DRYING CURVES
MICROWAVE - CONVECTION DRYING
INCREASED CONVECTION & MICROWAVE IN THIRD ZONE
VS
CONVENTIONAL CONVECTION DRYING (dashed)
0. 92. 184. 276. 368. 460. 552. 644. 736. 828. 920.
RESIDENCE TIME (seconds)
80. 100. 120. 140. 160. 180. 200. 220. 240.
BED SURFACE TEMPERATURE (deg F)
10. 12. 14. 16. 18. 20. 22. 24. 26. 28. 30.
PARTICLE MOISTURE (% wet basis)

Figure 7.2

After a short time the effectiveness of the additional convective energy decreases. Thus, the additional convective heating does not significantly increase the overall rate of drying in the first two zones.

7.3 ADDITION OF MICROWAVE HEATING TO ALL ZONES

It has been shown that addition of microwave energy in the third zone of the dryer results in an increase in the drying rate in the third zone. Therefore, additions of microwave heating in each zone should further increase drying rate of the dryer. Table 7.3 shows the conditions used to create a combination of microwave heating and impingement heating in all zones.

TABLE 7.3

MICROWAVE CONVECTION DRYER OPERATING CONDITIONS

MICROWAVE HEATING IN ALL ZONES

Zone	Residence Time (sec)	Air Temp (F)	Air Humidity (lbW/lbA)	Food Width (ft)	Air Velocity (ft/s)	Field Strength (v/m)
1	151.1	141.	0.085	4.0	12.0	25.0
2	260.9	141.	0.085	4.0	12.0	25.0
3	458.5	141.	0.085	4.0	12.0	25.0

Figure 7.3 shows the product temperature and moisture content. An increased rate of heating and drying occurs at

the surface resulting from the conditions detailed in Table 7.3.

The rate of heat transfer is constant through the dryer. The rate of moisture removal is slightly higher in the first zone of the microwave convection dryer than in the conventional system. The moisture transfer increases greatly in the second zone. The higher rate of moisture transfer in the second zone is due to the change in mass diffusivity. The third zone of the microwave dryer repeats the behavior of the second zone. The final moisture content of the product in Figure 7.3 is 13.6% wet basis. This represents a seven percent decrease in the final moisture compared to the conventional dryer. The time required to decrease the moisture content of the product to 21.5 percent in the microwave - convection dryer in Figure 7.3 is 447 seconds; the time required by the production system is 885 seconds. If the bed depth is held constant, a capacity increase of 29.9 (kg/min) is obtained.

Thus, a higher product velocity can be used and the physical size of the dryer can be decreased.

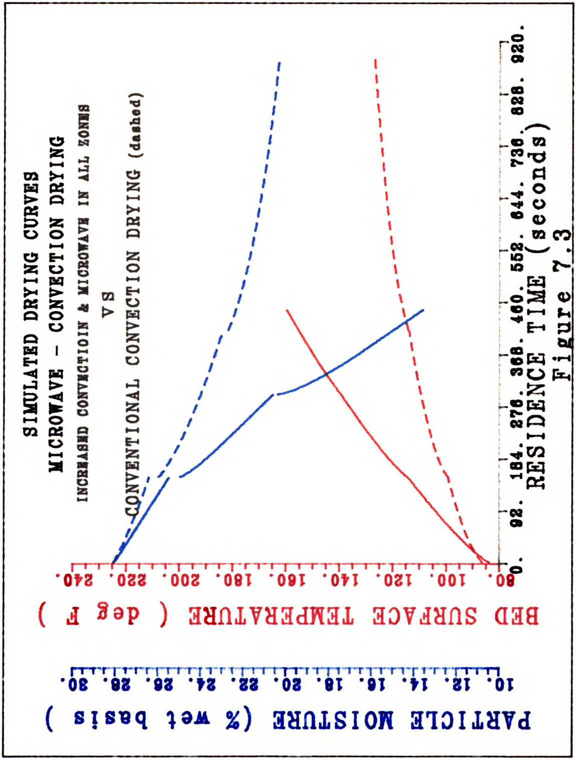

SIMULATED DRYING CURVES
MICROWAVE - CONVECTION DRYING
INCREASED CONVECTIOIN & MICROWAVE IN ALL ZONES
VS
CONVENTIONAL CONVECTION DRYING (dashed)
0. 92. 184. 276. 368. 460. 552. 644. 736. 828. 920.
RESIDENCE TIME (seconds)
80. 100. 120. 140. 160. 180. 200. 220. 240.
BED SURFACE TEMPERATURE (deg F)
10. 12. 14. 16. 18. 20. 22. 24. 26. 28. 30.
PARTICLE MOISTURE (% wet basis)

Figure 7.3

7.4 ADDITION OF HIGH LEVELS OF MICROWAVE HEATING IN ZONE 1

If the moisture diffusivity is a function of the local temperature, raising the local temperature with high levels of microwave heating, a lower resistance to moisture movement within the product can be expected. The change in resistance will speed up the rate of drying. The conditions inside the dryer used to create high levels of microwave heating combined with impingement convection heating are shown in Table 7.4.

No mixing occurs between the flights. Mixing is removed from the model to eliminate an additional source of error from the simulation

TABLE 7.4

MICROWAVE CONVECTION DRYER OPERATING CONDITIONS

HIGH LEVELS OF MICROWAVE HEATING IN FIRST ZONE

Zone	Residence Time (sec)	Air Temp (F)	Air Humidity (lbW/lbA)	Food Width (ft)	Air Velocity (ft/s)	Field Strength (v/m)
1	66.2	141.	0.085	4.0	25.0	75.0
2	64.0	141.	0.085	4.0	25.0	0.0
3	66.2	141.	0.085	4.0	25.0	0.0

Figure 7.4 is the result of the conditions of Table 7.4; it shows an increase in the rate of moisture removal of the

microwave dryer compared to the conventional dryer. The product temperature rises to a peak of 162 F^{o}, at the end of the first zone. The increase in the local product temperature results in an increase in the rate of drying.

The product temperature drops in the second and third zones of the dryer, due to evaporative cooling. The rate of drying slows in the second and third zones due to the cooling which is occurring to the product in these zones.

The final moisture content of the microwave dryer is 17.6% wet basis, this is 4% below the target moisture of 21.5% wet basis. The residence time required for the microwave dryer is 198 seconds. This is a 452% reduction in the time required to dry the product. The 452% decrease in residence time is of the same order as the decrease in residence time in drying pasta reported by Decareau (1986).

If the bed depth is held constant, a capacity increase of 135 (kg/min) is theoretically possible. The maximum capacity increase which can be expected from this system is 100 (kg/min). The capacity increase is conservative due to the assumptions which are made in using the model.

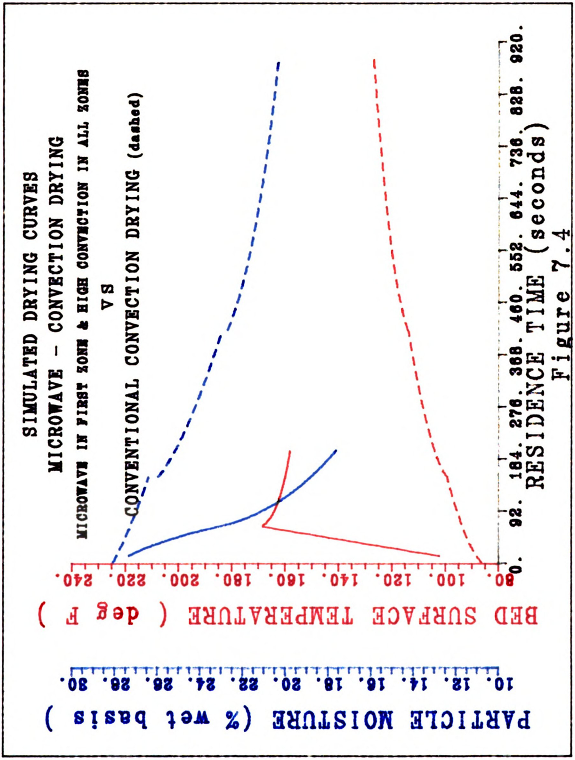

SIMULATED DRYING CURVES
MICROWAVE - CONVECTION DRYING
MICROWAVE IN FIRST ZONE & HIGH CONVECTION IN ALL ZONES
VS
CONVENTIONAL CONVECTION DRYING (dashed)
RESIDENCE TIME (seconds)
0. 92. 184. 276. 368. 460. 552. 644. 736. 828. 920.
BED SURFACE TEMPERATURE (deg F)
80. 100. 120. 140. 160. 180. 200. 220. 240.
PARTICLE MOISTURE (% wet basis)
10. 12. 14. 16. 18. 20. 22. 24. 26. 28. 30.

Figure 7.4

The change in residence time can be used to decrease the size of the dryer flights from 10.1 (meters) to 2.32 (meters) if the width and bed depth remain the same as the convection system. An conservative estimate of the minimum length of the dryer flights is 3.1 (m).

The microwave field strength of 75 (volts/meter) is within the standard operation of the Scan Pro microwave tunnel. This level is possible in a larger dryer if the cavity is designed to maintain that level.

CHAPTER 8 POST SCRIPT

The results shown in chapter 7 are based on a model developed in chapters 3 through 6. There are a number of assumptions made in developing this model. The most critical assumptions involve the rate at which the microwave energy is transferred to the product.

The assumptions made in chapter 6 to approximate the microwave field strength within the Scan Pro microwave tunnel are:

> The microwave field strength within the tunnel is independent of time.
>
> The microwave field strength in the tunnel is constant over the volume measured.
>
> All of the microwave energy generated is transmitted to the water bath.

These assumptions were made to estimate the field strength within the tunnel, and represent a macroscopic approach to the problem and not a microscopic view.

CHAPTER 9 CONCLUSIONS

The first objective of this study was to build a microwave - convection test unit to develop the basic information needed to develop a mathematical model of the process. Figure 4.1.2 illustrates the test unit which was constructed to collect basic information required.

Detailed experiments were undertaken to describe the amount of energy being transferred to the product by convective heating and microwave radiation.

A mathematical model was developed to simulate the heat and mass transfer occurring as the product passes through the test unit. The simulation program OVEN was obtained and modified to incorporate microwave heating of the product.

A verification step was undertaken to establish the ability of the model to predict the product temperature and moisture content within the test. A range of operational and initial conditions were used. Experimental measurements of the product temperature and moisture content were compared with the model predictions. The results show that the model is adequate agreement between the experimental and calculated data.

The model was used in Chapter 7 to test different operating conditions for a microwave - convection dryer and compare them to a conventional convection dryer.

The model predicts reduction in the residence time for the microwave-convection dryer of between 50 and 400% compared to a conventional convection system. The reduction in residence time is of the same magnitude as the reduction in residence time for pasta reported by Decareau (1986).

The decrease in residence time is due to the addition of microwave heating in the first zone of the dryer. The range in residence time is due to the level of microwave heating applied in the first zone. The operational conditions shown in Table 7.4, a 450% reduction in residence time when a 75 v/m field strength is applied in zone one. The operational conditions in Table 7.3 show a 50% reduction in residence time when a 25 v/m field strength is applied in all zones. Additional levels of convection heating did not significantly affect the residence time required.

The decrease in residence time can be used to increase the capacity of the current system, or to decrease the size of the dryer. A capacity increase of 95% can be expected if a high level of microwave heating is applied in zone one. The length of the flights can be reduced from 10.1 (meters) to 3.1 (meters). A combination of change in bed depth and dryer length can be selected to obtain the desired capacity.

The model has been used as a guide to develop engineering recommendations on the maximum capacity of a microwave-convection dryer. The accuracy of the model is within the limits needed to evaluate design changes to a drying system. The final results must be evaluated subject to the assumptions used to develop the model.

CHAPTER 10 RECOMMENDATIONS FOR FUTURE WORK

10.1 MICROWAVE FIELD STRENGTH

The model developed assumes a uniform microwave field strength within each zone of the dryer. This assumption is in question as pointed out in section 4.2. Part of the error illustrated in Chapter 6 can be attributed to the non-uniformity of the microwave field. In the opinion of the author, the capacity increase shown in Figure 7.4 is not possible unless the microwave field strength is uniform inside the dryer. I believe the manufactures of microwave equipment will need to develop methods to predict the field strength, and modify the design of the microwave cavity to match the product requirements. This process is currently ongoing, but outside of the microwave manufactures.

10.2 PRODUCT DIFFUSIVITY

The technique used to measure the product mass diffusivity outlined in section 4.3 is acceptable when relatively low rates of heat and mass transfer are occur. Microwave convection drying is characterized by very high rates of both heat and mass transfer. Therefore, testing is required to verify the relationship between the product temperature with the rate of moisture movement. In the opinion of the author, the thermal conductivity and the mass diffusivity are a function of the local product temperature and of local moisture content. In the model the mass diffusivity is assumed to be a function of the product temperature only. Thus, an expression for the moisture diffusivity as a function of product temperature and moisture content must be developed.

10.3 SURFACE EQUILIBRIUM

The model does not accurately predict the conditions at the outer surface of the drying particle because of the coarseness of the finite element grid at the surface. This can be corrected with the addition of more elements. Several researchers (Forets, and Okos 1980) who recommend a non equilibrium approach. Implementation of this method allows more accurate analysis of the movement of moisture to the outer surfaces of drying food products. Implementation of a non equilibrium approach is recommended.

10.4 PRODUCT GEOMETRY

The product geometry used in this model does not allow for internal convection in the product bed. In order to include the internal convection, a method is needed to develop a pseudo conductivity - convection between the particles which form the bed. A product bed with internal convection would move this model closer to representing the real world. Therefore internal convection should be added to the model of a microwave - convection drying of food particles in a belt dryer.

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APPENDICES

APPENDIX A

MICROWAVE FIELD STRENGTH MEASUREMENTS

MICROWAVE FIELD STRENGTH TESTS

TEST # 1

TUNNEL SECTION	INITIAL TEMPERATURE CONTAINER	INITIAL TEMPERATURE CYLINDER	FINAL TEMPERATURE CONTAINER	FINAL TEMPERATURE CYLINDER
A	19.10	19.10	19.50	19.50
B	19.50	19.50	20.40	20.50
C	19.10	19.10	25.90	26.10
D	19.30	19.30	23.00	23.20
E	19.30	19.30	26.20	26.20
F	19.60	19.50	21.80	21.90
G	19.40	19.40	20.50	20.50

TUNNEL SECTION	CYLINDER DEL T / TIME	ENERGY GAINED	POWER DISIPATED UNIT / VOLUME cal	FIELD STRENGTH WATTS V / M
A	0.01	16.88	1.18	21.60
B	0.02	42.20	2.95	34.15
C	0.12	295.40	20.66	90.36
D	0.06	164.58	11.51	67.45
E	0.11	291.18	20.36	89.71
F	0.04	101.28	7.08	52.91
G	0.02	46.42	3.25	35.82

TEST # 2

TUNNEL SECTION	INITIAL TEMPERATURE CONTAINER	INITIAL TEMPERATURE CYLINDER	FINAL TEMPERATURE CONTAINER	FINAL TEMPERATURE CYLINDER
A	19.50	19.50	19.80	19.50
B	20.70	20.50	22.90	22.90
C	26.20	26.10	40.20	41.10
D	23.40	23.30	29.40	30.20
E	26.40	26.30	40.10	40.00
F	21.80	21.90	23.70	23.90
G	20.50	20.50	20.60	20.60

TUNNEL SECTION	CYLINDER DEL T / TIME	ENERGY GAINED	POWER DISIPATED UNIT / VOLUME cal	FIELD STRENGTH WATTS V / M
A	0.00	0.00	0.00	0.00
B	0.02	101.28	3.54	37.41
C	0.13	633.00	22.13	93.53
D	0.06	291.18	10.18	63.44
E	0.11	578.14	20.21	89.39
F	0.02	84.40	2.95	34.15
G	0.00	4.22	0.15	7.64

TEST # 3

TUNNEL SECTION	INITIAL TEMPERATURE CONTAINER	INITIAL TEMPERATURE CYLINDER	FINAL TEMPERATURE CONTAINER	FINAL TEMPERATURE CYLINDER
A	19.70	19.50	19.80	19.70
B	22.40	22.40	24.10	24.10
C	37.90	37.40	51.10	51.80
D	29.20	30.10	35.90	36.20
E	37.80	40.00	51.60	52.10
F	24.20	24.00	26.20	26.20
G	21.10	20.80	21.30	21.30

TUNNEL SECTION	CYLINDER DEL T / TIME	ENERGY GAINED	POWER DISIPATED UNIT / VOLUME cal	FIELD STRENGTH WATTS V / M
A	0.00	8.44	0.30	10.80
B	0.01	71.74	2.51	31.49
C	0.12	607.68	21.25	91.64
D	0.05	257.42	9.00	59.65
E	0.10	510.62	17.85	84.01
F	0.02	92.84	3.25	35.82
G	0.00	21.10	0.74	17.08

TEST # 4

TUNNEL SECTION	INITIAL TEMPERATURE CONTAINER	INITIAL TEMPERATURE CYLINDER	FINAL TEMPERATURE CONTAINER	FINAL TEMPERATURE CYLINDER
A	20.80	20.60	21.00	20.70
B	24.10	24.20	26.00	26.20
C	45.40	45.60	55.80	56.60
D	34.90	34.40	41.20	41.40
E	47.90	47.50	60.20	60.20
F	26.40	26.80	27.90	28.90
G	21.80	21.80	22.10	22.10

TUNNEL SECTION	CYLINDER DEL T / TIME	ENERGY GAINED	POWER DISIPATED UNIT / VOLUME cal	FIELD STRENGTH WATTS V / M
A	0.00	4.22	0.15	7.64
B	0.02	84.40	2.95	34.15
C	0.09	464.20	16.23	80.10
D	0.06	295.40	10.33	63.89
E	0.11	535.94	18.74	86.06
F	0.02	88.62	3.10	35.00
G	0.00	12.66	0.44	13.23

TEST # 5

TUNNEL SECTION	INITIAL TEMPERATURE CONTAINER	INITIAL TEMPERATURE CYLINDER	FINAL TEMPERATURE CONTAINER	FINAL TEMPERATURE CYLINDER
A	20.50	20.50	20.90	20.70
B	25.70	25.90	27.50	27.50
C	50.60	51.20	61.30	62.10
D	40.40	40.60	45.40	45.60
E	56.60	56.80	68.10	68.20
F	27.40	27.80	28.90	29.10
G	22.00	22.30	22.40	22.30

TUNNEL SECTION	CYLINDER DEL T / TIME	ENERGY GAINED	POWER DISIPATED UNIT / VOLUME cal	FIELD STRENGTH WATTS V / M
A	0.00	8.44	0.30	10.80
B	0.01	67.52	2.36	30.55
C	0.09	459.98	16.08	79.73
D	0.04	211.00	7.38	54.00
E	0.10	481.08	16.82	81.54
F	0.01	54.86	1.92	27.53
G	0.00	0.00	0.00	0.00

APPENDIX B

MICROWAVE - CONVECTION DRYER TEST UNIT

OPERATIONAL DATA COLLECTION AND MODEL VERIFICATION

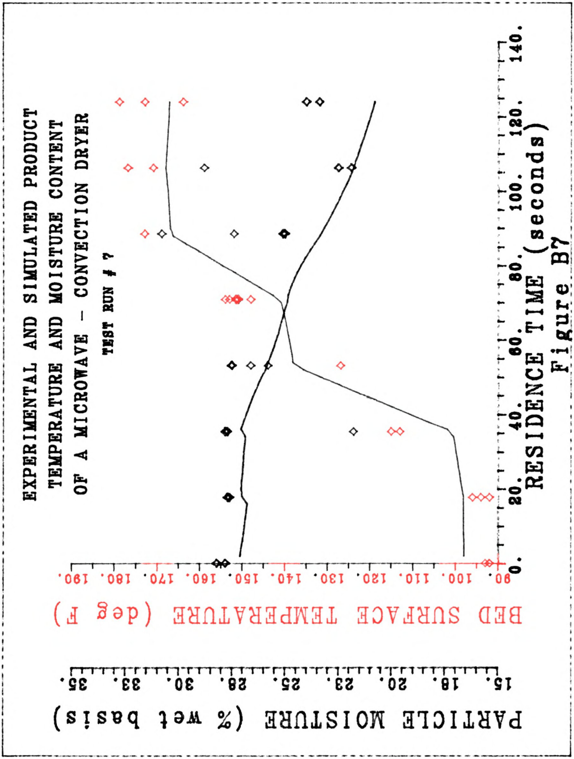
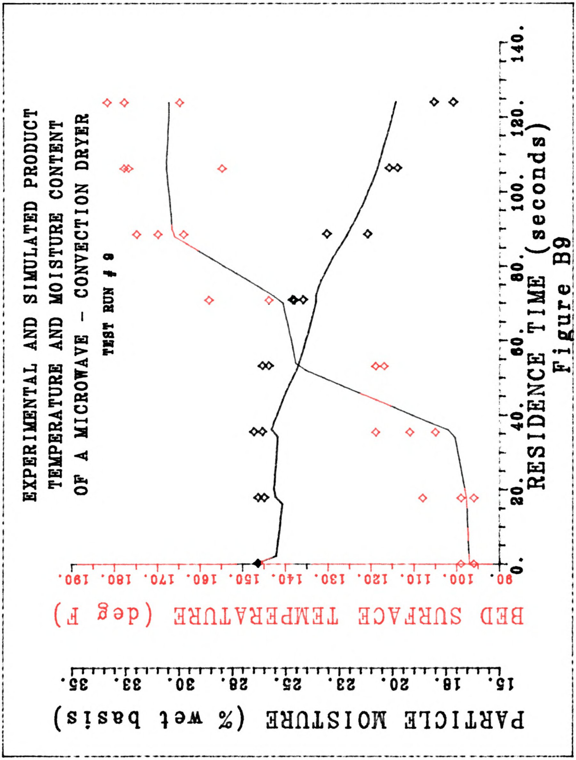

EXPERIMENTAL AND SIMULATED PRODUCT
TEMPERATURE AND MOISTURE CONTENT
OF A MICROWAVE - CONVECTION DRYER
TEST RUN # 7
PARTICLE MOISTURE (% wet basis)
15. 18. 20. 23. 25. 28. 30. 33. 35.
BED SURFACE TEMPERATURE (deg F)
90. 100. 110. 120. 130. 140. 150. 160. 170. 180. 190.
0. 20. 40. 60. 80. 100. 120. 140.
RESIDENCE TIME (seconds)

Figure B7



EXPERIMENTAL AND SIMULATED PRODUCT
TEMPERATURE AND MOISTURE CONTENT
OF A MICROWAVE - CONVECTION DRYER
TEST RUN # 9
RESIDENCE TIME (seconds)
0. 20. 40. 60. 80. 100. 120. 140.
BED SURFACE TEMPERATURE (deg F)
90. 100. 110. 120. 130. 140. 150. 160. 170. 180. 190.
PARTICLE MOISTURE (% wet basis)
15. 18. 20. 23. 25. 28. 30. 33. 35.

Figure B9

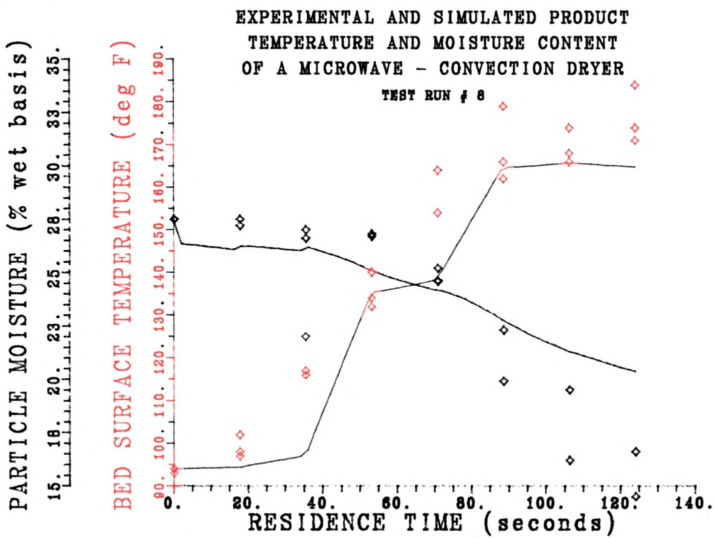

EXPERIMENTAL AND SIMULATED PRODUCT
TEMPERATURE AND MOISTURE CONTENT
OF A MICROWAVE - CONVECTION DRYER
TEST RUN # 8
PARTICLE MOISTURE (% wet basis)
15.
18.
20.
23.
25.
28.
30.
33.
35.
BED SURFACE TEMPERATURE (deg F)
90.
100.
110.
120.
130.
140.
150.
160.
170.
180.
190.
0.
20.
40.
60.
80.
100.
120.
140.
RESIDENCE TIME (seconds)

Figure B8

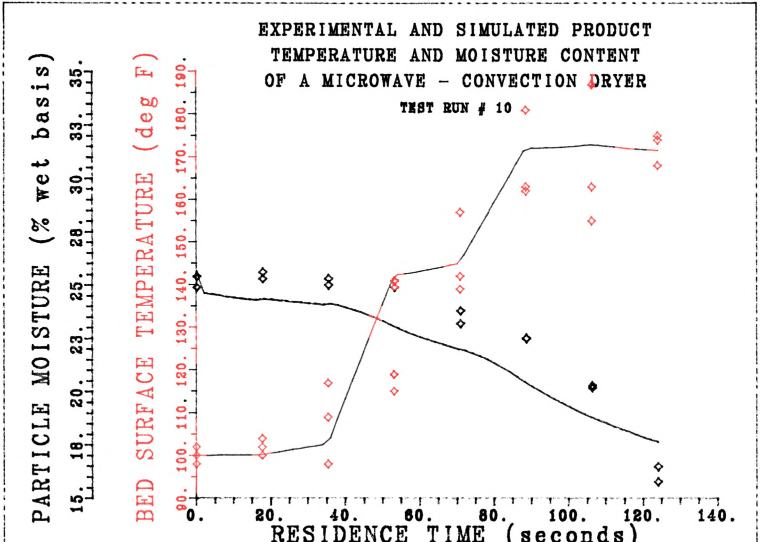

EXPERIMENTAL AND SIMULATED PRODUCT
TEMPERATURE AND MOISTURE CONTENT
OF A MICROWAVE - CONVECTION DRYER
TEST RUN # 10
PARTICLE MOISTURE (% wet basis)
15. 18. 20. 23. 25. 28. 30. 33. 35.
BED SURFACE TEMPERATURE (deg F)
90. 100. 110. 120. 130. 140. 150. 160. 170. 180. 190.
0. 20. 40. 60. 80. 100. 120. 140.
RESIDENCE TIME (seconds)

Figure B10

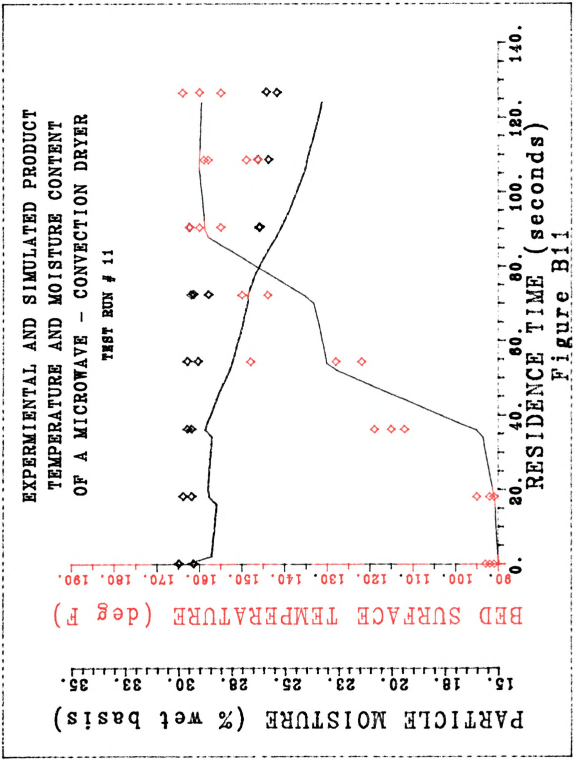
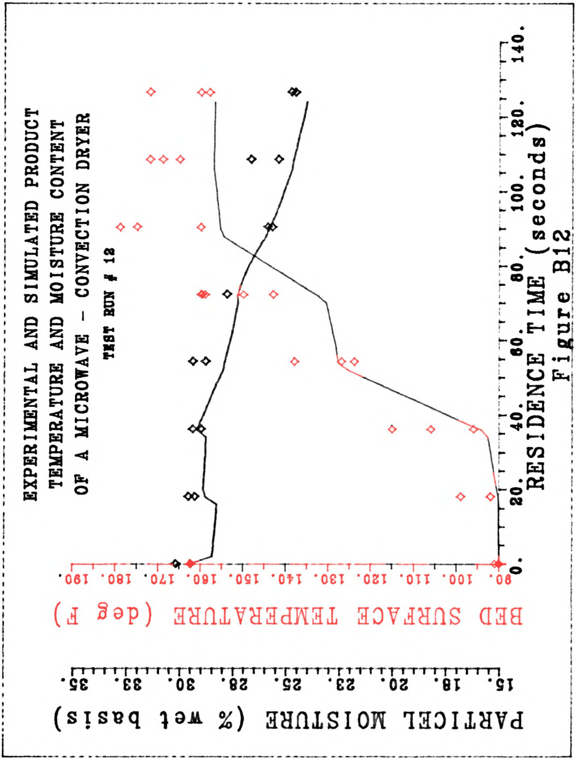

EXPERMIENTAL AND SIMULATED PRODUCT
TEMPERATURE AND MOISTURE CONTENT
OF A MICROWAVE - CONVECTION DRYER
TEST RUN # 11
RESIDENCE TIME (seconds)
0. 20. 40. 60. 80. 100. 120. 140.
BED SURFACE TEMPERATURE (deg F)
90. 100. 110. 120. 130. 140. 150. 160. 170. 180. 190.
PARTICLE MOISTURE (% wet basis)
15. 18. 20. 23. 25. 28. 30. 33. 35.

Figure B11


EXPERIMENTAL AND SIMULATED PRODUCT
TEMPERATURE AND MOISTURE CONTENT
OF A MICROWAVE - CONVECTION DRYER
TEST RUN # 12
PARTICEL MOISTURE (% wet basis)
15. 18. 20. 23. 25. 28. 30. 33. 35.
BED SURFACE TEMPERATURE (deg F)
90. 100. 110. 120. 130. 140. 150. 160. 170. 180. 190.
RESIDENCE TIME (seconds)
0. 20. 40. 60. 80. 100. 120. 140.
Figure B12

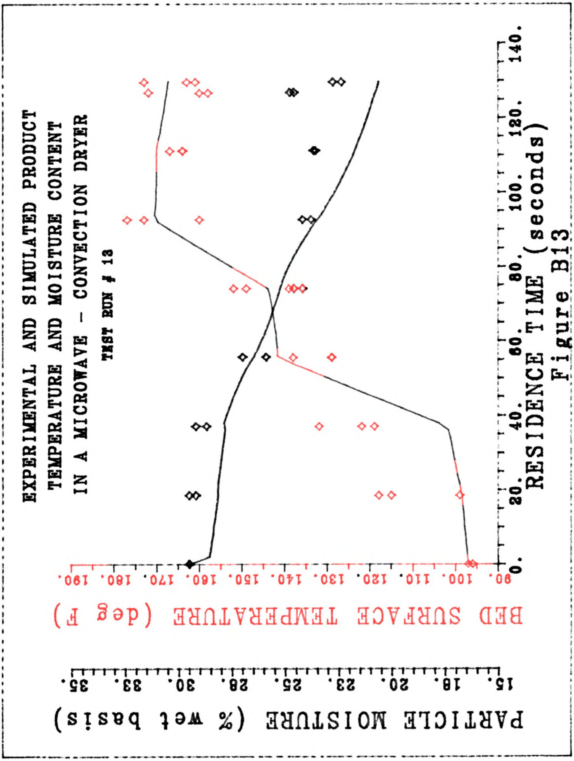

EXPERIMENTAL AND SIMULATED PRODUCT
TEMPERATURE AND MOISTURE CONTENT
IN A MICROWAVE - CONVECTION DRYER
TEST RUN # 13
RESIDENCE TIME (seconds)
0. 20. 40. 60. 80. 100. 120. 140.
BED SURFACE TEMPERATURE (deg F)
90. 100. 110. 120. 130. 140. 150. 160. 170. 180. 190.
PARTICLE MOISTURE (% wet basis)
15. 18. 20. 23. 25. 28. 30. 33. 35.

Figure B13

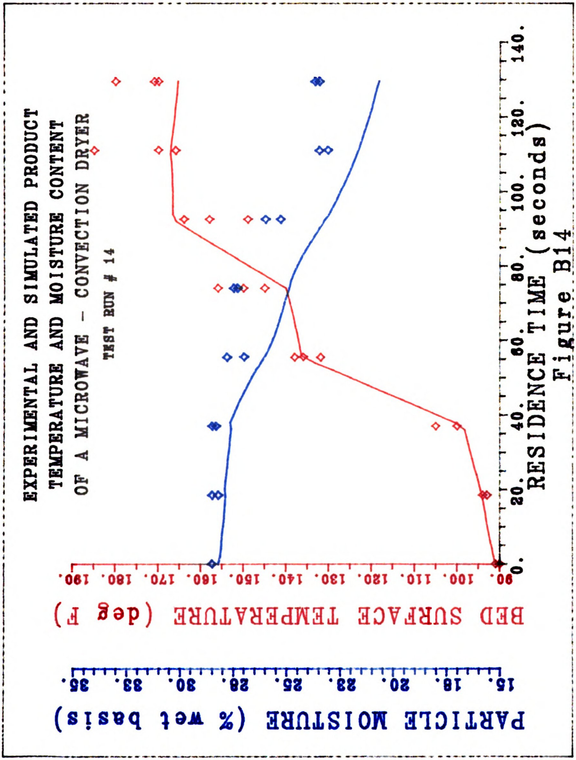

EXPERIMENTAL AND SIMULATED PRODUCT
TEMPERATURE AND MOISTURE CONTENT
OF A MICROWAVE - CONVECTION DRYER
TEST RUN # 14
RESIDENCE TIME (seconds)
BED SURFACE TEMPERATURE (deg F)
PARTICLE MOISTURE (% wet basis)
0. 20. 40. 60. 80. 100. 120. 140.
90. 100. 110. 120. 130. 140. 150. 160. 170. 180. 190.
15. 18. 20. 23. 25. 28. 30. 33. 35.

Figure B14

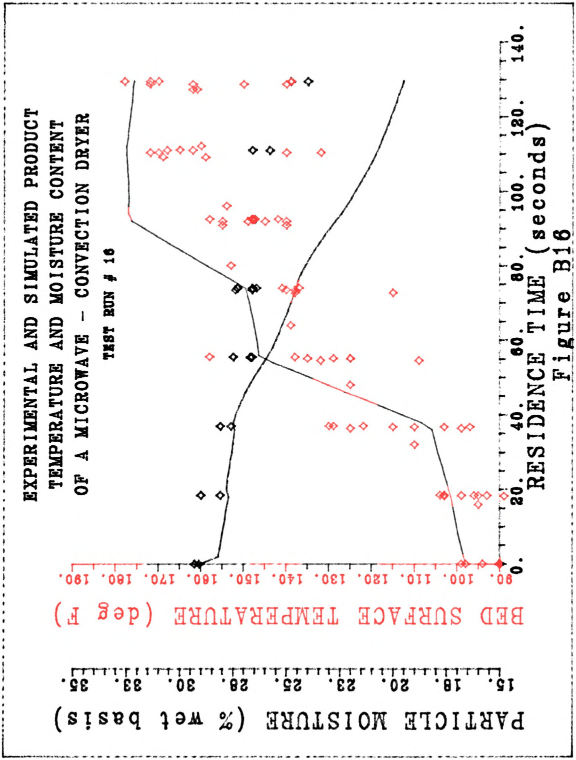

EXPERIMENTAL AND SIMULATED PRODUCT
TEMPERATURE AND MOISTURE CONTENT
OF A MICROWAVE - CONVECTION DRYER
TEST RUN # 16
RESIDENCE TIME (seconds)
0. 20. 40. 60. 80. 100. 120. 140.
BED SURFACE TEMPERATURE (deg F)
90. 100. 110. 120. 130. 140. 150. 160. 170. 180. 190.
PARTICLE MOISTURE (% wet basis)
15. 18. 20. 23. 25. 28. 30. 33. 35.

Figure B16

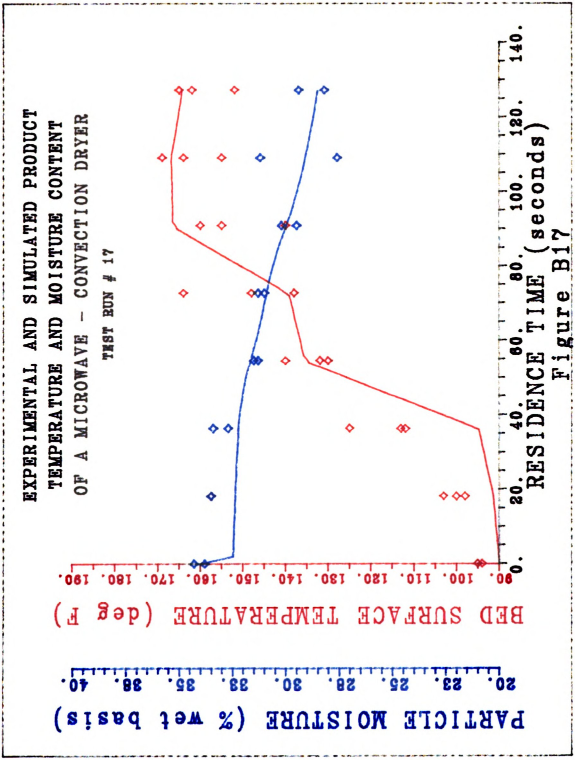

EXPERIMENTAL AND SIMULATED PRODUCT
TEMPERATURE AND MOISTURE CONTENT
OF A MICROWAVE - CONVECTION DRYER
TEST RUN # 17
RESIDENCE TIME (seconds)
BED SURFACE TEMPERATURE (deg F)
PARTICLE MOISTURE (% wet basis)
0.
20.
40.
60.
80.
100.
120.
140.
90.
100.
110.
120.
130.
140.
150.
160.
170.
180.
190.
20.
23.
25.
28.
30.
33.
35.
38.
40.

Figure B17

EXPERIMENTAL AND SIMULATED PRODUCT
TEMPERATURE AND MOISTURE CONTENT
OF A MICROWAVE - CONVECTION DRYER

TEST RUN # 18

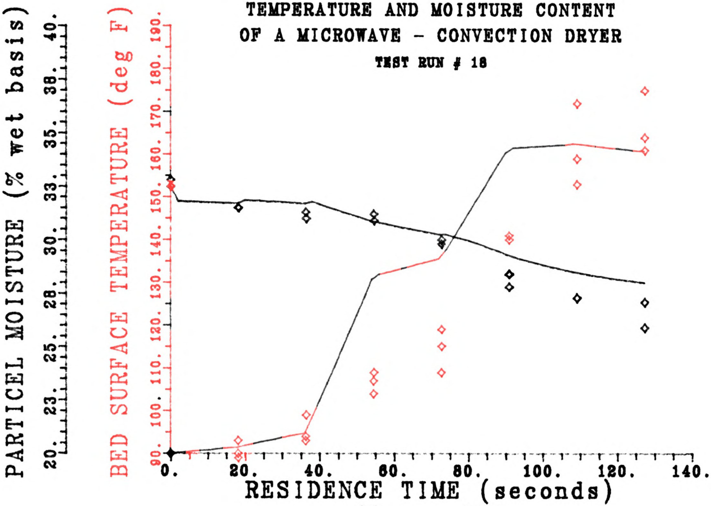


figure B18

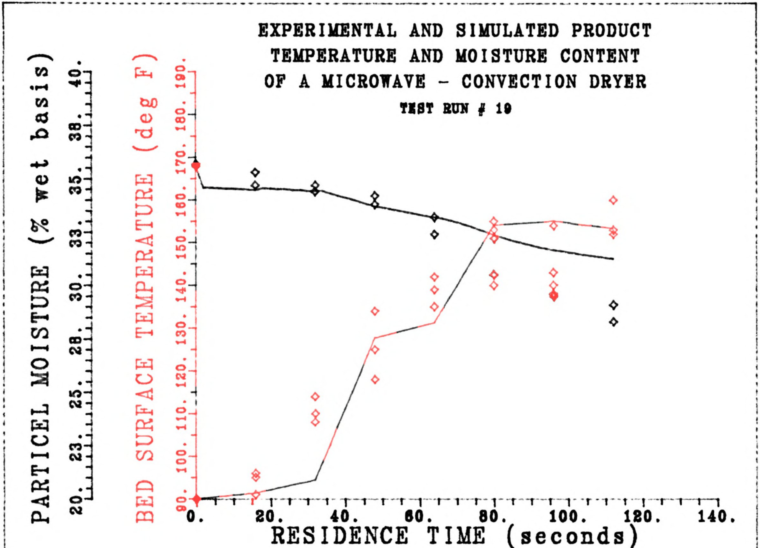

EXPERIMENTAL AND SIMULATED PRODUCT
TEMPERATURE AND MOISTURE CONTENT
OF A MICROWAVE - CONVECTION DRYER
TEST RUN # 19
PARTICEL MOISTURE (% wet basis)
20. 23. 25. 28. 30. 33. 35. 38. 40.
BED SURFACE TEMPERATURE (deg F)
90. 100. 110. 120. 130. 140. 150. 160. 170. 180. 190.
0. 20. 40. 60. 80. 100. 120. 140.
RESIDENCE TIME (seconds)

Figure B19

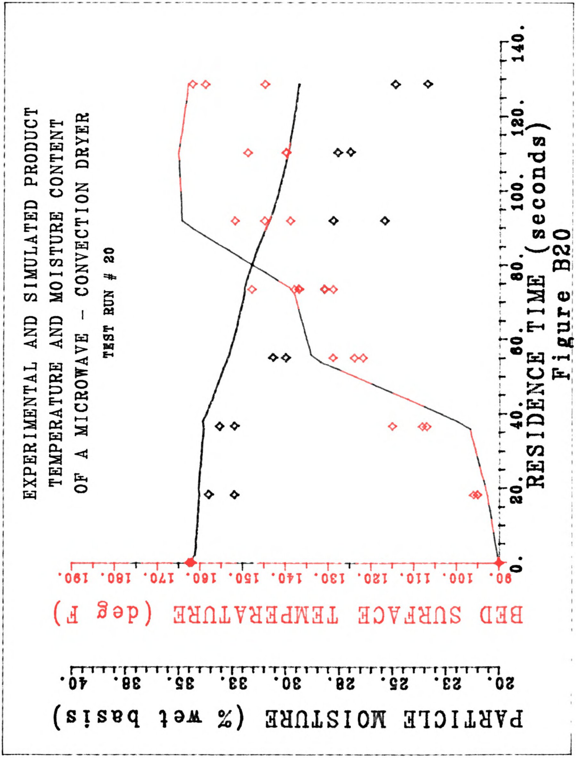

EXPERIMENTAL AND SIMULATED PRODUCT
TEMPERATURE AND MOISTURE CONTENT
OF A MICROWAVE - CONVECTION DRYER
TEST RUN # 20
RESIDENCE TIME (seconds)
0. 20. 40. 60. 80. 100. 120. 140.
BED SURFACE TEMPERATURE (deg F)
90. 100. 110. 120. 130. 140. 150. 160. 170. 180. 190.
PARTICLE MOISTURE (% wet basis)
20. 23. 25. 28. 30. 33. 35. 38. 40.

Figure B20

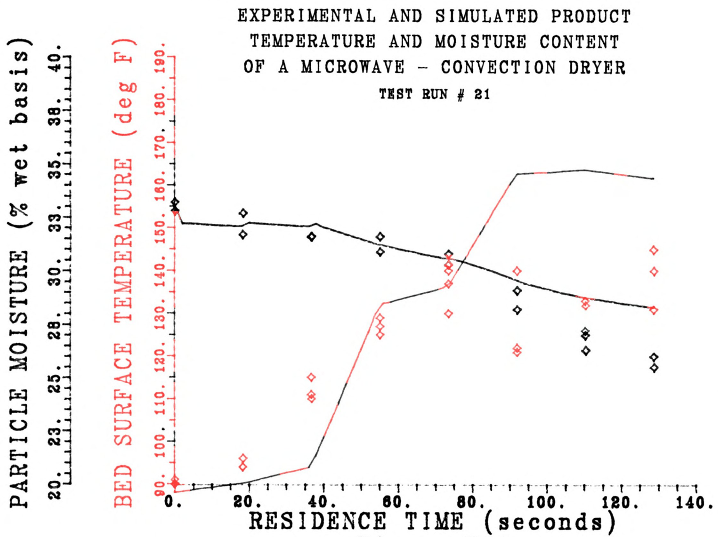

EXPERIMENTAL AND SIMULATED PRODUCT
TEMPERATURE AND MOISTURE CONTENT
OF A MICROWAVE – CONVECTION DRYER
TEST RUN # 21
PARTICLE MOISTURE (% wet basis)
20.
23.
25.
28.
30.
33.
35.
38.
40.
BED SURFACE TEMPERATURE (deg F)
90.
100.
110.
120.
130.
140.
150.
160.
170.
180.
190.
0.
20.
40.
60.
80.
100.
120.
140.
RESIDENCE TIME (seconds)

Figure B21

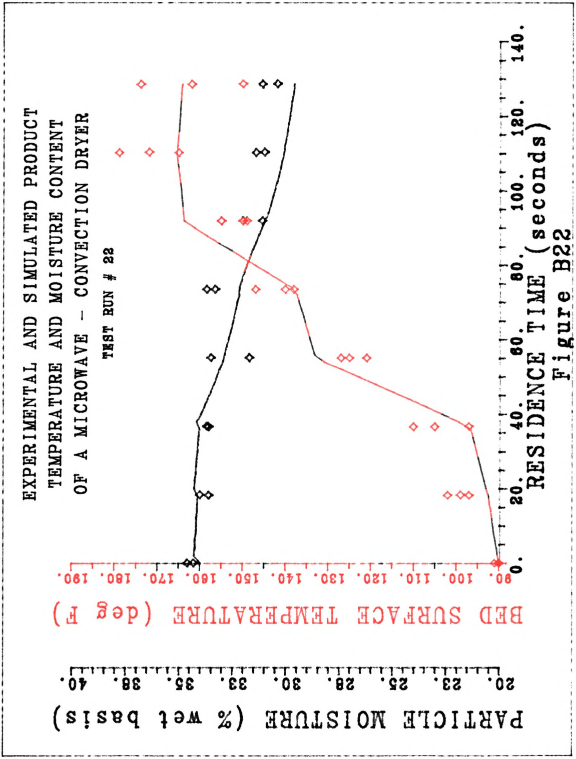
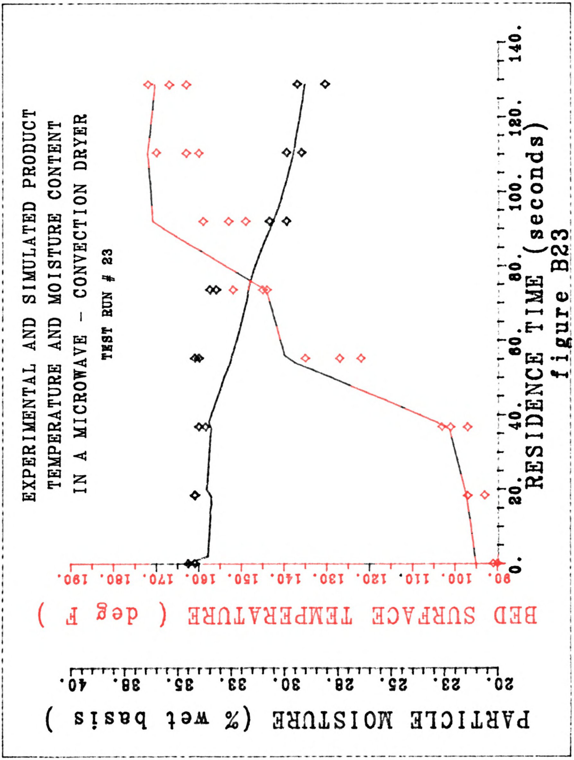

EXPERIMENTAL AND SIMULATED PRODUCT
TEMPERATURE AND MOISTURE CONTENT
OF A MICROWAVE - CONVECTION DRYER
TEST RUN # 22
RESIDENCE TIME (seconds)
0. 20. 40. 60. 80. 100. 120. 140.
BED SURFACE TEMPERATURE (deg F)
90. 100. 110. 120. 130. 140. 150. 160. 170. 180. 190.
PARTICLE MOISTURE (% wet basis)
20. 23. 25. 28. 30. 33. 35. 38. 40.

Figure B22


EXPERIMENTAL AND SIMULATED PRODUCT
TEMPERATURE AND MOISTURE CONTENT
IN A MICROWAVE - CONVECTION DRYER
TEST RUN # 23
RESIDENCE TIME (seconds)
0. 20. 40. 60. 80. 100. 120. 140.
BED SURFACE TEMPERATURE (deg F)
90. 100. 110. 120. 130. 140. 150. 160. 170. 180. 190.
PARTICLE MOISTURE (% wet basis)
20. 23. 25. 28. 30. 33. 35. 38. 40.
figure B23