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THERMAL CONDUCTIVITY AND DIFFUSIVITY OF SHELLED CORN AND GRAIN

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ABSTRACT

Increasing energy costs have stressed the importance of calculation of heat and mass transfer in a grain bulk in order to be able to optimize drying facilities. Therefore values for the thermal conductivity and diffusivity of grain and especially shelled corn were determined. The investigations were carried out for single kernels as well as for grain and corn in bulk. Thermal conductivity and diffusivity were found to be mainly dependent on moisture content. Regression analyses showed a good correlation between moisture content and thermal conductivity or diffusivity, respectively.

INTRODUCTION

Increasing mechanization and the introduction of new processes in the drying and storage of cereal grains has stressed the importance of calculation of heat and mass transfer in a grain bulk in order to be able to optimize drying and storage facilities. The requirement that the quality of the grain be retained, limits the increase of dryer capacity and reduction of specific energy consumption through higher drying air temperatures. Experiments have shown (Muhlbauer and Christ 1974) that damage to grain structure and grain nutritional value is dependent upon grain temperature and drying time. For that reason it is important to be able to calculate the heat transfer and the resulting temperature gradient in the grain kernel. Therefore values

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of thermal conductivity and thermal diffusivity as well as those of other thermophysical properties such as specific heat and drying rate have to be available.

For example for heat treatment of corn thermal conductivity has to be known (Mohsenin 1980). If thermal conductivity is known, the Biot-number which gives the relation between surface heat transfer coefficient and thermal conductivity inside the kernel can be calculated as follows

$$\mathrm{Bi} = \frac{h \cdot R}{k} \tag{1}$$

where h is the surface heat transfer coefficient, k is the thermal conductivity and R is the average kernel radius.

With Biot-number and the characteristic number for unsteady heat transfer, the Fourier-number

$$F_o = \frac{\alpha \cdot t}{R^2} \tag{2}$$

the time limit for heat treatment can be calculated. The Fourier-number increases with thermal diffusivity and time t. The time limit for heat treatment is governed by injury to the treated material (e.g. germinative ability, nutrient losses . . .). These injuries occur, when the maximum tolerable temperature is exceeded.

Thermal conductivity and diffusivity have been experimentally determined by various authors. A newer survey of the published investigations is contained in (Scherer 1979). Some of the values which are offered in these publications differ considerably; the differences between the values of thermal conductivity of the same product at the same moisture content vary by an average of ± 30 %. The differences between the given values of thermal diffusivity are even greater, for high moisture contents there are no values at all. Nor has the influence of temperature and bulk porosity been determined.

For this reason a research project was funded by the DFG (German Research Society) with the aim of determining simultaneously the thermal conductivity and diffusivity as a function of moisture content, temperature and bulk porosity. The use of an appropriate method allowed the measurements to be carried out with an accuracy which is high enough for values being of practical use.

THERMAL CONDUCTIVITY AND DIFFUSIVITY OF SINGLE KERNELS

Apparatus and Method

Thermal conductivity and diffusivity of single kernels were determined with a transient method using a hot-wire probe developed by Sweat (1973).

The apparatus used to measure the thermal conductivity (Fig. 1) of single kernels consists of the probe, a direct current source for the hot-

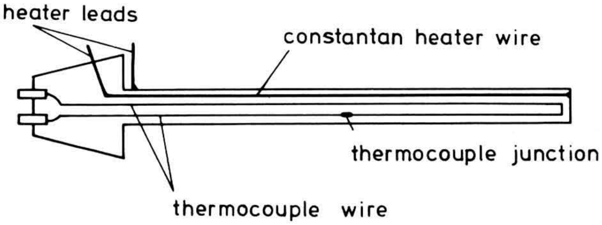


FIG. 1. SCHEMATIC OF THE PROBE

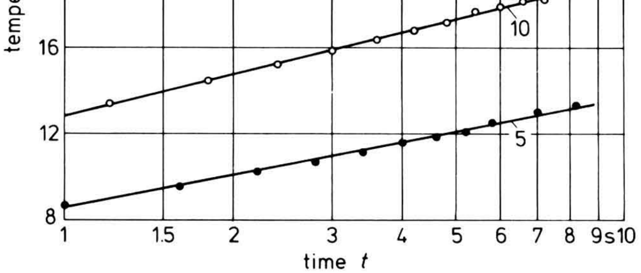


FIG. 2. TIME-TEMPERATURE PLOT AS RECORDED USING SWEAT'S PROBE (ϑ_A IS THE TEMPERATURE AT THE BEGINNING)

wire and appropriate digital voltmeters and amperemeters. The probe is heated from the inside and temperature is measured with a thermocouple in the middle of the probe. The probe is heated at constant power and the time-temperature characteristic recorded (Fig. 2).

For the experiments with corn several moist kernels were pierced then threaded onto the probe and pressed together. Special attention was given to avoiding a gap between the kernels and the probe (Fig. 3). Although the probe has a diameter of only 0.8 mm, the experiments could solely be conducted with corn, since other cereal grains are too small to be threaded onto the probe.

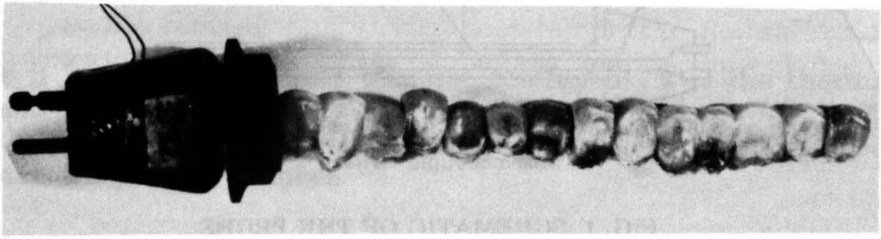


FIG. 3. VIEW OF KERNELS THREADED ONTO THE PROBE

With respect to the method proposed by Underwood and MacTaggart (1960) and with respect to the probe size there is no need for a time correction factor as mentioned by Van der Held and Van Drunen (1949). There is also no correction necessary for axial flow error in the thermal conductivity probe for the probe size used here (Mohsenin 1980).

The investigated corn kernels are of finite size contrary to the assumption of the line-heat-source theory. Therefore the maximum measuring time up to which the effect of finite sample size may be neglected has to be calculated. Vos (1955) gives the following expression

$$4 \cdot F_o < 0.6 \tag{3}$$

to estimate the moment at which boundary influences become noticeable. With Eq. (2) and (3) the time without noticeable boundary influences becomes

$$t < \frac{0.6 \cdot R^2}{4 \cdot \alpha} \tag{4}$$

where t is the measuring time, R is the smallest distance between the source and the sample boundary and α is the thermal diffusivity of a single kernel. Since there are no data found in the literature for thermal diffusivity of single kernels a value from an early test ($\alpha = 4.0 \cdot 10^{-4}$ m²/h at $M_W = 30\%$) was used for this estimate. With R = 2.4 mm (Scherer and Kutzbach 1978) the maximum measuring time becomes

$$t_{max} = \frac{0.6 \cdot (2.4 \cdot 10^{-3}) \cdot 3600}{4 \cdot 4.0 \cdot 10^{-4}} = 7.8 \text{ s} \qquad (5)$$

With respect to this estimate, the time during which the data for determination of thermal conductivity and thermal diffusivity were collected, was restricted to the interval from 1.5 to 8 s since energizing the probe. Figure 2 shows that within this interval no noticeable influence of the finite sample size occurs. If there would be any noticeable influence, the slope of the time-temperature plot would lessen.

Thermal conductivity of a material can be determined by solving the differential equation for heat conduction from a line-heat-source within an assumed homogenous medium which gives us the following equation:

$$k = \frac{\dot{Q} \cdot \ln (t_2/t_1)}{4 \cdot \pi \cdot (\vartheta_2 - \vartheta_1)} \qquad (6)$$

k thermal conductivity
t time
ϑ temperature.

If the values of specific heat c and density ρ of the product are also known, the thermal diffusivity α can be calculated with the definition equation

$$\alpha = \frac{k}{\rho \cdot c} \qquad (7)$$

Measurements to determine the effect of moisture were done with kernels which were successively dried while being threaded on the probe. Moisture content was recorded before and after each test. Thermal conductivity was determined by recording the temperature in one second intervals while the probe was heated with a constant current. A linear regression of the ϑ/ln t values was done and the slope s of the regression curve entered into the equation for thermal conductivity:

$$k = \frac{\dot{Q}}{4 \cdot \pi \cdot s} \tag{8}$$

The amount of heat energy supplied was calculated from the current and the electrical resistance of the probe.

Results and Discussion

Figure 4 shows the influence of moisture on thermal conductivity of single corn kernels. The data points are means of several replications with standard deviations between 0.0047 for the smallest value and 0.0354 for the greatest. The linear characteristic of the curve shows that there is no vapor diffusion and that the increase of thermal conductivity with moisture content is caused by heat conduction of water contained in the kernel.

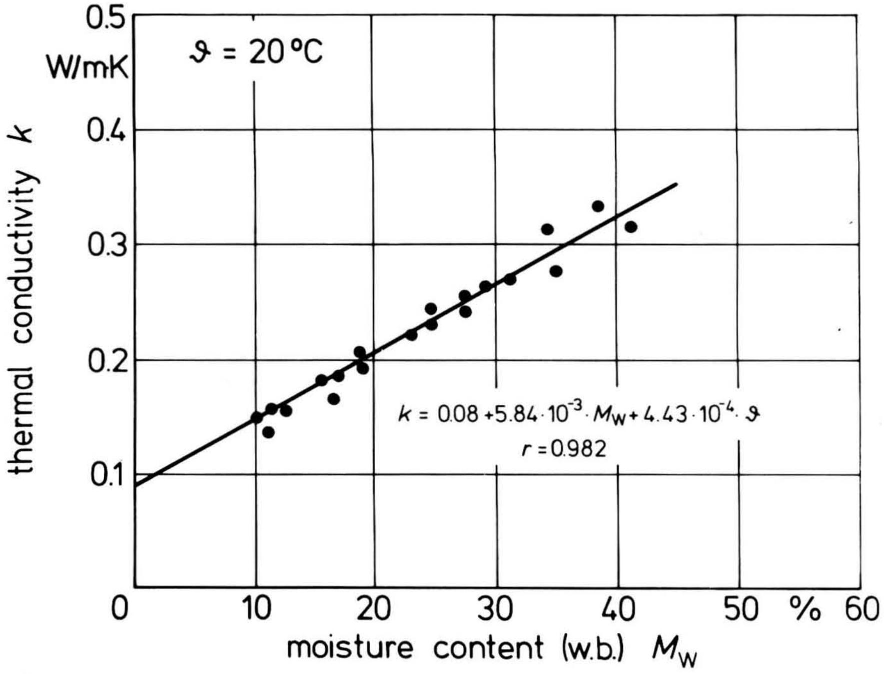


FIG. 4. THERMAL CONDUCTIVITY VERSUS MOISTURE CONTENT (w.b.)

Temperature effect on thermal conductivity is linear, too. Compared to the moisture effect it is considerably less. Based on data of more than 100 tests a multiple linear regression analysis was carried out in order to evaluate one equation for calculating thermal conductivity.

$$k = 0.08 + 5.84 \cdot 10^{-3} \cdot M_W + 4.43 \cdot 10^{-4} \cdot \vartheta \qquad (9)$$

$$r = 0.982$$

This equation is valid for moisture contents between 8 and 45% and temperatures between 5 and 45°C. The regression coefficient $r = 0.982$ proves a very good correlation.

Separate experiments with germs threaded onto the probe showed that at the same moisture content, there is no significant difference between thermal conductivity of endosperm and germ.

Thermal diffusivity of single kernels as a function of moisture content and temperature is shown in Fig. 5. It was determined with Eq. (7) using values for specific heat measured by Mühlbauer and Scherer [1977]. Kernel density was measured with an air pycnometer.

The influence of variety or year of harvest on thermal conductivity and diffusivity could not be determined among the varieties which were investigated, namely Inra 258, Brillant, Anjou, Limac and the American high-protein variety XL 22; the registered differences were

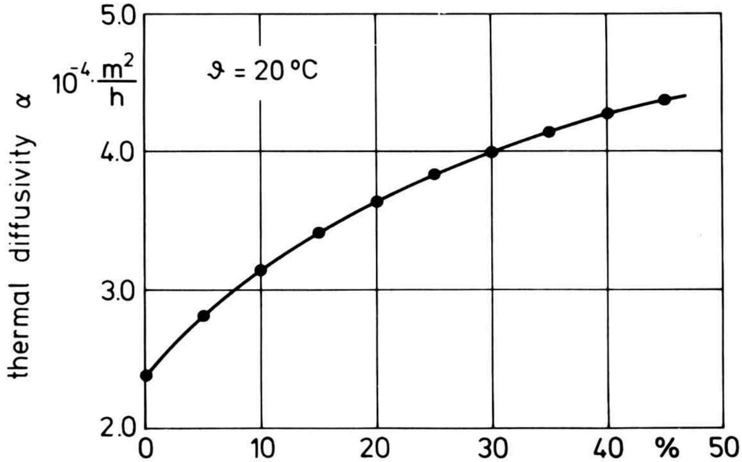


FIG. 5. THERMAL DIFFUSIVITY VERSUS MOISTURE CONTENT (w.b.)

within the errors of measurement, which were found in calibration experiments to be less than 9%.

Thermal conductivity of dry corn is slightly lower than that of dry nonfat organic substances (carbohydrates, proteins) and fat, for which Kostaropoulos (1971) published approximations of 0.27 and 0.15 W/mK, respectively. This can be explained by the low thermal conductivity of the air contained in the spaces in the kernel which are left after water is removed.

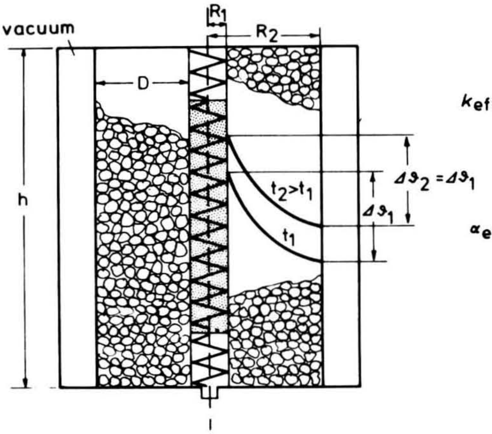
THERMAL CONDUCTIVITY AND THERMAL DIFFUSIVITY OF GRAIN IN BULK

Apparatus and Method

Thermal conductivity and diffusivity of grain in bulk was determined with a quasi-steady hollow cylinder method. Quasi-steady methods offer an ideal combination of steady-state-methods with their high accuracy and the faster transient methods. Steady-state-methods cannot be used because of the time it takes for moist porous materials to reach a steady state and more importantly because of moisture migration and respiration in biological materials. The accuracy of transient methods for measurement of thermal conductivity is limited because the time factor is an additional variable. Methods for experimental determination of thermal conductivity and diffusivity are all designed to facilitate the solution of the differential equation for heat conduction by making the boundary conditions geometrically simple.

The experimental apparatus consists of a hollow cylinder, control and metering units, an electricity supply and a temperature plotter. The dimensions of the hollow cylinder are shown in Fig. 6. Temperature is measured with thermocouples on the inner and outer cylinder. A heater in the inner cylinder supplies the energy.

The solution of the differential equation of heat conduction requires that no heat is lost to the atmosphere. This has been realized by surrounding the outer cylinder firstly by a vacuum and additionally by a 100 mm layer of polyurethane. To prevent an axial temperature gradient, additional heaters were placed at the ends of the cylinder and controlled to keep the temperature equal to that in middle. The experiments were carried out with a vertical cylinder to minimize convection. All these provisions together led to an accuracy of ± 3.32%.



$$k_{eff} = \frac{\dfrac{D^2 \cdot \dot{q}_F \cdot R_1}{R_2{}^2 - R_1^2}\left\{\dfrac{R_1^2 - R_2{}^2}{2D^2} + \dfrac{R_2{}^2}{D^2} \cdot \ln \dfrac{R_2}{R_1}\right\}}{\vartheta_{R_1,t} - \vartheta_{R_2,t}}$$

$$\alpha_{eff} = \frac{R_1{}^2 - R_2{}^2 + 2R_2{}^2 \ln R_2/R_1}{4(\vartheta_2 - \vartheta_1)} \frac{\partial\vartheta}{\partial t}$$

FIG. 6. SCHEMATIC OF THE HOLLOW-CYLINDER APPARATUS ($R_1 = 11$ mm; $R_2 = 50$ mm)

After filling and closing the hollow cylinder, and after equalization of temperature across the cylinder, the main heater was turned on and the additional heaters regulated to compensate axial heat losses. After reaching the quasi-steady-state the current in the main heater and the temperatures of inner and outer cylinder were registered. Thermal conductivity and diffusivity were calculated with the equations in Fig. 6 which are described in detail by Scherer [1979].

Results and Discussion

Experimental values of thermal conductivity and diffusivity of corn in bulk as a function of moisture content, temperature and bulk density are shown in Fig. 7-12. Each data point in these diagrams represents the obtained value of one test. The experimentally determined curves can be described by equations of the following general form:

$$k_{eff} = A + B \cdot M_W + D \cdot \vartheta \tag{10}$$

$$\alpha_{eff} = A' + B' \cdot M_W + C' \cdot M_W^2 + D' \cdot \vartheta \tag{11}$$

The coefficients of Eq. (10) and (11) for corn, wheat, barley, oats, rye and rape seed are shown in Table 1.

Since the characteristics of all the cereals are similar in their respective moisture ranges, only corn is discussed here. Figures 4 and

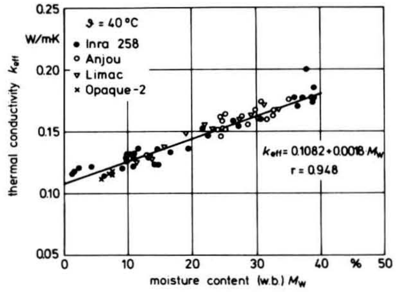


Fig. 7

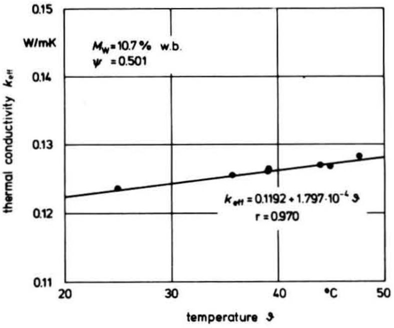


Fig. 8

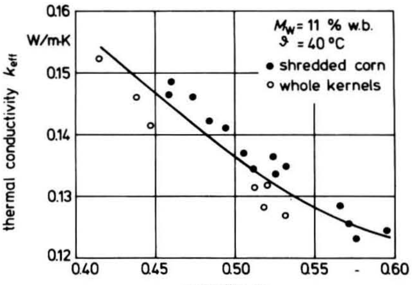


Fig. 9

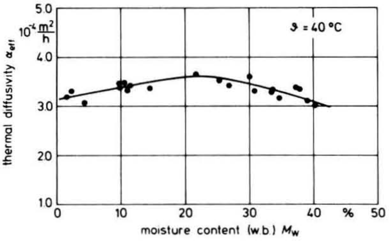


Fig. 10

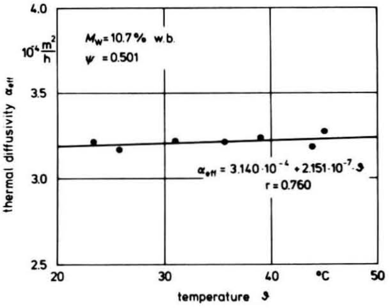


Fig. 11

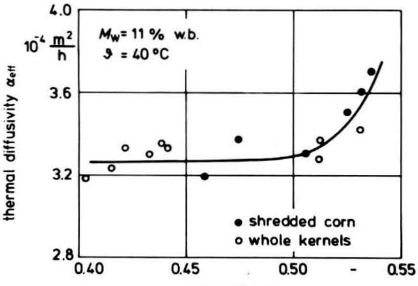


Fig. 12

FIG. 7-12. THERMAL CONDUCTIVITY AND DIFFUSIVITY VERSUS MOISTURE CONTENT, TEMPERATURE AND POROSITY

7, respectively, show that thermal conductivity of the bulk is less than that of single kernels, which is attributed to the lower thermal conductivity of the air contained in gaps between individual kernels.

Thermal conductivity of bulk corn increases, within the investigated temperature range, as a linear function of moisture content (Fig. 7). This is attributed to the fact that, due to its colloidal characteristics, the volume of corn is a nearly linear function of moisture content.

Thermal conductivity rises in the investigated temperature range as a linear function of temperature, as it does in the case of single kernels (Fig. 8). Increasing pore volume lowers the thermal conductivity because the number of contact points between the kernels decreases and the relative volume of air in the bulk increases. The pore volume of bulk corn can only be varied within the small range between loose and packed. To enable a larger variation of pore volume, corn was shredded. Figure 9 shows that there is practically no difference between shredded corn and whole kernels at equal bulk density. Therefore there is no noticeable effect of kernel size on thermal conductivity. That also explains why there are no significant differences between the thermal conductivities of the investigated varieties.

Thermal conductivity reaches a maximum at a moisture content of 25% (w.b.) and drops again at higher moisture contents (Fig. 10). This can be explained by the fact that, while both thermal conductivity and specific heat increase with moisture content, bulk density reaches a minimum at 25% (w.b.). Due to the increase in bulk density above this moisture content, the amount of heat remaining in the bulk increases relative to the amount of heat being transferred, leading to a lower thermal diffusivity. Similar to thermal conductivity, thermal diffusivity is a linear function of temperature (Fig. 11), but with a lower temperature coefficient due to the strong influence of temperature on specific heat. As opposed to thermal conductivity thermal diffusivity of the bulk increases with increasing pore volume because thermal diffusivity of air is higher than that of corn kernels.

In a comparison of the different cereals (Table 1) wheat and rye have the highest thermal conductivities, corn and oats have the lowest. The opposite is true for thermal diffusivity. Significant differences in thermal conductivity and diffusivity could not be detemined between different varieties of the same grain. Nor could any influence of the year of harvest be determined.

Table 1. Coefficients for Eq. (10) and (11)

Material	A	B	D	Corr. Coef. r	A′	B′	C′	D′	Corr. Coef. r
Corn	0.108	$1.80 \cdot 10^{-3}$	$1.79 \cdot 10^{-4}$	0.97	3.095	$4.22 \cdot 10^{-6}$	$-1.06 \cdot 10^{-7}$	$2.15 \cdot 10^{-7}$	0.83
Wheat	0.133	$1.70 \cdot 10^{-3}$	$1.69 \cdot 10^{-4}$	0.89	$3.01 \cdot 10^{-4}$	$2.35 \cdot 10^{-6}$	—	$2.05 \cdot 10^{-7}$	0.55
Barley	0.125	$1.28 \cdot 10^{-3}$	$1.76 \cdot 10^{-4}$	0.89	$3.09 \cdot 10^{-4}$	$2.84 \cdot 10^{-6}$	—	$1.98 \cdot 10^{-7}$	0.58
Oats	0.104	$2.21 \cdot 10^{-3}$	$1.82 \cdot 10^{-4}$	0.98	$3.44 \cdot 10^{-4}$	$1.55 \cdot 10^{-6}$	—	$1.97 \cdot 10^{-7}$	0.56
Rye	0.131	$9.29 \cdot 10^{-4}$	$1.72 \cdot 10^{-4}$	0.81	$3.05 \cdot 10^{-4}$	$1.42 \cdot 10^{-6}$	—	$2.01 \cdot 10^{-7}$	0.39
Rape Seed	0.110	$2.15 \cdot 10^{-3}$	$1.57 \cdot 10^{-4}$	0.94	$1.89 \cdot 10^{-4}$	$7.06 \cdot 10^{-6}$	—	$2.69 \cdot 10^{-7}$	0.68

COMPARISON WITH OTHER EXPERIMENTAL DATA

Only a few authors have reported thermal conductivity and diffusivity data of corn. Most of the data found in the literature are for bulk shelled corn. Table 2a gives a survey of thermal conductivity data where Table 2b does the same for thermal diffusivity data.

Obviously Egorov's [1960] data differ strongly from the data obtained by the other authors. Data obtained by Oxley [1944], Kazarian and Hall [1965] and Pabis *et al.* [1970] are in the same range as the data reported in this paper. Differences between the data may be due to different test methods as well as to different sample preparation (e.g. natural moist versus rewetted).

SUMMARY

Of special interest for the heat transfer processes during drying and storage of cereal grains are the thermophysical properties, thermal conductivity and thermal diffusivity. They were determined for corn, wheat, barley, oats, rye and rape seed.

Thermal conductivity of single grain kernels was determined with a hot-wire probe. The kernels are threaded onto the probe which is 0.8 mm in diameter. The probe is heated from the inside and the temperature characteristic measured with a thermocouple. The time-temperature characteristic obtained proved the admissibility of assuming negligible boundary influences.

Thermal conductivity and diffusivity of grain in bulk were determined with a quasi-steady method, in which the sample is filled into the ring-shaped gap of a hollow cylinder. The thermal conductivity can be calculated from the temperature characteristics of the heated inner cylinder and the outer cylinder which is insulated to avoid heat loss. It is also possible to calculate thermal diffusivity directly out of time-temperature data from the cylinders. Most decisive for thermal conductivity and diffusivity is the moisture content of the grain.

The values obtained for the thermal conductivity of single kernels with moisture contents between 8 and 45% (w.b.) range from 0.13 to 0.40 W/m K. The influence of temperature compared with that of moisture content is negligible and in the case of grain in bulk less than the influence of the porosity.

Table 2a. Comparison of thermal conductivity values for corn in bulk

Author	Moisture Cont. (w.b.) M_W %	Temp. ϑ °C	Bulk Density ρ kg/m^3	Equation for k W/m · K	Thermal Conductivity k W/m · K	$k_{13\%}$ W/m · K	Testing Method	Testing Apparatus	Sample Preparation
Oxley 1944	13.2	26.8-31.1			0.1765	0.1765	steady-state	2 concentric spheres, inner one heated, outside at tempered air	
Egorov 1960	9.1-20.0			$k = 0.37 + 0.62 \cdot M_D$	0.43-0.53	0.470	transient	plate apparatus	
Kazarian, Hall 1965	0.9-30.2	8.7-35.2	682.4-754.5	$k = 0.1207 + 0.993 \cdot 10^{-3} \cdot M_W$	0.121-0.148	0.134	transient	cylinder with axial heater	$M_W < 13.2$ nat. moist $M_W > 13.2$ rewetted
Pabis, Bilovitska, Gadai 1970	0-26.6		753 ($M_W = 0$)	$k = 0.158 + 0.442 \cdot M_D$	0.16-0.33	0.23	transient	plate apparatus	
This paper	2.0-40.0	22.0-45.0	620.0-720.0	$k = 0.1082 + 0.0018 \cdot M_W$ $k = 0.1192 + 1.794 \cdot 10^{-4} \cdot \vartheta$	0.11-0.18	0.13	quasi-steady	2 concentric cylinders, inner one heated	natural moist

M_D moisture content d.b. kg/kg
M_W moisture content w.b. %

Table 2b. Comparison of thermal diffusivity values for corn in bulk

Author	Moisture Cont. (w.b.) M_W %	Temp. ϑ °C	Bulk Density ρ kg/m^3	Equation for k m^2/h	Thermal Diffusivity α m^2/h	$k_{13\%}$ $10^{-4}m^2/h$	Testing Method	Testing Apparatus	Sample Preparation
Oxley 1944	13.2	26.8-31.1					steady-state	2 concentric spheres, inner one heated, outside at tempered air	
Egorov 1960	9.1-20.0			$\alpha = (1.44 + 0.14 \cdot M_D) \cdot 10^{-3}$	$12.9\ 10^{-4}$ to $10.9\ 10^{-4}$	12.2	transient	plate apparatus	
Kazarian, Hall 1965	0.9-30.2	8.7-35.2	682.4-754.5		$3.12\ 10^{-4}$ to $3.64\ 10^{-4}$	3.29	transient	cylinder with axial heater	$M_W < 13.2$ nat. moist $M_W > 13.2$ rewetted
Pabis, Bilovitska, Gadai 1970	0-26.6		753 ($M_W = 0$)				transient	plate apparatus	
This paper	2.0-40.0	22.0-45.0	620.0-720.0		$3.2\ 10^{-4}$ to $3.0\ 10^{-4}$	3.5	quasi-steady	2 concentric cylinders, inner one heated	natural moist

M_D moisture content d.b. kg/kg
M_W moisture content w.b. %

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This study was carried out as part of the special research project 140 (agricultural engineering) of the DFG (German research foundation). The authors are grateful for the aid of Mrs. D. Dörrer-Ibrahim who carried out the measurements and did a lot of work in doing the regression analyses. The authors also would like to thank Dr. N.N. Mohsenin for the suggestion to this article which he gave during his stay in Hohenheim in 1980.

LIST OF SYMBOLS

Bi	—	Biot-number
c	kJ/kg · K	specific heat
F_o	—	Fourier-number
h	$W/m^2 \cdot K$	surface heat transfer coefficient
k	W/m · K	thermal conductivity
k_{eff}	W/m · K	thermal conductivity of bulk material
M_D	%	moisture content (d.b.)
M_W	%	moisture content (w.b.)
$\dot{Q}$	W	supplied heat energy
R	m	smallest kernel size
s	m · K	slope of regression curve
t	s	time
α	m^2/h	thermal diffusivity
α^{eff}	m^2/h	thermal diffusivity of bulk material
ϑ	°C	temperature
ρ	kg/m^3	density

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ENERGY CONSERVATION IN DRYING OF FRUITS IN TUNNEL DEHYDRATORS

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ABSTRACT

This study reports the energy use and thermal losses associated with tunnel dehydrators and discusses methods of increasing energy efficiency. These dehydrators can operate with an efficiency of water removal greater than 50%. It is shown that energy conservation techniques such as minimizing air leakage, increasing air recirculation, utilizing a furnace heat shield to prevent heat losses, and maximizing input can result in significant energy savings.

INTRODUCTION

Tunnel dehydrators are most widely used in artificial drying of fruits. Raisins, prunes and apples make up by far the bulk of the fruits dried in the USA and among these all the prune crop is artificially dried in tunnel dehydrators. Natural gas, propane or other fossil fuel sources are employed in supplying necessary thermal energy to accomplish dehydration. With the prospect of continuously rising cost and shortage of fuel supply, it is becoming increasingly important to economize the fuel consumption in this highly energy intensive

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operation. This study is based on the investigation of prune dehydrators but should be applicable to other fruit drying situations.

The first reported study on energy efficiency of dehydrators was conducted by Cruess and Christie (1921) when heated, forced-air dehydrators were introduced as a substitute for sun-drying of prunes. They indicated that countercurrent prune dehydratros should operate at an efficiency of at least 40%. They also recommended that energy could be saved by recirculating 75% or more of the air; preventing air from passing between the trays and walls and by-passing the fruit; and dipping the fresh fruit in lye to "check" the skin and increasing the drying rate. Subsequent reports dealt primarily with proper operation of dehydrators (Christie 1926; Christie and Ridley 1923; Kilpatrick *et al.* 1955; Perry 1944; Perry *et al.* 1946; Van Arsdel *et al.* 1973) and development design criteria with little or no specific mention of energy use except for indicating the value of recirculation. Recirculation was emphasized primarily to prevent case hardening. Case hardening is believed to be rapid drying of the surface of the fruit which restricts movement of the moisture from the interior of the fruit.

Most investigators agreed that relative humidities in the exhaust air of a countercurrent flow tunnel should be in the range of 35–40%. Guillou (1942) indicated that drying rate of prunes is not affected by relative humidity below 40%. Perry (1944) subsequently reported that relative humidity above 35% at 75°C (167°F) reduced drying rates. Mrak and Perry (1948) recommended countercurrent flow dehydrators could be operated at an exhaust end relative humidity of 60%, although the wet bulb temperature should never exceed 49°C (120°F).

Gentry *et al.* (1965) demonstrated that concurrent (parallel) flow operation of tunnels designed for traditional countercurrent flow operation would significantly increase fruit throughput. Initial tests revealed a 12% increase in heating energy consumption per ton of fruit dried for concurrent versus countercurrent flow. Since then, many of the older tunnels have been converted to concurrent flow operation and new tunnels are designed for this mode of operation. McBean *et al.* (1966) demonstrated that lye dipping of prunes was not effective in reducing drying time in concurrent flow tunnels.

A majority of the dehydrators were built when there was a cheap and unlimited supply of natural gas, and fuel efficiency of the dehydrators was not a major concern. Very little research focussed on energy conservation aspects of tunnel dehydrators has been reported. Groh (1978) suggested that increased recirculation and the use of heat exchangers would reduce energy use although he had no test data to support his suggestions. Carnegie (1980) has investigated the effectiveness of various heat exchange systems for recovering heat from exhaust air but has not discussed other areas of losses and means to reduce them.

The objectives of this study were to:

(1) Determine a heating energy budget for selected dehydrator types.
(2) Identify areas where heat losses could be minimized and energy conserved.
(3) Compare the energy consumption of concurrent versus countercurrent flow dehydrators.

PROCEDURE

Dehydrators

Three different types of dehydrators were selected. Distinct features of these dehydrators are listed in Table 1. Figures 1 and 2 are sketches of the dehydrators investigated. All dehydrators are concurrent flow, air recirculating tunnel dehydrators. They operate by removing a car of dry fruit from the cooler end of the tunnel and adding a car of fresh fruit to the other end, approximately every two hours, which is called a pull cycle. Approximately 18 h are required to dry a car of fruit.

Temperature Measurement

All the temperatures except the ambient air temperature were measured using copper-constantan thermocouples connected to a recording potentiometer. Temperatures measured were: (1) dry bulb and wet bulb temperatures of the drying air at various location in the

Table 1. Various tunnel dehydrators selected for testing

Location No.	Distinctive Features
1	Concrete tunnels with fan belt opening on the roof located downstream of fan. Partial recirculation of air. Tunnel originally designed for countercurrent flow.
2	Transite tunnels. Partial recirculation of air. Tunnel designed for concurrent flow.
3	"Miller" type tunnels made of cinder block. Partial recirculation of air.

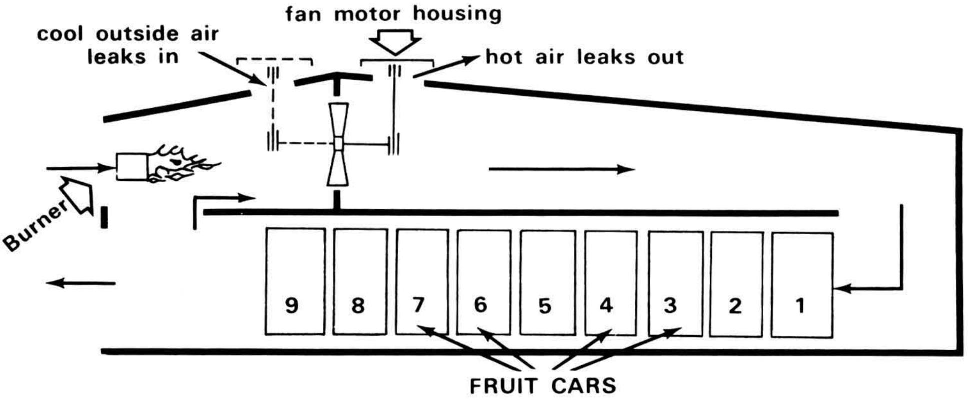

FIG. 1. TUNNEL DEHYDRATOR AT SITE 1 AND 2

At Location 1 the motor is downstream of the fan indicated by solid lines and at Location 2 motor is upstream of fan as indicated by dashed lines.

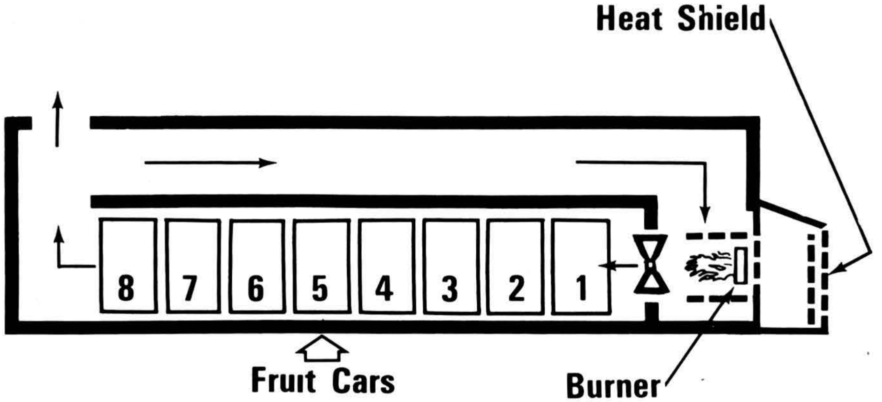

FIG. 2. MILLER TYPE DEHYDRATOR AT LOCATION 3 WITH SUGGESTED HEAT SHIELD

dehydrator, (2) temperatures of inside and outside surfaces of the dehydrator.

Wet bulb temperatures were measured by enveloping a thermocouple in a cotton wick supplied with water from a small water reservoir keeping the wick moist. Dry bulb temperature and relative humidity of the outside air were recorded by a mechanical hygrothermograph.

Air Flow Measurements

Air flow measurements were taken using a hot-wire anemometer or a vane anemometer. Measurements were made at various points in the cross-sections of interest and average flow calculated for use in energy balance computations.

Natural Gas Consumption

Five bellows-type in-line gas meters supplied by the Pacific Gas and Electric Company were installed to record the natural gas use at the burners. Each meter measured the gas consumption of one burner which supplied heat for a dual tunnel unit. Four of the meters were installed at location 1, and one at location 2 (Table 1). Gas flow measurements at location 3 were made using an orifice meter. Pressure gauges were installed in the gas supply line. Readings were taken at the end of each pull cycle.

Moisture Content

Samples were taken before and after the product was dried. The moisture content was determined using a vacuum oven (AOAC) for high moisture samples and calibrated conduction type meter for low moisture samples (DFA-AOAC). Net weight of dried product for each drying period was measured to compute the quantity of water removed in the dehydrator.

Test Conditions

In most of the tests the dry bulb temperature, humidity, air flow, initial moisture content, and the final moisture content of the prunes were not controlled by the investigators. These parameters were set by the management of the dehydrating units according to normal commercial operation.

Selected tunnels were modified as indicated to test various conservation techniques. Comparison of the energy consumption of concurrent versus counter flow was studied by analyzing three years of gas consumption data available from a drying cooperative (Dominik 1979).

RESULTS AND DISCUSSION

Table 2 lists an energy budget for the concrete, concurrent flow tunnel dehydrator at location 1. Fifty-three percent of energy is used for evaporating water. This represents a fairly high moisture removal efficiency compared to many types of other agricultural drying operations, especially such as nut and grain drying operations. However, this should be expected since the fruit enters the tunnel at about 70% moisture (wet basis) and energy use is relatively efficient at high moisture levels (Henderson and Perry 1966). The main areas of heat loss are in the exhaust air, burner inefficiency and air leaks. Heat lost by conduction through the wall and by hot fruit and trays leaving the tunnel is relatively small.

Table 2. Energy budget of a concrete, concurrent flow tunnel dehydrator for prunes at location 1

Thermal Energy Loss/Utilization	Percent of Total Thermal Energy Input
Moisture evaporation	58
Exhaust air	16
Burner and other losses	12
Air leaks (door, fan belt opening)	8
Walls and ceiling	3
Fruit and trays	3
Total	100

Pertinent data comparing performance of three dehydrator types studied are presented in Table 3. The wide range of energy efficiencies observed is due to factors such as tunnel design, level of maintenance, and operation procedure. This study revealed that energy use efficiency is affected by the following specific factors:

(1) Heat loss in exhaust air.
(2) Heat loss through air leaks.
(3) Amount of fruit dried per tunnel-day.
(4) Conductive and radiative heat loss through walls.
(5) Burner losses.

Table 3. Observed and calculated data showing comparison of various tunnel dehydrators

	Heated Air									
	Temp, °C									
Location #	Dry Bulb t_d	Wet Bulb t_w	Flow[1] at t_d and t_w m^3/s	Moisture Content % (Wet Basis) Initial	Final	Average Moisture Removed kg/h	EnergyQ Output kW	Energy Input From Fuel Consumption kW	Energy[3] Input MJ/kg of Water Removed	Efficiency[4] of Water Removed %
Col #: 1	2	3	4	5	6	7	8	9	10	11
1	84	46	14.01	77.1	21.2	590	418	715	4.54	58
2	87	46	12.41	69.4	17.2	520	368	706	4.88	52
3	82	46	9.02	71.1	20.5	380	269	686	6.50	39

[1] 1 m^3/s = 2575 cfm implying flow rate at location 1 is 36050 cfm

[2] Enthalpy gain of the moisture in column 7 entering as part of the fresh fruit and discharged in exhaust. It refers to first heating the water to 74°C and then vaporizing at 74°C

[3] Computed from column 7 and 9 and using the conversion factor of 1 kW = 3.599 MJ/h

[4] Computed from column 8 and 9

Exhaust Air

The rate of energy lost in the exhaust air is determined by the amount of sensible plus latent heat (enthalpy) in the exhaust air and the quantity of air exhausted per unit time. Increasing recirculation will reduce the amount of exhaust air with a slight increase in enthalpy of the air. The net effect is a reduction in the amount of energy needed per unit time to keep the tunnel at operating temperature. The effect of increasing recirculation in a prune tunnel based on typical airflow and temperature conditions measured at all three dehydrator sites is illustrated in Fig. 3. The upper limit on the level of recirculation is a humidity above which it results in increased drying times. Perry (1944) indicated that 35% relative humidity at 74°C (165°F), or a wet bulb temperature of 52°C (125°F) at 74°C (165°F), to be this upper limit. At location 2 this effect was tested by comparing the seasonal energy use of a group of 18 tunnels under normal recirculation levels versus energy consumption of these tunnels with doors placed on the air exit of the tunnel to increase recirculation. Table 4 shows a 15% reduction in gas consumption can be achieved by

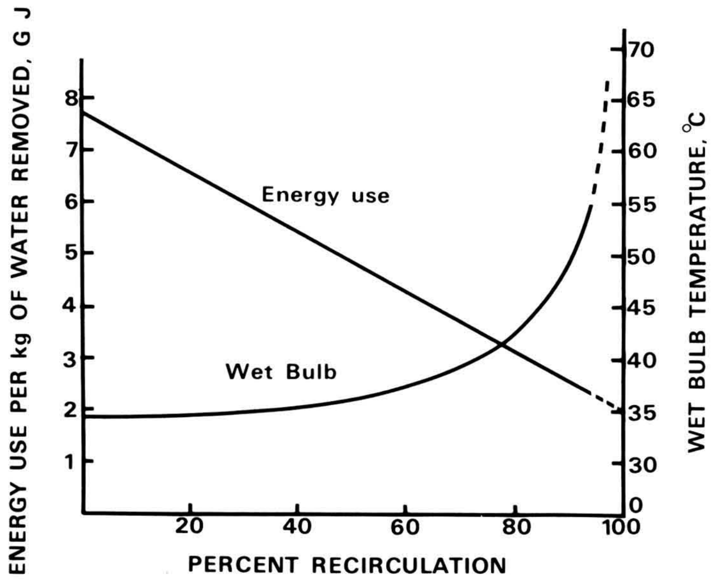

FIG. 3. EFFECT OF RECIRCULATION ON ENERGY USE AND HUMIDITY IN A CONCURRENT FLOW DEHYDRATOR

Table 4. Effect of increased air recirculation on energy usage in a prune tunnel operated at an exhaust dry bulb temperature of 68°C at location 2

	Wet Bulb Temp. (°C)	Seasonal Average Natural Gas Consumption (m^3/h)	Seasonal Average Existing Fruit Moisture (%)	Reduction in Gas Use (%)
Control tunnels	46	68	19.1	—
Tunnels with doors on air exhaust end	52	58	18.6	15%

increased recirculation. A graphic illustration of tunnel dehydrators operating under different modes with maximum, partial and no recirculation is presented on a skelton psychrometric chart in Fig. 4. The mixture (m) of fresh air (f) and some exhaust air (e) is heated from (m), to the desired hot air temperature (h). Now (m) to (h), the rise in dry bulb temperature required is less in the case of tunnel operating with the doors placed on the air exit than the conventional operating mode. Thus, resulting in significant energy use reduction.

For a two day period, one tunnel with doors was operated at a 60°C (140°F) wet bulb temperature. Although gas use for this tunnel could not be measured separately the exiting fruit moisture was not noticeably higher than that from neighboring tunnels with lower wet bulb temperatures. Wet bulb temperatures at this level require that outside air be ducted directly to the burner inside the tunnel. Without this, the burner will not remain lighted at these high levels of air recirculation.

Air Leakage

Air leakage was found to be a significant source of energy loss at location 1. This tunnel had been originally designed to operate in a counter-current mode. The tunnel was converted to concurrent flow by changing the direction of air flow. This resulted in the fan belt opening on the roof being on the positive pressure side of the fan, forcing 71°C (160°F) air out of the openings around the motor. Such air losses resulted in 8% of the energy requirements for the tunnel. This leakage can be prevented by sealing the openings. Tunnels designed with the opening on the negative pressure side of the fan do not have this problem but let too much cold air in unless the opening is reasonably well sealed. Air leakage around door seals and through holes was also seen to be a problem, although the magnitude of these losses were not measured and would vary from tunnel to tunnel.

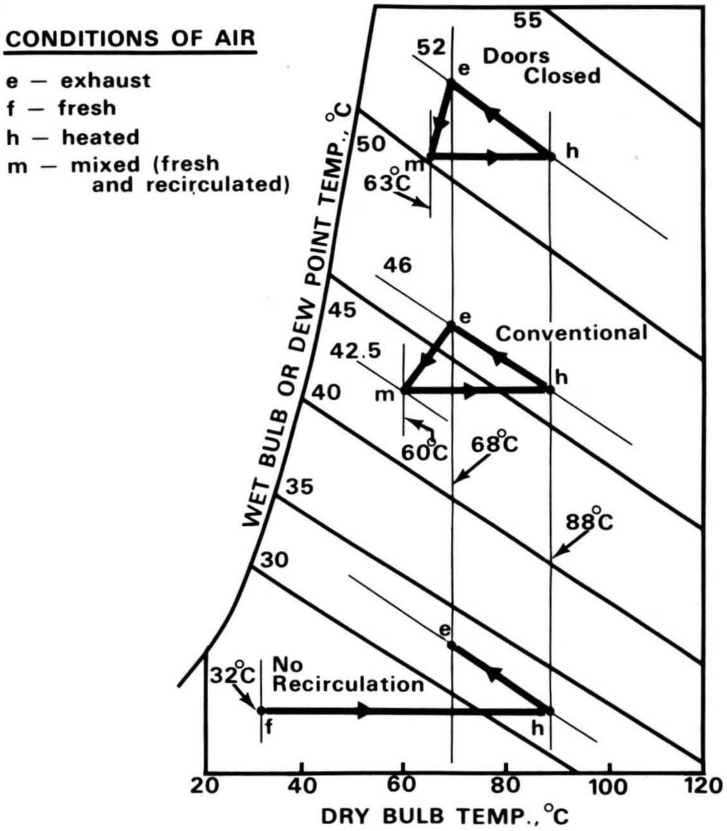

FIG. 4. PSYCHROMETRIC REPRESENTATION OF TUNNEL DEHYDRATORS AT LOCATION 2 UNDER DIFFERENT OPERATIONAL MODES

(a) no recirculation of air, (b) partial recirculation—conventional mode, (c) maximum recirculation with doors on air exhaust end closed.

Proper design and maintenance will reduce these losses to a minimum.

Tunnels at location 1 and 2 had canvas belt baffles installed in them. These baffles prevented hot and high velocity air from bypassing the fruit, traveling between the trays and the tunnel walls, and channelling out of the tunnel. The actual energy savings associated with properly installed baffles could not be calculated exactly because of difficulty in measuring the air flow between the tunnel walls and the tray, but rough estimates indicate savings of about

3-4%. Absence of such baffles at location 3 is one of several causes for low moisture removal efficiencies indicated in Table 3 (other causes for low efficiency at this location are discussed later in this section). The baffles would not be needed if doors were placed on the air exit end of the tunnel.

Fruit Dried Per Day

Fuel consumption and fruit output data revealed that fuel consumption per ton of fruit is directly affected by the quantity of fruit dried per unit time (Fig. 5). The data were collected for a three year period for 14 dehydrator locations each having a number of tunnels. The block effect for each location was removed, by subtracting the difference between the average of all the data and the average for an individual location. The linear regression equation indicates that for every additional ton per tunnel per day of fruit output the fuel use is reduced by equivalent of 193 MJ (183,000 Btu) of natural gas per tunnel-day (the relatively low R^2 value of 0.40 is expected since the fuel usage is a function of the various other factors that have been

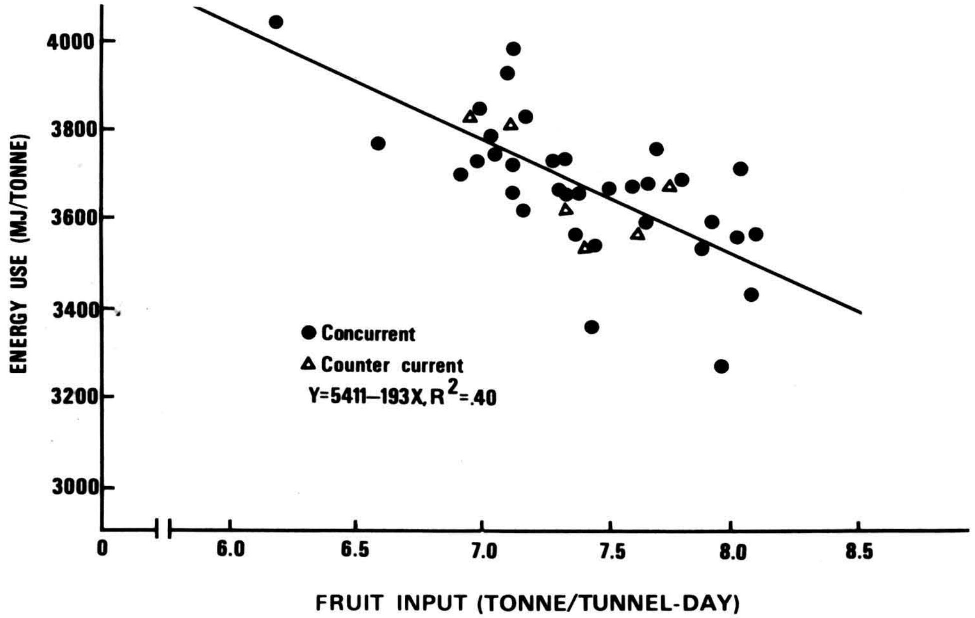

FIG. 5. EFFECT OF RATE OF FRUIT OUTPUT ON FUEL CONSUMPTION

mentioned). The range of fruit output for the cooperative was 4.3 to 9.5 tonne/tunnel-day (9480 to 20945 lb/tunnel-day) corresponding to fuel usages of 4849 MJ/tonne (2086 Btu/lb) and 3619 MJ/tonne (1557 Btu/lb). This variation is caused by varying amounts of fruit on the trays and in some cases by shutting down the dryer because of insufficient fruit deliveries to the drying facility. Bringing the output of the lowest up to the highest rate would result in an energy savings of 25%.

This effect can be explained by separating energy use that is associated with fruit output from energy use which is a function of time. The energy budget indicated that about one-half of the total energy use is for evaporating water. This use will increase as fruit output increases. Othe energy uses such as heat loss through walls, through heated trays and fruit leaving the tunnel, hot air leaving the tunnel and some burner losses are a function of hours of operation. Since increasing fruit output (primarily by increasing the amount of fruit on the drying trays) does not appreciably increase drying times, it will result in proportionately lower energy use for the time dependent energy uses.

Heat Loss Through Tunnel Surfaces

Heat lost through the walls and roof of a concrete tunnel was estimated as 18.5 KW (63,000 Btu/h). As indicated in Table 2 this is a small proportion of total heat input of 715 KW (Table 3). Tunnels (location 2, Table 1) constructed of transite (asbestos-cement board) have the potential of losing from 5% to 8% of the total energy consumption through the roof and walls. This heat loss can be reduced through the use of added insulation and by adding an extra layer of transite suspended at least a half inch below the roof in the area of the flame. This added layer of transite will prevent the flame from radiating heat to the roof and causing excessive heat loss.

In the 1930's and 1940's many "Miller" type prune dehydrators (Fig. 2) were built in California. These tunnels have the burner assembly located at the back end of the tunnel. The burner is located immediately behind a large steel plate which forms a portion of the rear wall. This steel plate gets very hot and becomes a large source of heat loss.

An experiment was performed on such a tunnel where a heat shield was placed behind the rear wall. The heat shield was constructed of three layers of expanded metal each separated by about an inch. This device shielded the rear steel plate from convective heat losses and absorbed radiant heat from the steel plate transferring it to the air that was passing through the shield into the dehydrator. With the shield in place the gas consumption was reducted by 10%.

Burner and other Losses

Table 2 indicates that 12% of the heat input was lost at the burner or was unaccounted for. Major proportion of such losses may be due to incomplete combustion of the gas, formation of water during combustion and radiant losses from a flame partially exposed to the outside. The efficiency data was generated by calculating the difference between the total heat input and all measured energy uses, the remainder was considered to be equal to the losses indicated here. It is to be noted that the total energy (heat) input into the system was calculated from the amount of fuel (natural gas) consumption and high/gross heat value of the fuel. Gross heat value includes the heat of formation of water during combustion. Gross and net heat values for methane are reported to be 4.581 MJ/m^3 (1013 Btu/ft^3) and 4.129 MJ/m^3 (913 Btu/ft^3) respectively (Perry and Chilton 1973). It is known that natural gas mainly consists of methane, thus, approximately 10% of the total energy input may be associated with the formation of water. As a result it is only 2% of the losses which were not accounted for. No measurements were made of the products of combustion (CO_2, CO, O_2, hydrocarbons), to indicate incomplete burning, because of the large amount of excess combustion air in the system. It is believed that properly installed and maintained burners should further reduce these losses.

Concurrent versus Countercurrent Operation

The data points in Fig. 4 indicated no significant difference between the two types of operation. This observation confirms the data reported by McRae (1951) which indicated that a selected group of countercurrent dehydrators in operation from 1935 to 1950 had an average efficiency of moisture removal of 45%. The average efficiency of moisture removal for the dehydrator cooperative during 1975-1977 was also equal to 45% with only 10% of the sampled tunnels operated in a countercurrent manner.

SUMMARY

The key to energy conservation is good management, proper maintenance of tunnels, and tray loading. The existing types of driers can operate efficiently if they are well maintained and properly operated. The list given below summarizes various techniques which can be employed to conserve energy in tunnel dehydrators and the anticipated fuel savings from those techniques:

Technique	*Fuel Savings*
Increased air recirculation (especially by adding doors to the exhaust end of the tunnel)	at least 15%
Fully loaded trays	0-25%
Use of a heat shield on "Miller" type tunnels	10%
Enclosure of motor well, sealing air leaks	8%
Properly installed and maintained burner	0-2%
Insulation of roof and use of radiant heat shield below roof on transite tunnels	3-5%
Properly installed baffles when doors are not installed on the exit.	0-4%

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THE EFFECTS OF DESIGN AND OPERATING CONDITIONS ON PARTICLE MORPHOLOGY FOR SPRAY-DRIED FOODS

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ABSTRACT

An experimental program was carried out in order to provide insight into the effects of the design and operating conditions of spray drying on the morphological behavior of the product. Single streams of uniform-size drops fell through a column in which air temperature profiles could be monitored and manipulated. Scanning electron microscopy and optical microscopy were used to measure shrinkage (or expansion) and to observe physical characteristics. The effects of varying the type of feed, the feed concentration, initial drop size, and air temperature history were investigated. Results are compared with previous investigations related to bulk density.

INTRODUCTION

Spray drying is a convenient and economical method of dehydration which is used extensively in the food industry. It offers several advantages over other dehydration methods, including continuous operation, short retention times, and a stable, packageable product. Common spray-dried food products include instant coffee, milk powder, tomato powder, condiments, and coffee whitener. Spray drying principles and applications are reviewed in detail by Masters (1979).

However, spray-dried foods often suffer from poor quality resulting from one or more of the following factors: (1) loss of volatile aroma compounds which are important to the taste and smell of the food;

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(2) thermal degradation of heat-labile compounds present in the food, resulting in off-flavors; (3) poor redispersibility; and (4) stickiness. These quality factors are a direct result of the design and operating conditions of spray drying (King *et al.* 1981) and can often be related to physical characteristics of the drying drop (Fig. 1), such as crust formation, shrivelling, and expansion.

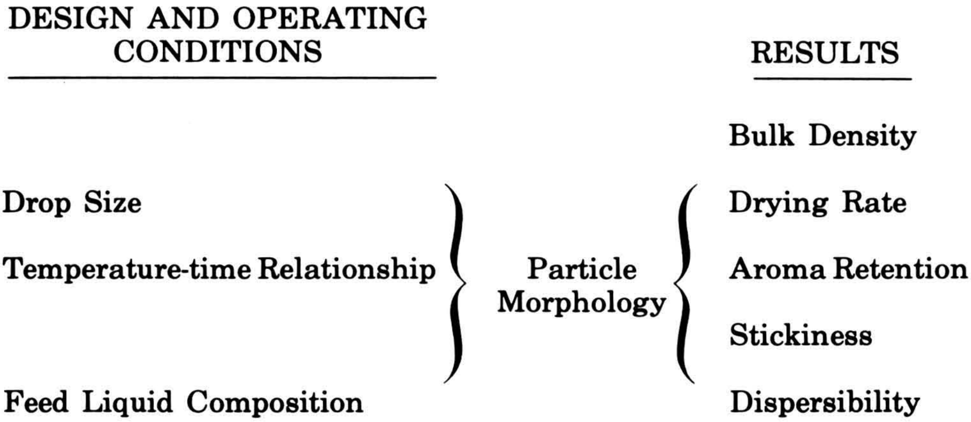


FIG. 1. CAUSE-AND-EFFECT RELATIONSHIPS IN SPRAY DRYING

Spray drying has been the subject of extensive research since the late 1940's, although, unfortunately, few of the experimental results relate to particle characteristics, and most of those that do are qualitative. Experimental studies concerning physical characteristics of the product have focussed mostly on bulk density, which is often an important quality-control variable. Marshall and coworkers (Charlesworth and Marshall 1960; Duffie and Marshall 1953; Crosby and Marshall 1958) conducted a series of experimental investigations in the 1950's which related particle size and density to operating conditions. Rulkens and Thijssen (1972) measured bulk densities of spray-dried maltodextrin solutions at varying air temperatures, feed temperatures, and feed concentrations.

Buma and Henstra (1971; Henstra and Buma 1971) used the scanning electron microscope to examine the physical properties of spray-dried milk and milk products. Verhey (1972a, 1972b, 1973) studied the phenomenon of vacuole formation in spray-dried skim milk particles.

Most of the experimental spray-drying research which has been done to date falls into one of two categories: (1) laboratory-scale or pilot plant experiments utilizing conventional atomization methods, or (2) drying of single large drops suspended by means of a filament. For analysis of particle drying characteristics, both methods have disadvantages. Conventional atomization produces a range of drop sizes, and drop trajectories and temperature histories cannot be monitored. On the other hand, a suspended macrodrop, since it is not free to rotate, dries in a very different manner from a freely-falling drop. The larger size may also alter drying characteristics.

Recently Toei and Furuta (1980; see also Toei *et al.* 1978) have implemented a method for observing an unsupported drop held stationary in an ultrasonic field. This allows continuous measurement of changes in size and shape, and also allows the drying rate to be inferred. However, only relatively large (about 1 mm) drops have been used. Also, realistic drying behavior at very short times characteristic of spray drying cannot be observed, and the ultrasonic field may affect the particle morphology.

To obtain more fundamental insight into the morphological (size and shape) behavior of drops of food liquids during drying, an experimental program was designed to dry a single stream of freely-falling drops. The drop sizes and exposure times were in the range of those encountered in spray dryers. Since the drop trajectories were known, the time-air temperature histories to which the drops were exposed could be measured and manipulated. In addition, the drops were uniform in size, so that the effects of varying initial drop diameter could be studied.

The design and operating conditions that were varied included the feed material, the air temperature profile, the feed liquid concentration, and the initial drop size. These variables were chosen because they are known to have important effects on product quality factors such as bulk density and aroma retention in conventional spray drying. Thus, the results of this work should help make it possible to relate the morphological behavior of drying drops to the quality of the product.

EXPERIMENTAL APPARATUS

The spray drying system shown in Fig. 2 was designed to dry a single stream of uniformly-sized drops, allowing for collection of drops at various points during the drying process and manipulation of the air-temperature profile experienced by the drops. The column

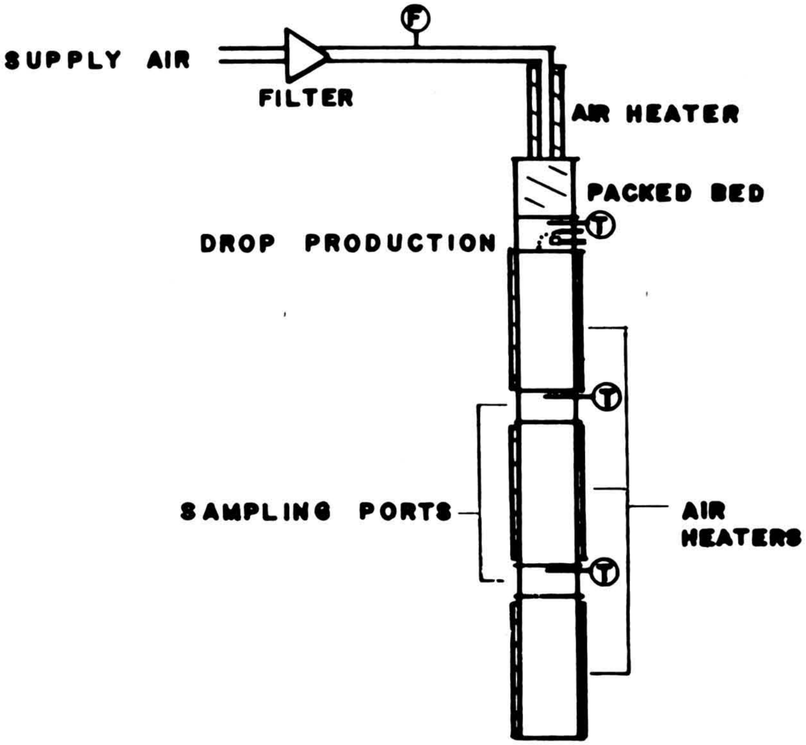


FIG. 2. UNIFORM DROP SPRAY DRYER (DIMENSIONS OF COLUMN NOT TO SCALE)

was 7.62 cm in diameter and 2.28 m in length below the drop production point. It was composed of three 0.61-m lengths of Pyrex glass pipe, alternating with three 0.15-m lengths of copper tube, through which samples could be taken and air temperatures measured. Heat was supplied to the cocurrent air flow by air heaters located on the inlet air line and on the column walls. The air passed through a bed of 2-mm spherical molecular sieve particles upon entry to the column, so as to achieve uniform flow and avoid deflection of drops. Further details of the experimental design are given by Greenwald (1980).

In the production of a uniform stream of drops for the spray drying experiments, several operating characteristics were desired: (1) Satellite droplets were undesirable. (2) The stream of drops should remain very uniform in size and in production frequency over long periods of time. (3) Production frequency could not be so large that drops coalesced with or substantially affected the drying history of neighboring drops. (4) The drop production apparatus had to be capable of producing drops less than 250 μm in diameter, because drops above that size could not be dried with the column length and air heating capabilities available. (5) The drop size produced should be variable, so that the effects of initial drop size on drying characteristics could be investigated.

The vibrating-reed drop production device that was used in these experiments (Fig. 3) was developed, with some modifications, from a similar device described by Wolf (1961). In the present work, a short (ca. 2.5 cm) length of nickel-chrome wire, 0.025 cm in diameter, served as the reed. To produce a drop, the reed tip impinges on the liquid surface and, as it emerges, it draws out a ligament of liquid. Eventually the ligament breaks free from the reed tip and the liquid surface and collapses to form a drop. Wolf described the mechanism in more detail and included selected photographs of the process taken with a high speed motion picture camera.

Additional details concerning the apparatus are given by Greenwald (1980).

OPERATING PROCEDURES

Four food or food-model solutions—coffee, nonfat milk, sucrose, and malto-dextrin—were studied experimentally. The solutions were prepared from readily-available commercial products. The coffee and milk solutions were made from commercial spray-dried products. The maltodextrin used was Morrex 1918 (CPC International, dextrose equivalent between 9 and 12).

Drop size was often varied during an experiment by raising or lowering the reed tip, or by adjusting the amplitude of the vibration of the reed by increasing or decreasing the power. In this way, the effects of varying the initial drop diameter for a given solution at a given air temperature level could be studied.

During an experiment, liquid and partially-dry drops were collected at four points in the column (Fig. 2)—at the production point, at each of the two sampling ports, and at the bottom of the column. The total sampling time was about 30 s and caused minor fluctuations in the air temperature.

Liquid drops were collected in a small amount of an almost neutrally-buoyant silicone fluid of high viscosity, which was spread on a

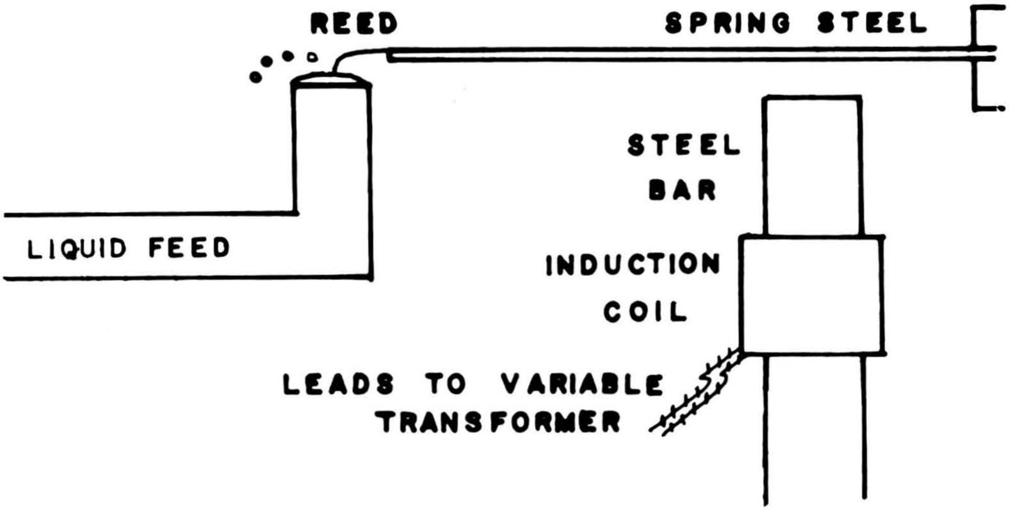


FIG. 3. VIBRATING REED DROP DEVICE

glass microscope slide. They were then examined under an optical microscope with an eyepiece which had a built-in scale, so that drop size could be directly measured to within ± 2.5 μm. In later experiments, physical features of the particles were also noted, including bubbles or voids. A Polaroid camera was available for photographic records.

Dried particles were collected on clean glass slides or in the silicone fluid; their diameters were also measured by examination under the optical microscope. The particles were usually spherical; however, if they were not, the largest dimension was measured.

Scanning electron microscopy (SEM) was used to study the external and internal features of the dried particles. The microscope employed was a Stereoscan 600 (Cambridge Scientific Instruments), with a magnification range from 20X to 50,000X at 10 mm working distance. Samples taken for this purpose were collected on dry microscope slides and dried to completeness under a vacuum at ambient temperatures. The size and physical features of the particles were checked before and after the vacuum drying using an optical microscope. For particles which were mostly dry at the time of collection, no noticeable differences could be seen. If a rigid crust had not yet formed, the particles partially collapsed on the slide, resulting in a flat circular bottom surface. These samples were of course eliminated from SEM study.

Fracturing the particles for examination of internal features was done by crushing them between two glass microscope slides. Best results were obtained when spacers of thickness somewhat less than the particle diameter were inserted to prevent total fragmentation. Cutting the particles with a knife or razor was attempted, following the suggestion of Buma and Henstra (1971), but successful results could not be obtained. Conventional methods of using a fixative and then sectioning or infiltrating a sample with a solvent and then freeze-fracturing are not practical, since carbohydrates are at least partially soluble in most organic solvents.

To prepare a fractured or unfractured sample for SEM examination, the particles were deposited directly on the small aluminum stubs commonly used for mounting and coating of samples. No fixative was used. Also, since very high resolution was not required in this work, the samples were examined at low electron beam voltage (1.5 kV) without prior coating. Charging of the specimens was not usually a problem at the low beam voltage used, and good results were obtained.

EXPERIMENTAL RESULTS AND DISCUSSION

Drying Behavior at Low Air Temperatures

When food solutions are dried at low air temperatures, steep concentration gradients do not form within the drop. The drops remain at or near the wet-bulb temperature for a considerable time and begin to heat up only late in the drying proces when average water content is low. Therefore, particle expansion does not occur. The final product is dense and often exhibits uneven surface shrinkage, as seen in Fig. 4. These properties are characteristic of drops dried at low air temperatures.

Drying Behavior at Higher Air Temperatures

As air temperatures increase to levels above 100°C, the behavior of the drying drops changes substantially, but only if the high air temperature level is maintained in the lower part of the column (late in the drying process). If the air temperature, initially high, decreases to low (<100°C) levels late in drying, the particle behavior is usually similar to that described above for drying at low air temperatures.

When air temperature remains high (>100°C) throughout the column, some of the particles tend to expand. Ranges of dry particle sizes were often seen at the lower sampling ports and could be related to

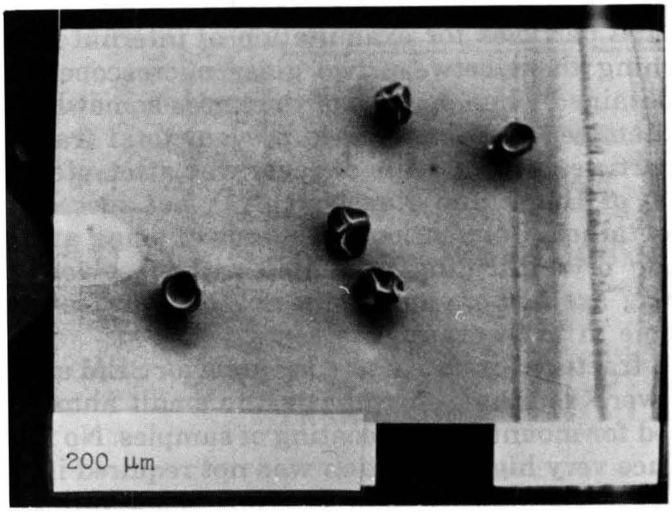


FIG. 4. SEM PHOTOGRAPH OF NONFAT MILK PARTICLES DRIED IN AIR AT APPROXIMATELY 70°C
Initial diameter—145 μm, length of fall—0.76 m

expansion having occurred in only a fraction of the particles. However, as air temperature increases, both the fraction showing expansion and the degree of expansion increase.

This behavior is well illustrated with the photographs of Fig. 5 and 6. Both samples were collected after 2.28 m of fall, and in both cases the initial drop diameter was 180 μm. For the lower-temperature case (Fig. 5), not all particles expanded, so that a drop size range of approximately 140 to 180 μm was observed.

At the higher temperature level (Fig. 6a), expansion occurred more frequently, and most of the particles collected at the bottom of the column lay within a narrow range of sizes (170 to 180 μm). However, at the second sampling port, size ranges were large (160 to 190μm), and blowholes could be seen in some of the particles (Fig. 6b). These blowholes may have produced contraction in some of the larger particles at Port 2, accounting for the narrower range of sizes observed at the bottom of the column.

When fractured, these particles exhibit various forms of internal morphology. The two photographs in Fig. 7 were taken from the same sample collected after 2.28 m of fall, with a temperature profile that increased to 135°C. The "hollow shell" in Fig. 7a was seen more frequently, but the multiple voids in Fig. 7b were by no means uncommon.

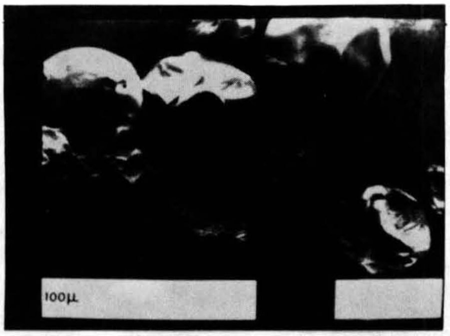


FIG. 5. SEM PHOTOGRAPH OF COFFEE PARTICLES DRIED WITH AIR TEMPERATURES INCREASING TO 125°C
Initial diameter—180μm, length of fall—2.28 m

Mechanisms of Bubble Formation and Expansion

Greenwald and King (1980) explore possible mechanisms of bubble formation and particle expansion in some detail. They conclude that a two-step mechanism is operative, both in the present apparatus and for spray drying with pressure atomizers in general. First, an air bubble must form by desorption of air which either is present in the feed liquid or absorbs shortly below the atomizer. Desorption of this air comes about because of temperature increase, loss of water by evaporation and/or increase in dissolved-solids concentration in the drops. The second step needed to bring about expansion is for the drop temperature to approach or exceed the boiling point, whereupon a large mole fraction of water vapor will form in the bubble, causing it to grow substantially in size.

The fact that only some particles expand for drops initially of the same size and exposed to the same temperature-time history is a strong indication of the importance of the initial nucleation step. Nucleation is a statistical event, and will occur only in those particles containing a suitable (probably heterogeneous) nucleation site.

The increased degree of expansion observed when the air temperature remained high lower in the column can be attributed to greater vaporization of water into the bubbles at the higher temperatures.

Effect of Initial Drop Size on Drying Behavior

At air temperatures that were sufficiently high to cause particle expansion, the effect of initial drop size was pronounced, with smaller drops showing more tendency toward early expansion; however,

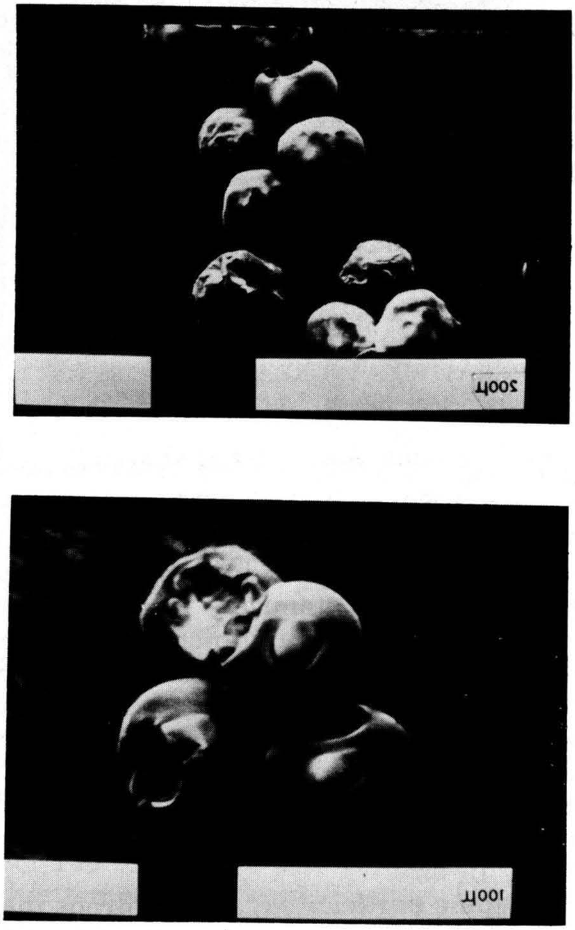


FIG. 6. SEM PHOTOGRAPHS OF COFFEE PARTICLES DRIED WITH AIR TEMPERATURES INCREASING TO 160°C
Initial diameter = 180 μm

smaller initial drop sizes tended to yield expansion in a lesser fraction of the particles. This behavior is in accord with a lesser probability of nucleation sites in smaller drops. These results are presented and discussed by Greenwald and King (1980).

Effect of Feed Concentration on Drying Behavior

The standard concentrations which were used in all experimental results discussed so far and in the next section were maltodextrin—20%, coffee—20%, nonfat milk—10%, and sucrose—40% (all on weight basis). Since these concentrations are all lower than those typically used in commercial applications, use of higher concentrations was attempted. However, difficulties were encountered with use of the vibrating reed drop-production device with high-viscosity liquids. It was necessary to increase the power to the vibrating reed, causing production of larger drops. Under these conditions, drop production often became erratic. As a result, concentrations could not be increased much above the standard levels, and it was difficult to identify any trends.

Some results were obtained for 30% w/w coffee solutions (Greenwald 1980). For these solutions, the range of particle sizes observed was smaller (in all cases less than ± 10μm) than those noted with 20% w/w coffee solutions. Bubbles, when they appeared, were seen in almost all the particles. Although results are sparse, it appears that, when expansion occurs, it takes place in a larger fraction of the particles for solutions of higher concentrations. This can be attributed to an increased density of nucleation sites.

External and internal morphological characteristics were very similar to those observed with 20% coffee solutions.

Meaningful results were also difficult to obtain at concentrations below the standard levels. Solutions were then too dilute to dry appreciably at the air temperatures available, and crust formation was not observed.

Effect of Material Properties on Drying Behavior

The food materials dried included a pure sugar solution (sucrose), a solution of a mixture of sugars and longer-chain carbohydrates (maltodextrin), and two complex food materials (coffee and nonfat milk) containing carbohydrates, proteins, and other compounds. The morphological characteristics of the drying drops were quite dissimilar.

A few experiments were conducted with 40% w/w sucrose solutions. These drops did not form crusts and never exhibited internal voidage or expansion behavior at the air temperatures studied. Dried sucrose particles were transparent and spherical. They exhibited the properties of a very viscous liquid; most notably, they tended to collapse when collected on dry slides. They were therefore unsuitable for SEM study.

Maltodextrin solutions were dried extensively, and representative examples of the experimental results are discussed by Greenwald (1980). These drops did have some tendency to expand although the fraction of drops which did so was generally smaller than for coffee and milk solutions. Fractured particles which had expanded were always of the "hollow shell" type, like the coffee particle in Fig. 7a. Shrivelled particles showed large, deep surface dents and folds, as shown in Fig. 8.

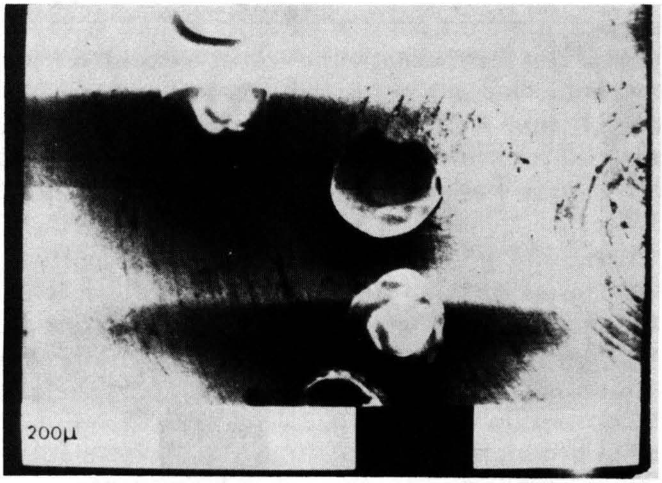
Nonfat milk solutions were difficult to dry with the present experimental apparatus. Some property of the solutions, possibly the surface activity of the proteins or a visco-elastic character, impeded production of uniform drops. In addition, at increased temperatures the solutions had a tendency to foam at the surface of the liquid reservoir. The sample shown in Fig. 9 is one of a few which were obtained at elevated temperatures. Thus, only a few expanded particles were available for fracturing; they also were hollow shells.

At lower temperatures, milk particles shrivelled and were very similar in appearance to maltodextrin (see Fig. 4 and 8).

Experimental results were also obtained for 20% w/w coffee solutions. These solutions were relatively easy to handle with the present apparatus.

Coffee particles had a high tendency to exhibit internal voidage. Frequently, more than one bubble was visible in the particles examined with the optical microscope; this behavior was illustrated in Fig. 7b. In addition, even shrivelled particles contained internal voids. The ranges of particle sizes observed seems to indicate that nucleation takes place sooner in some particles than in others.

The shrivelled coffee particles were different in appearance from malto-dextrin and milk. The surface dents were smaller and more numerous, giving the particles a rocklike appearance. The dents were also more shallow, which may have resulted from the bubbles present in the particles.



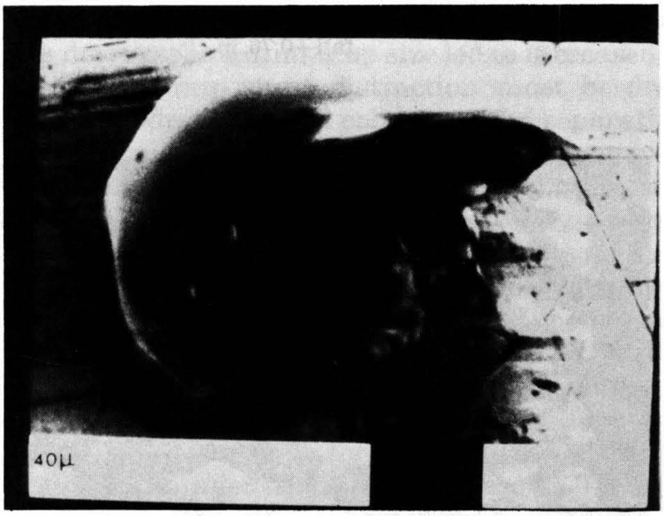


FIG. 7. SEM PHOTOGRAPHS OF FRACTURED COFFEE PARTICLES DRIED WITH AIR TEMPERATURES INCREASING TO AND MAINTAINED AT 135°C
Initial diameter—210 μm, length of fall—2.28 m

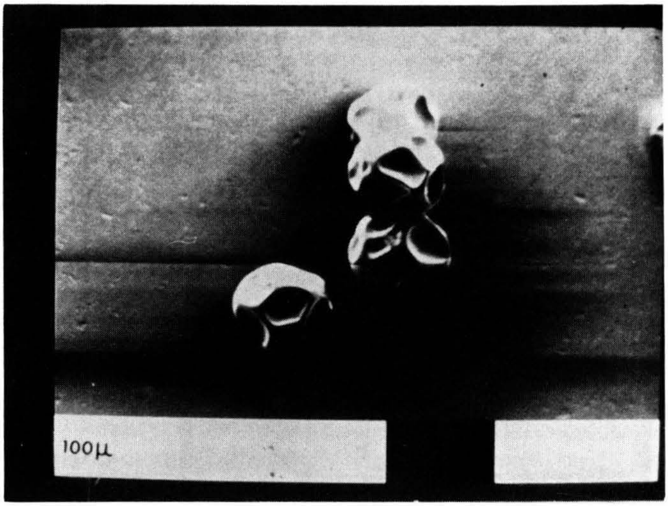


FIG. 8. SEM PHOTOGRAPH OF DRIED MALTODEXTRIN PARTICLES
Air temperatures decreased from 136°C to 26°C; initial diameter—160 μm, length of fall—0.76 m

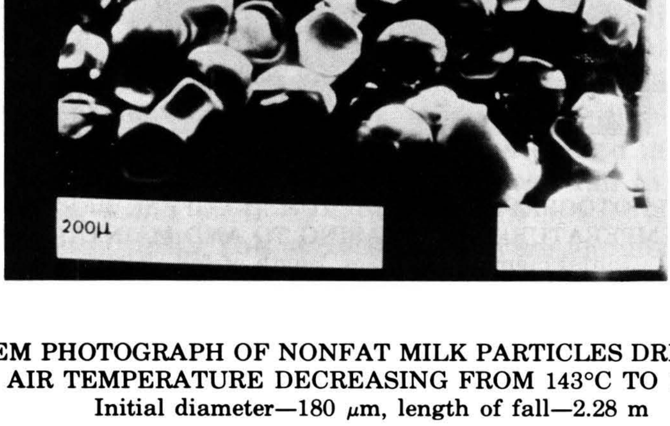


FIG. 9. SEM PHOTOGRAPH OF NONFAT MILK PARTICLES DRIED WITH THE AIR TEMPERATURE DECREASING FROM 143°C TO 122°C
Initial diameter—180 μm, length of fall—2.28 m

Comparison of Experimental Results to Published Work

Although little work has been done to document the effects of design and operating conditions on particle morphology, much experimental work has been carried out to measure their effects on important quality control variables such as bulk density. Since bulk density can be easily related to particle expansion, which was observed in detail in this work, some results of earlier studies are examined further here.

Increasing air temperature has been shown by many researchers to cause a decrease in bulk density (see, e.g., Duffie and Marshall 1953; Rulkens and Thijssen 1972). The increased expansion with increasing air temperature that was seen in the results discussed above was therefore expected in view of past work.

The effect of initial drop size has not been well quantified, since most experimental workers have utilized conventional atomization methods, which give a range of drop sizes. A few workers (Charlesworth and Marshall 1960; Verhey 1972a) have noted that the smaller-sized fractions collected from conventional spray driers have larger bulk densities. This would seem to be in conflict with the present results, in which a decrease in initial drop size led to increased particle expansion. However, an important distinction must be drawn between decreasing initial drop size and collecting and separating dried particles. The results cannot be compared for three reasons: (1) Some of the fine particles collected from spray dryers are attrition dust, i.e., broken particles. (2) The smallest drops produced by conventional atomizers are of order 10μm or less in diameter, which is much smaller than any produced in this work. If the tendency to expand depends on the presence of nucleation sites, these tiny drops will be far less likely to develop bubbles and expand. (3) Drops of a given initial diameter that do not expand at all or begin to expand only late in drying produce smaller particles that have higher densities. This was often seen as a range of final particle sizes for a given initial drop diameter in these results, and the smaller fractions were denser. Therefore, the observed increased expansion for smaller drops does not conflict with past results.

The effect of feed concentration has been similarly difficult to quantify with conventional atomization methods. Changing the concentration of the feed changes many material properties, notably the viscosity, which has a pronounced effect on the drop sizes produced. Rulkens and Thijssen (1972) noted no discernible effect of increasing dissolved solids concentration on bulk density for maltodextrin solutions. They therefore concluded that the degree of expansion had increased, since, if it had not, bulk density would have been expected to increase with increasing feed concentration. Similarly, Verhey (1972a) noted increasing expansion at higher solids content for skim milk. The results discussed above seem to agree with these observations, but more work is needed for confirmation.

CONCLUSIONS

To obtain an increased fundamental understanding of particle morphology in spray drying, an experimental program was designed to dry a single stream of uniform-size drops falling through a column with an imposed air temperature profile. A laboratory apparatus was built and experiments were conducted with several food solutions, varying the air temperature history, the initial drop size, and the feed concentration.

At low air temperatures, the products exhibited uneven surface shrinkage resulting in deep dents and folds. Bubbles did not form in the drops and very little internal voidage could be seen. The drops remained in the constant-rate period of drying for a substantial portion of their fall through the column.

At higher air temperatures, particles frequently exhibited large internal voids. Increasing the air temperature caused both the sizes of the voids and the fraction of the particles which contained voids to increase. Particles that began to form internal voids early in drying sometimes developed blowholes and subsequently contracted.

Decreasing the initial drop size caused expansion to appear at an earlier fall height because of the increased drying rates and lower terminal velocities for small drops. However, experiments with maltodextrin and coffee solutions indicated that the fraction of particles which exhibited internal voidage was smaller for smaller drop diameters. This may be attributable to the reduced probability of the presence of heterogeneous nucleation sites in smaller drops.

Increasing the feed solids concentration did not noticeably affect the sizes of the internal voids observed, but the fraction of particles exhibiting expansion was larger. This observation may be explaineed by the increased probability of finding nucleation sites in more concentrated drops.

The experimental results generally agreed with published work on the effects of operating conditions on bulk density. The observed increase in particle expansion with increasing air temperatures was expected, corresponding to the decrease in bulk density which has been commonly observed. The increased bulk density measured for smaller-size fractions of conventional spray-dried products could result from the decreased probability that very small drops contain nucleation sites, or from the presence of broken particles. Finally, the increased tendency to form internal bubbles as feed concentration increases agrees with published conclusions that the degree of expansion increases.

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LITERATURE ABSTRACTS

ABSTRACTS FROM TRANS. ASAE

ENERGY USE PROFILES IN CITRUS PACKING PLANTS IN CALIFORNIA. L. P. Mayou, R. P. Singh. Trans. ASAE. *23FE*, 234.

A study on consumption of energy in lemon, orange, and grapefruit packing plants was conducted with the following objectives: (a) to collect and analyze monthly electrical and natural gas use data from several packing plants, and (b) to explore the potential of energy conservation in citrus packing operations. Energy data for the period July 1976 to July 1977 were obtained from 17 citrus packing plants representing three different geographical regions in California. Energy analyses revealed information on monthly energy consumption, type of energy use, and influence of environmental conditions on energy use. To explore energy conservation, use of a heat recovery unit in the refrigeration system was examined for using heat discharged at condensers for heating water for washing fruit.

THE VIEWS OF A FOOD SCIENTIST ON PROMISES AND PROBLEMS OF LEAF PROTEIN INCORPORATED INTO OUR FOODS. L. D. Satterlee. Trans. ASAE. *23FE*, 237.

Leaf protein has been shown to have real potential as a protein source for feeds and foods. The acceptance of leaf protein as a protein source for humans will be based on several factors:
(1) its high nutritive quality, (2) its economics of production, (3) its safety as demonstrated by toxicological testing, (4) its ability to compete with food proteins currently available in the world market.

SOLAR DRYING OF TARO ROOTS. J. H. Moy, W. Bachman, W. J. Tsai. Trans. ASAE. *23FE*, 242.

Experimental solar drying of taro roots in slice and shred forms indicated that the direct absorption dryer with plastic mirrors as reflectors and two mixed mode solar dryers were reasonably efficient in achieving drying of taro into stable forms for storage. With taro slices at a loading density of 7.3kg/m^3, the direct dryer with reflectors was very efficient; the mixed mode dryer and the direct cage dryer were equally efficient, but slightly less than the direct dryer with reflectors; the indirect mode of solar drying was the least efficient.

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MECHANICALLY ASSISTED GRADING OF ORANGES CONTAINING EXCESSIVE DECAYED FRUIT. W. L. Bryan, J. Jenkins, J. M. Miller. Trans. ASAE. *23FE*, 247.

Mechanically assisted manual grading was effective for sorting truckloads of 'Valencia' oranges that contained higher numbers of decayed fruit than could be removed by conventional grading procedures at usual unloading rates. A mechanical separator diverted most of the unwholesome oranges by differences in bouncing behavior into a small side stream that contained less than 10% of the original fruit stream. Only the side stream required manual grading before storing fruit in bins. The process was particularly effective for grading loads of mechanically harvested oranges that contained more than 5% decayed fruit.

SWEET POTATO FOOD SYSTEMS IN THE TROPICS. J. K. Wang, W. E. Steinke, M. O'Brien. Trans. ASAE. *23FE, 251.*

A system of continuous production of sweet potatoes in the tropics has been modelled using linear programming techniques. Two land management strategies have been defined and evaluated. Each was optimized under conditions of limited availability of machinery and labor individually and in combination. Land utilization and level of output was also studied.

It has been shown that there is a cost tradeoff between a steady harvest, thus requiring no storage, and full utilization of labor, land, and machinery. Drops of at least 5% in output per input used indices are the minimum to be expected if a steady supply of sweet potatoes must be produced. Larger drops in productivity can be expected, depending on system design. These drops in productivity must be weighed against storage costs and other factors in each locality before a decision as to which land management strategy to adopt can be made.

USE OF RECORDING PENETROMETER FOR EVALUATION OF DENSITY PROFILES IN BALES OF TOBACCO. Trans. ASAE. *23FE*, 261.

A recording penetrometer was calibrated for use on compacted tobacco. A prediction equation was obtained for tobacco density as a function of penetrometer pressure. Tobacco moisture content and amount of stems and midribs in the tobacco had only nonsignificant effects on density prediction. The penetrometer was used on two types of experimental tobacco bales to demonstrate the determination of relative magnitudes of compaction gradients within bales. Possibly both types of bales were unacceptable for palletizing and storage, because compaction varied significantly with the depth and length of all bales tested.

WASTE HEAT FROM FOOD PROCESSING PLANTS IN THE PACIFIC NORTHWEST. Trans. ASAE. *23FE*, 498.

Food processing plants in Washington, Oregon, and Idaho have been studied to determine the quantity, quality, and recoverability of waste heat. Thirty-eight plants of 14 types provided data for energy consumption and waste heat production. Teams of engineers, having visited the plants, analyzed the energy use and waste heat data to determine compatibility of the data with the characteristics of each plant. The teams also assessed the recoverability of energy from each waste stream.

MATURITY EVALUATION OF BANANAS BY DELAYED LIGHT EMISSION. Y. Chuma, K. Nakaji, M. Ohura. Trans. ASAE. *23FE,* 1043.

The fundamental characteristics of the delayed light emission (DLE) of bananas, such as decay period, dark period, exciting time and illuminance, and fruit temperature were determined, and the changes of DLE due to ripening were investigated. Intensity of DLE had a high correlation with the ripening indices of bananas such as the hue of peel color, sugar content, and firmness. Hence, the intensity of DLE proved to be useful as a means of maturity evaluation of bananas.

DATA ACQUISITION FOR ENGINEERING ANALYSIS OF CITRUS EVAPORATORS. W. M. Miller, T. A. Wheaton, R. D. Carter, P. G. Crandall. Trans. ASAE. *23FE,* 508.

A data acquisition system using a minicomputer was developed to monitor and control a pilot plant citrus evaporator. Juice feed, solids (Brix), steam flow, temperature, and vacuum were measured to formulate a heat and mass relationship for the multiple effect unit. The process model compared favorably with actual operating conditions when adequate system losses were incorporated.

STEAM MUFFLER EVALUATION FOR THE FOOD PROCESSING INDUSTRY. S. A. Waggoner, S. Humpert, R. E. Garrett. Trans ASAE. *23FE,* 511.

Steam exhausts which are prevalent in food processing plants have been found to exceed the limits set up by OSHA. To comply with OSHA standards, food processors have begun using commercial mufflers. This article provides the food processor with comparative data on 16 types of commercial mufflers in sizes 1/8 in., 1/4 in., 3/8 in., and 1/2 in. N.P.T. Having this information the food processor is better able to pick the most cost effective muffler for his needs.

MATURITY SORTING OF GREEN TOMATOES BASED ON LIGHT TRANSMITTANCE THROUGH REGIONS OF THE FRUIT. V. R. Nattuvetty, P. Chen. Trans. ASAE. *23FE,* 515.

A high-density spectrophotometer with fiber optic attachment was used to study the light transmittance through different regions of green tomatoes. The average of transmittance readings taken at four locations around the fruit was found to correlate with the maturity of the fruit. The correlations between optical criteria and the maturity of four varieties of tomatoes are given.

LIGHT TRANSMITTANCE THROUGH A REGION OF AN INTACT FRUIT. P. Chen, V. R. Nattuvetty. Trans. ASAE. *23FE,* 519.

A technique which utilizes fiber optics to measure light transmittance through a region of an intact fruit was evaluated experimentally. Results given in this report include the variation of measurements around the fruit, the effect of the distance between the incident and detection points on the transmittance, and the depth through which the detected light penetrated into the fruit.

EVALUATION OF NEW SOYBEAN DEHULLER. B. J. Shyeh, E. D. Rodda, A. I. Nelson. Trans. ASAE. *23FE*, 523.

An evaluation of a new soybean dehuller using a roller and stationary concave plate gave dehulling efficiencies up to 88%. Best results were obtained with a preheating treatment at 93 °C (200 °F) for 15 min. The dehulling operation was followed by a rubber roller treatment to loosen adhering hulls.

COMPATIBILITY OF SOLAR ENERGY WITH FLUID MILK PROCESSING ENERGY DEMANDS. Trans. ASAE. *23FE*, 762.

Compatibility of solar energy collection, storage and supply with energy demands for a fluid milk processing plant was assessed using TRNSYS (Transient Simulation Program) and F-CHART (economic analysis program). The results show that solar energy can supply up to 34% of the processing energy demand but that the economic climate must change markedly for the system to be economically feasible.

LIQUID DIFFUSIVITY OF ROUGH RICE COMPONENTS. J. F. Steffe, R. P. Singh. Trans. ASAE. *23FE*, 767.

Data were collected to determine the liquid diffusivity of the starchy endosperm, bran and hull of rough rice. Mathematical equations based on Fick's law of diffusion were used to model the thin-layer drying of white, brown and rough rice. Diffusion coefficients were determined by minimizing the sum of squared deviations between the theoretically predicted and observed drying curves. Diffusivities were calculated for temperatures ranging from 35 to 55 °C and were found to be an Arrhenius-type function of temperature.

THEORETICAL AND PRACTICAL ASPECTS OF ROUGH RICE TEMPERING. J. F. Steffe, R. P. Singh. Trans. ASAE. *23FE*, 775.

A theoretical model was developed to simulate the drying and tempering of rough rice. The model was based on liquid diffusion theory and assumes the grain to consist of a spherical core (starchy endosperm) surrounded by two concentric shells (bran and hull respectively). During tempering, measured changes in relative humidity in the void volume of a mass of rough rice were compared to predicted changes in surface liquid concentration of a rough rice kernal. The results of modeling are presented in terms of equations which predict tempering time. The effects of drying variables on the tempering model were investigated. Multipass drying was simulated to determine how various degrees of tempering effected the drying curve.

PREDICTION OF AIRCOOLING CHARACTERISTICS OF MOIST FOOD PRODUCTS. P. M. A. Majeed, S. S. Murthy, M. V. K. Murthy. Trans. ASAE. *23FE*, 788.

An analysis of the aircooling characteristics of food products is presented. The coupled effects of heat and moisture transfer at the product surface are taken into account. The one-dimensional heat conduction equation in rectangular, spherical and cylindrical coordinates is solved using finite difference technique. The variation of product temperature with time is obtained in dimensionless form in terms of Biot number, wet bulb temperature of cooling air and initial product temperature. Typical results are presented in the form of charts. To facilitate quick estimation of cooling characteristics, correlations are obtained for the time variation of temperature as a function of the governing parameters. The theoreticl predictions yield good agreement with experimentally determined time-temperature histories.

VARIATION OF YOUNG'S MODULUS OF POTATO AS A FUNCTION OF WATER POTENTIAL. H. Murase, G. E. Merva, L. J. Segerlind. Trans. ASAE. *23FE*, 794.

The Young's modulus of potato tuber was studied. A distinction was made between the apparent modulus measured in response to an applied strain and the actual modulus which was postulated to be a constant material property. A theoretical analysis showed the two were related by the free energy present in tissue due to water. It is shown that the Young's modulus is a linear function of tissue water potential for a constant rate of strain.

FOOD RESEARCH EXPERIMENTAL DESIGN: EFFECTS OF VARIATION. D. R. Thompson. Trans. ASAE. *23FE*, 1034.

Selected experimental designs for determining integrals of response, sequentially locating optimums and developing response surface equations have been evaluated for the influence of variation in the independent variables and the response. The level and type of variation are both important considerations in the selection of the experimental designs tested in this study.

MODELING THE KINETICS OF HEAT INACTIVATION OF TRYPSIN INHIBITORS DURING STEAM-INFUSION COOKING OF SOYMILK. L. A. Johnson, W. J. Hoover, C. W. Deyoe, L. E. Erickson, W. H. Johnson, J. R. Schwenke. Trans. ASAE. *23FE*, 1326.

The effect of heat on trypsin inhibitor (TI) activity during steam-infusion cooking of soymilk was studied. At 154°C only 40 s process time reduced TI to the same level as conventional cooking at 99°C for 60 min. Between 99 and 154°C the kinetics of TI inactivation followed behavior exemplified by the summation of two first-order reactions. Spline fitting functions effectively modeled the data with r^2 ranging from 0.984 to 0.999. The heat-labile reaction was attributed to Kunitz inhibitor and the heat-stable reaction, to Bowman-Birk inhibitor. The former accounted for approximately 85% of the iriginal TI activity. Arrhenius equation kinetic constants for each reaction were calculated.

REDUCING POULTRY PROCESSING ELECTRIC DEMAND. W. K. Whitehead, W. L. Shupe. Trans. ASAE. *23FE*, 1586.

Several methods are available for the reduction of electric demand in poultry processing plants. This paper discusses opportunities for energy reduction in two operations: ice making and ventilation for live broilers. A program designed to reduce demand in one plant reduced the peak demand by about 15% by installing more energy efficient fans in the live-holding area and changing the time of ice-making operations during the warm months. In addition, a method of using electric hot water heaters for heating scalder water without incurring added demand charges is presented. A large, two-shift processing plant can pay for the cost of an electric hot water heater in 50 operating days when compared to using No. 2 fuel oil.

SINGLE CELL PROTEIN RECOVERY FROM ALFALFA PROCESS WASTES. R. E. Mudgett, K. Rajagopalan, J. R. Rosenau. Trans. ASAE. *23FE*, 1590.

Cultivation of the yeast *Candida utilis* on waste brown juice obtained from a pilot-scale process for mechanical extraction of alfalfa protein gave high biomass conversion yields with significant reductions in total dissolved solids and organic carbon levels. Protein content of the yeast product was improved considerably by supplementing the brown juice with nitrogen and phosphorus.

MEASURING THE STEAM HEAT TRANSFER COEFFICIENT TO VEGETABLES. T. Rumsey, D. F. Farkas, J. S. Hudson. Trans. ASAE. *23FE*, 1048.

The steam heat transfer coefficient to fresh cut sweet potatoes is calculated from internal temperature measurements. The coefficient is shown to vary with time; decreasing from an initial value in an exponential manner.

MICROWAVE DIELECTRIC PROPERTIES OF FRESH FRUITS AND VEGETABLES. S. O. Nelson, Trans. ASAE. *23FE*, 1314.

The dielectric properties of some fresh fruits and vegetables were measured at 2.45 GHz and 23 °C by the short-circuited coaxial-line technique, and data are presented for the dielectric constant and loss factor of several peach cultivars, two sweet potato cultivars and single cultivars of potato, apple, cantaloupe, and carrot. With the measurement techniques used, no differences in dielectric properties were distinguishable between mature green and full-ripe peaches or between cured sweet potatoes and those that had been subjected to chilling injury after curing for induction of the hardcore condition. The dielectric constant was correlated with moisture content and also appeared to be influenced by tissue density. No correlation was observed between dielectric properties and soluble solids as measured by a refractometer. For better assessment of the usefulness of electromagnetic fields for measurement of fruit and vegetable quality, study of the frequency dependence of the dielectric properties of such materials over a wide range of frequencies is recommended.

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HASSON, E. P. and LATIES, G. G. 1976. Separation and characterization of potato lipid acylhydrolases. Plant Physiol. *57,* 142—147.

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