

DRYING RATE AND DAMAGE TO NAVY BEANS

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ABSTRACT

The effect of drying air temperature and relative humidity on the rate of drying and damage to navy beans was investigated. A thin-layer apparatus was developed to dry beans from an initial moisture content of around 25% to 14% wet basis (w.b.) using temperatures between 32° and 62° C and relative humidities between 7.5% and 45%.

The rate of moisture diffusion from the beans was mathematically defined as a function of drying air temperature and bean moisture content. The degree of bean damage was inversely proportional to the relative humidity of drying air when it was below 26%. No damage was observed for relative humidities greater than 26% for the range of temperatures used. **KEYWORDS.** Grain drying, Beans.

INTRODUCTION

Navy beans are grown in Central Queensland for producing canned baked beans. Bean quality is of the greatest importance as any stained, damaged, split or cracked beans are not suitable for canning. Most staining occurs in the field when rain falls on mature beans and water enters the pods. Staining is the major cause of beans being rejected for canning. Bean damage (splits and cracks) can occur in the field or during harvesting and handling, especially when beans are at low moisture contents.

The normal practice in Queensland is to harvest beans at moisture contents between 15% and 16% w.b. and then dry to 14% w.b.

Two methods are used to harvest navy beans: cutting/windrowing and threshing, or direct harvesting. With the first method, threshing is done either by an auto header fitted with a special pickup front, or by a modified peanut combine. The direct harvesters for navy beans are designed so that the machine pulls the entire plant out of the ground and feeds it into the header. Beans are dried on-farm in batch dryers originally designed for peanut drying, or dried commercially in batch cross-flow dryers. Drying conditions cannot be easily controlled and therefore some of the beans are damaged during the drying process. In Queensland, local varieties of beans are different from

those used in the United States and Canada, and beans are dried to a lower moisture content than in those countries. The price structure is also different with the present value of prime grade at more than 700 \$/t, while rejected grades attract less than 100 \$/t as stock feed.

The aim of this work was to investigate a method for decreasing bean losses by harvesting at a higher moisture content and using a controlled drying, or curing, to bring the beans down to a safe storage moisture content.

THEORETICAL BACKGROUND

Most of the research related to bean harvesting and drying has been done in the United States and Canada. Mechanical damage of beans during harvesting is directly related to moisture content and the method of harvesting. The lowest losses are usually recorded when the pods are 12% to 15% w.b., but the kernel moisture content is high (Narayan and Stout, 1972; Hoki and Pickett, 1973; Pickett, 1973; Singh and Linvill, 1977; Heit, 1983; Otten et al., 1984; Smith and Biere, 1985; Smith, 1986; Radajewski and Gaydon, 1990).

Hutchinson and Otten (1983) recommended the use of an exponential thin-layer equation for modeling the thin layer drying of navy beans. Their equation is:

$$M_t = \exp(-K t^N) \quad (1)$$

where K equals $0.0466 - 0.0104 R_h^2$, N equals $0.04002 + 0.00728 T_d R_h$, and moisture ratio is defined as:

$$M_r = \frac{M_t - M_e}{M_o - M_e} \quad (2)$$

The expression for equilibrium moisture content presented by Henderson (1974) was used:

$$M_e = \left[\frac{-\ln(1-R_h)}{F(T_d + G)} \right]^{1/E} \quad (3)$$

Parameter values were determined from experiments and found to be:

$$G = 190.62 + 10.632 T_d$$

$$F = 0.08855 - 0.002414 T_d + 0.0000224 T_d^2$$

$$E = 1.8033 - 0.0728 T_d$$

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Hutchinson and Otten (1983) reported on the drying of beans from 32.5% d.b. to 17% d.b. They used drying temperatures ranging from 32° to 49° C and relative humidities ranging from 34% to 65%. A one-dimensional spherical diffusion model,

$$\frac{\delta M}{\delta \Theta} = \frac{1}{r^2} \frac{\delta}{\delta r} \left(r^2 D \frac{\delta M}{\delta r} \right) \quad (4)$$

which takes into account temperature and moisture content, has been proposed. Colson and Young (1990) used a diffusion model to describe the thin-layer drying of peanuts and obtained more accurate results than had previously been obtained with thin layer equations like equation 1.

For the spherical diffusion model used in this study the initial conditions ($t=0$) were:

$$\Theta = 0, \quad M = M_0, \quad r_0 \geq r \geq 0$$

and boundary conditions ($r=0$) were:

$$\frac{\delta M}{\delta r} = 0 \quad (5)$$

and at $r=r_0$, from the balance of internal and external moisture flux,

$$-r_0 D \frac{\delta M}{\delta r} = h_m (Y_s - Y_r) \quad (6)$$

The surface mass transfer coefficient, h_m , can be calculated using the method of Keey (1979):

$$h_m = h_c / 1090. \quad (7)$$

As shown by Holman (1986), the heat transfer coefficient is given by:

$$h_c = 0.37 k_f \left(\frac{v d}{v} \right)^{0.6} \quad (8)$$

The surface moisture, Y_s , and local moisture, Y_r , can be defined from the equilibrium moisture content curves defined by equation 3.

The spherical diffusion model (eq. 4) is non-linear since the diffusivity, D , is a function of temperature and moisture content. Bruce (1985) describes a numerical method of solving equation 4 and defined diffusivity as follows:

$$D = \alpha \exp(\beta M) \quad (9)$$

The specific objective of the investigation was to establish the effect of drying conditions on both the rate of drying and grain damage.

EXPERIMENTAL METHOD

The effect of drying conditions on the rate of drying and the quality of beans was investigated using a thin-layer drying apparatus. Accuracy in the control of drying conditions and in the collection of experimental data was the main aim in the design of the apparatus.

DRYING APPARATUS

As shown in the schematic (fig. 1), the amount of air required for drying was delivered by a centrifugal fan (A) driven by a variable speed motor. The air was pumped into an insulated tank (B) in which the water used for humidification was either heated by two 3 kW heaters (C) or cooled by a 0.5 kW refrigeration unit (D). The water flow-rate delivered by the pump (E) to the nozzle (F) was controlled by valve (G). From the tank (B), air passes through the humidification tower (H). At the outlet from the tower the air temperature was equal to the water temperature and had a relative humidity close to 100%. From the humidification tower, air passed through a duct fitted with airflow meter (I). For air heating, 6 kW electric heaters (J), controlled by variable voltage transformer (K) were used.

Air at the required dry bulb temperature was delivered to the valve (M) which could be used to direct the air to chamber (N1) or chamber (N2). During the drying process, air from chamber (N1) passed through an air diffuser (O), the grain sample (P), and was released to the atmosphere. The oil seal (Q) prevented air from by-passing the grain sample. Air was directed to chamber (N2) and column (S) whenever the sample was being weighed by the electronic balance (T). This airflow diversion was done to eliminate the effect of airflow on the balance reading.

For data acquisition and control of the dryer, a logger/controller (Datataker DT 100, Data Electronic Pty. Ltd., Boronia 3155, Australia) driven by a microcomputer was used. A custom-written program in Fortran was used to communicate with the logger/controller and balance. A complete scan of the sensors, with exception of the balances, was done every two seconds.

An electronic balance of 2 kg capacity with 0.01 g resolution (Sartorius L2200S, Sartorius A.G., D-3400, Goettingen, Germany) was used for weighing the grain sample. The maximum expected error of the balance, 0.12% of the reading, was defined using the method of Holman and Gajda (1981). The balance was directly linked with the microcomputer and the mass recording frequency was specified in the input data of the program.

Thermocouples (type T) were used to measure air and water temperatures. Current temperatures were compared with the set values, and the current to the heaters was automatically adjusted if needed.

A hygrometer (Hygrostat 6400, Testoterm D7825, Lenzkirch, Germany) was used to record the relative humidity of the air at the inlet to the drying chamber. The temperature of the bean sample was recorded by infrared thermometer (Model 4301.JA, Everest Interscience Inc., Fullerton, CA 92631 USA).

Average airflow rate was calculated from the pressure drop through the orifice plate designed according to British Standards (1983). Pressure drop was recorded by a

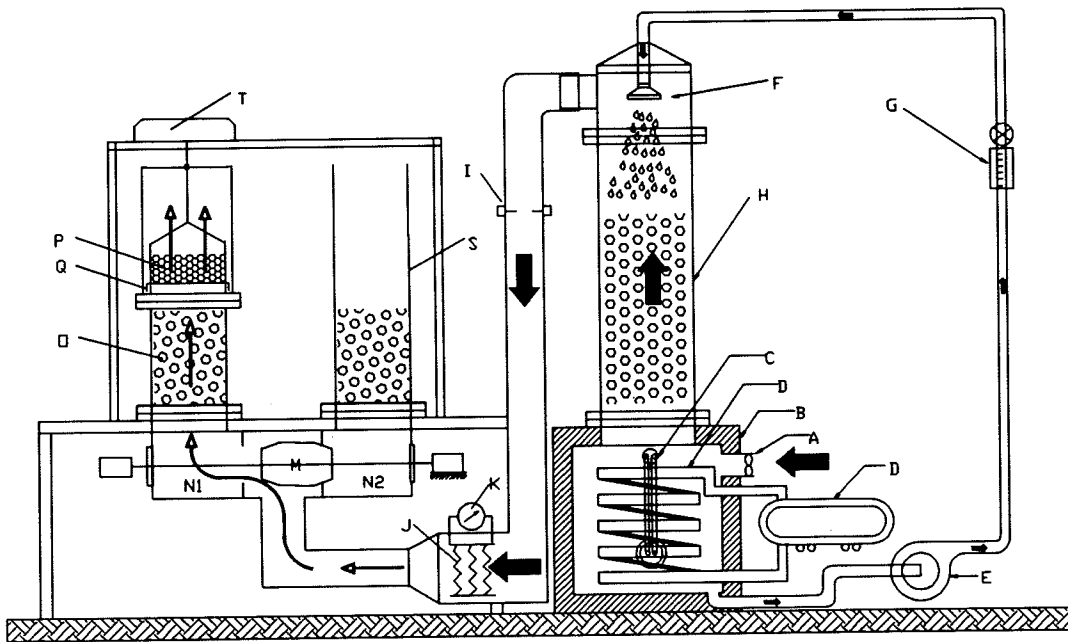


Figure 1—Schematic diagram of thin-layer apparatus. (A) fan; (B) insulated tank; (C) electric water heater; (D) refrigeration unit; (E) water pump; (F) nozzle; (G) water valve; (H) humidification tower; (I) airflow meter; (J) electric air heater; (K) voltage controller; (M) air valve; (N1, N2) air chambers; (O) air diffuser; (P) grain sample; (Q) oil seal; (S) auxiliary column; (T) electric balance.

pressure transducer (WIKA Tronic, AWG & Co., Kongenberg D-8763 Germany).

The drying apparatus was installed in an air-conditioned room, and air from the drying chamber was exhausted to outside the room so there was a minimum change in the surrounding air conditions.

DRYING PROCESS CONTROL

In the experiments, the required humidity of drying air was achieved by initial saturation of the air at the temperature, T_s , defined by:

$$T_s = \frac{273.3 \ln Z}{17.2694 - \ln Z} \quad (10)$$

where Z is a function of relative humidity and temperature of drying air:

$$Z = 1.637 R_h \exp$$

$$\left(72.7294 - 8.2 \ln T_k + 0.00571 T_k - \frac{7237.46}{T_k} \right) \quad (11)$$

and

$$T_k = T_d + 273.15 \quad (12)$$

The humidifying tower exit air temperatures (dry and wet bulb) were measured and were practically equal to the temperature of the water used for humidification.

The required drying air temperature was obtained by modulating the power delivered to the electric air heaters with a thyristor controller. With this control the maximum air temperature fluctuation was $\pm 0.3^\circ \text{C}$ from the set point.

The experimental dryer was capable of producing air at temperatures within the range 5° to 150°C . An air velocity of 1 m/s through the sample was easily achieved and practically no change in this velocity was recorded during the drying process. Typical results for one of the experiments are given in figure 2.

SAMPLE PREPARATION

Samples of navy bean (*Phaseolus vulgaris-Actolac*) were harvested on commercial farms at a moisture content of around 25% w.b. At harvest, the difference in moisture content between beans in various pods can be as much as 20% w.b. depending upon variety and weather conditions. For the experiments, undamaged beans with uniform moisture content were required. Therefore, harvesting and threshing was done manually so pods of similar maturity could be selected and any damage to beans from these operations eliminated. After threshing, the samples were divided into sub-samples (around 150 g) and kept in sealed bags in a cooler at a temperature of around 8°C for at least one week so that the moisture content of all kernels could equalize. No evidence of fungi growth or other changes was observed during storage. After storage, the moisture content was determined by oven drying at 103°C and 72 hours method (ASAE, 1989).

DRYING EXPERIMENTS

Researchers in grain drying generally agree that air velocity has little effect on drying rate (Pabis and Henderson, 1962; Misara and Brooker, 1980; Syarif et al., 1984; and others). A 1 m/s air velocity through the beans was used for all experiments.

The following input data were required to run an individual experiment: initial moisture content, temperature of drying air, relative humidity of drying air and initial mass of sample. The single layer of beans (approximately

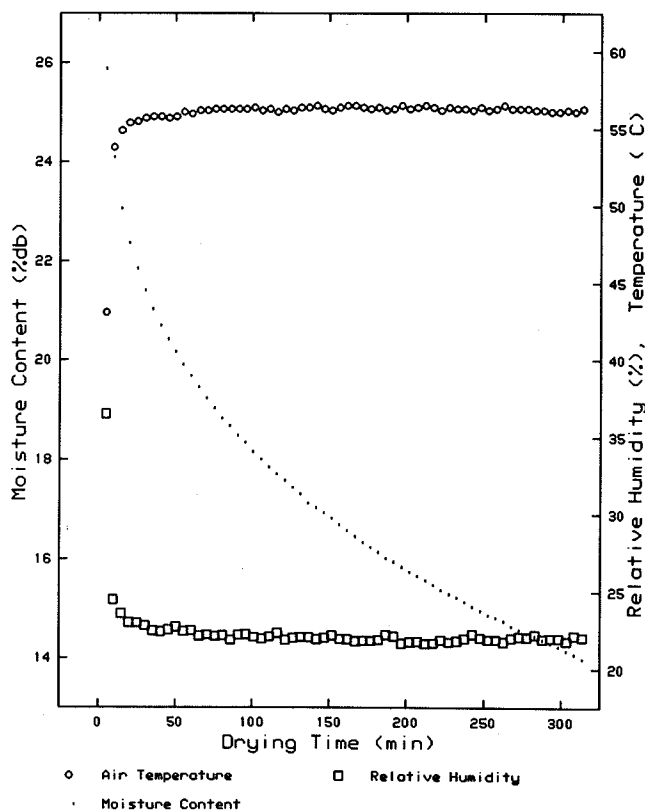


Figure 2—Change of moisture content, relative humidity, and temperature of drying air during the drying process.

150 g), was put into the dryer when stable conditions were achieved, that is, when the temperature of air was within 0.3° C. of the required value.

The time interval between recordings of sample mass was between 10 and 30 minutes and depended on the drying conditions used. At the time when the sample mass was measured, the air flow to the sample was diverted to the auxiliary column (fig. 1) for about three seconds.

Moisture content was calculated after each scan of the balance and when it reached the required final level (within the range 14.25% to 13.75% w.b.) drying was stopped automatically. Dried samples were sealed in plastic bags and sent for standard commercial quality testing (Heit, 1983) by the Navy Bean Board.

ANALYTICAL METHODS

The experimental data was used to develop a mathematical relationship which could predict the total time of drying at a full range of temperatures and relative humidities used in the experiments. Equation 4 combined with equation 3 was solved numerically (finite difference) for the boundary conditions as defined by equations 5 and 6.

Diffusivity was obtained interactively by comparing the experimental drying times with the model prediction. The multiple regression used to define diffusivity for the whole range of the experimental data is:

$$D = A \exp(B + (0.05572 + 0.001591 T_d) M_a) \quad (13)$$

where

$$A = 0.02488 (90.89 - T_d) \quad (14)$$

$$B = -11.0854 + 0.0529327 T_d - 0.000117277 T_d^2 \quad (15)$$

RESULTS AND DISCUSSION

A summary of the results for the 42 experiments is given in Table 1. Drying time ranged from 171 minutes when the air temperature was 60.9° C and relative humidity 7.6% to 1095 minutes when the air temperature was 34.7° C and relative humidity 45.7%.

A plot of diffusivity as a function of moisture content and temperature (fig. 3) shows that D varies with moisture content and temperature over four orders of magnitude. It should be noted that the function for D (eq. 13) was correlated with average grain moisture content, M_a , instead of the local moisture content within the kernel. This approach was necessary, since it was not possible to measure local moisture content.

TABLE 1. Summary of drying experiments

Sample No.	Air Conditions		Drying Time t (min)	Grain Damage	
	T_d (°C)	R_h (%)		Cracks (%)	Splits (%)
1	33.8	24.1	825	3.17	0.00
2	33.7	24.5	783	0.69	0.00
3	34.7	35.4	922	0.00	0.00
4	34.5	35.7	925	0.00	0.00
5	34.7	45.7	1095	0.00	0.00
6	34.6	45.6	1006	0.00	0.00
7	34.3	46.5	1077	0.00	0.00
8	43.3	16.3	464	23.6	0.24
9	43.4	16.3	455	23.5	0.24
10	44.2	16.2	459	23.1	0.00
11	42.3	23.0	533	1.58	0.04
12	43.9	21.0	473	3.07	0.00
13	44.5	35.6	510	0.00	0.06
14	44.8	35.1	541	0.29	0.00
15	45.9	42.6	531	0.00	0.00
16	45.1	43.9	602	0.00	0.00
17	40.7	39.7	506	0.00	0.00
18	54.0	10.5	238	28.20	0.00
19	54.8	10.2	263	32.67	0.00
20	55.5	14.5	245	28.60	0.00
21	53.7	15.9	281	17.04	0.00
22	52.4	22.5	340	2.18	0.00
23	53.4	21.4	314	2.43	0.00
24	56.0	32.7	312	0.00	0.00
25	55.3	33.8	309	0.00	0.00
26	57.1	39.8	321	0.00	0.00
27	56.2	41.1	320	0.00	0.00
28	51.3	23.8	310	5.71	0.00
29	61.9	12.2	158	17.56	0.00
30	62.8	12.4	179	27.25	0.00
31	38.6	23.3	510	6.19	0.00
32	38.5	22.7	525	8.98	0.36
33	43.5	16.1	382	18.27	0.00
34	44.4	15.5	423	19.45	0.32
35	43.7	21.2	403	10.27	0.1
36	44.6	20.3	383	15.39	0.00
37	49.4	13.3	294	21.75	0.2
38	54.7	10.1	224	31.72	0.38
39	54.9	20.1	252	12.63	0.00
40	54.8	10.1	226	28.64	0.00
41	54.9	15.0	554	21.81	0.07
42	60.9	7.6	171	34.17	0.00

Typical drying curves obtained with the Hutchinson model (eq. 1) and the Diffusion model (eq. 4) are compared to experimental data in figures 4 and 5.

There was good correlation between the experimental data and computed results from both the Diffusion and Hutchinson models at $T_d = 46^\circ\text{C}$, $R_h = 42\%$ (fig. 4). When drying conditions were outside the range specified for the Hutchinson model, good correlation with the experimental data was given with the Diffusion model (fig. 5).

It should be noted that the drying model will lose its accuracy with decreasing moisture content as the tail of the drying curve flattens out. This occurs because a small change in moisture content can result in a large variation in predicted drying time. However, for a specified time of drying, the uncertainty in the computed final moisture content will be less than 0.2% w.b.

Figure 6 shows the relationship between the temperature of drying air and the total time of drying obtained from experimental data.

At low air temperatures relative humidity has a greater influence on the total drying time than at higher air temperatures. At high drying air temperature (55°C), the drying time increases little with an increasing relative humidity (fig. 7), however, at a low drying air temperature the drying time increases as humidity increases.

The drying time becomes shorter with decreasing relative humidity if the temperature of drying air is between 35° and 45°C . However, at a temperature of 55°C , there is a minimal difference in the time of drying for the whole range of the relative humidities. This effect is explained by the fact that at low temperatures, for a given

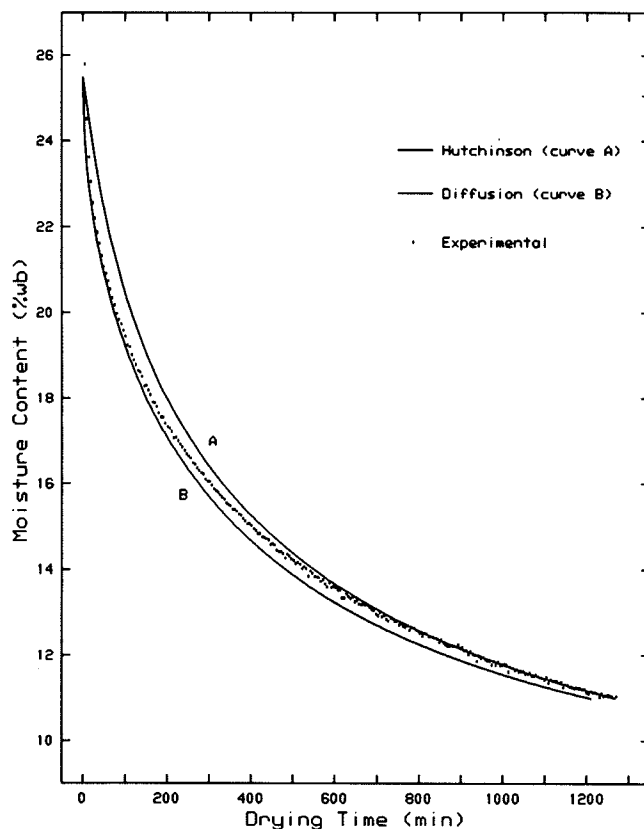


Figure 4—Experimental and computed drying curves for $R_h = 42\%$; $T_d = 46^\circ\text{C}$.

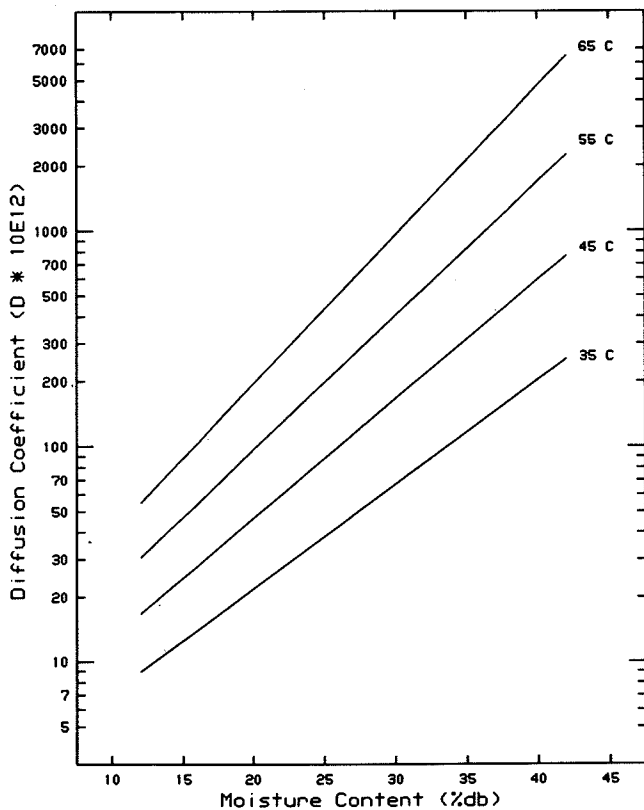


Figure 3—Diffusivity as a function of moisture content at different temperatures.

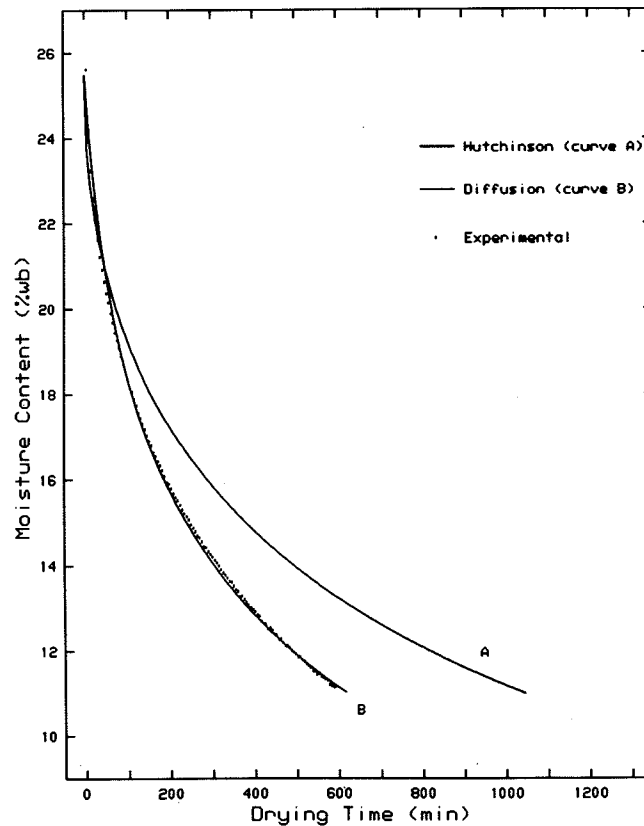


Figure 5—Experimental and computed drying curves. $R_h = 21\%$; $T_d = 54^\circ\text{C}$.

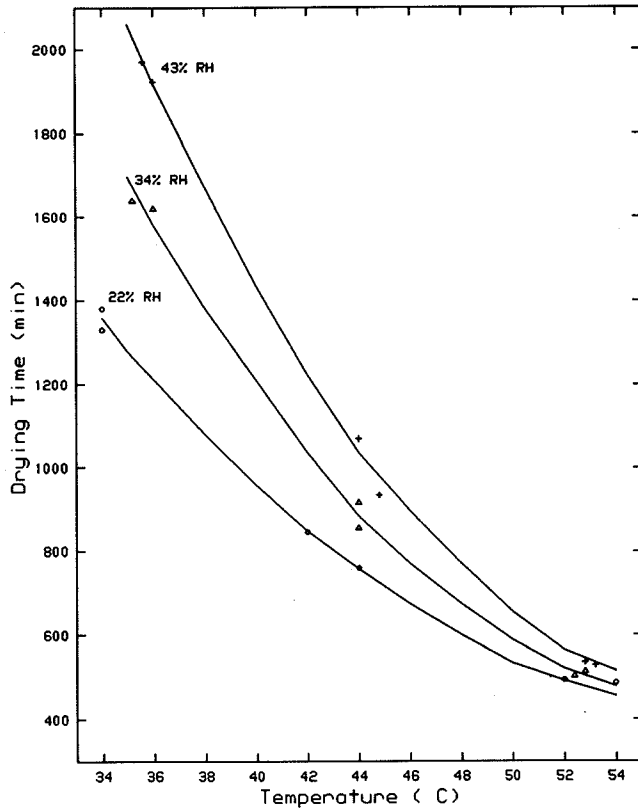


Figure 6—The relationship between temperature and relative humidity of drying air and the total drying time at different relative humidities for experimental data points and lines of best fit.

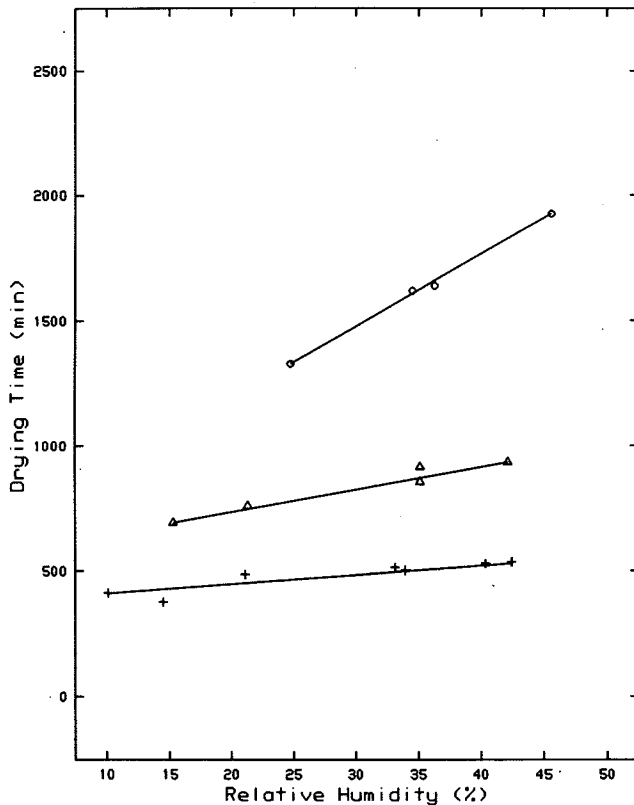


Figure 7—The relationship between relative humidity of drying air and the total drying time at different air temperatures for experimental data and lines of best fit.

product moisture content, the effect of surface humidity on drying potential is low. Thus the conditions of the surrounding air at low temperature affect the rate of drying much more than at high temperature.

BEAN DAMAGE

As reported by Hutchinson and Otten (1983), the major factor affecting the degradation of bean during drying is the relative humidity of drying air. Figure 8 shows the percentage of damaged kernels after drying as related to the relative humidity of drying air. A linear regression line ($r^2 = 0.883$) was fitted to the experimental data (eq. 16) so an approximate degree of bean damage could be predicted. Damaged beans are defined as those that are cracked and split and therefore are not acceptable to the food processing industry.

$$C_r = 49.72 - 191.23 R_h \quad (16)$$

The above equation is valid for relative humidities between 7.5% and 26%. For relative humidities above 26%, $C_r=0$, and humidities below 7.5% were not investigated because they have no practical value due to the extensive bean damage. Figure 8 also shows percentage of bean damaged as recorded by Otten et al. (1984). These data vary considerably from that presented in this study. Since the experimental conditions in both studies were similar, the variation in bean damage may be due to different varieties used and possibly difference in definition of damage.

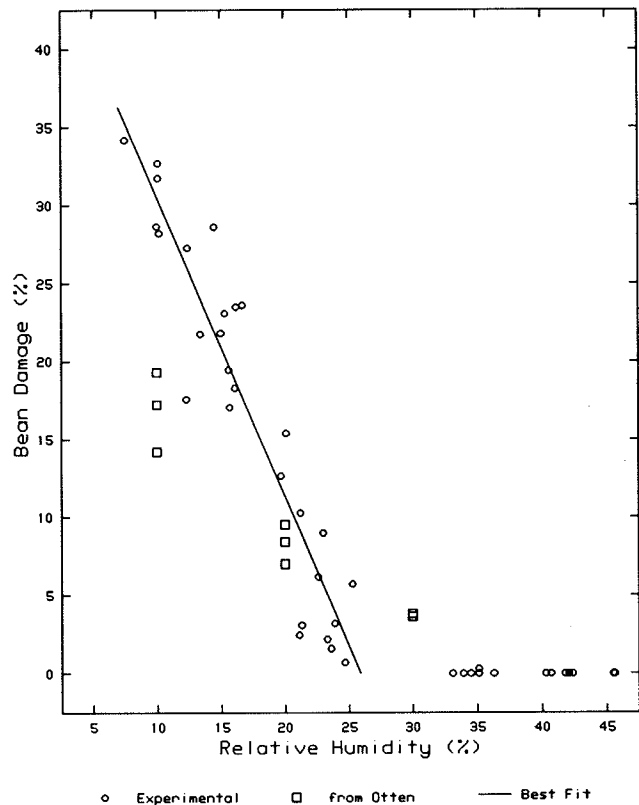


Figure 8—The effect of the relative humidity on bean damage for the full range of temperatures used in experiments.

As shown in the previous section, the temperature of drying air is the major factor affecting the drying rate. Therefore, the degree of bean damage is not related to the average rate but to local rate (surface) of moisture removal from the beans.

Figure 9 shows the moisture content of the surface and average bean moisture content at different relative humidities of the drying air.

Figure 10 shows computed moisture profile within the bean kernel dried at different relative humidities. Both figures show that the surface moisture content drops rapidly to the equilibrium moisture content. Low humidities imply low moisture contents and therefore high drying rate of bean near the surface.

It is believed that the cracking results from the steep moisture gradients and accompanying shrinkage stress occurring near the surface. However, because of difficulties in measurement of moisture profile there is a lack of experimental data for grain and it is not known how precisely moisture profile is predicted.

SUMMARY AND CONCLUSIONS

A thin-layer drying apparatus was developed and used for establishing the relationship between drying conditions, rate of drying, and degree of navy bean damage.

A one-dimensional spherical diffusion equation was developed using the experimental data which take into account temperature and moisture content of the kernel. Use of this equation allows prediction of the drying time within a range of drying conditions wider than previously reported by other researchers.

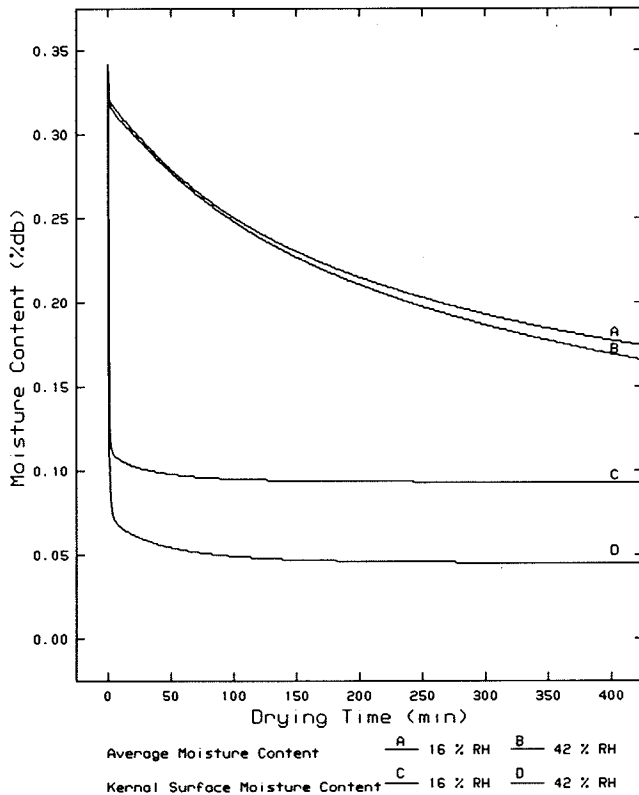


Figure 9—Average and surface moisture loss as predicted by the diffusion model at different relative humidities.

Drying beans from a moisture content as high as 25% w.b. at air temperatures between 32° and 62° C had no effect on bean damage, and when relative humidities of drying air was above 25%, no cracks were recorded.

It is difficult, if not impossible to measure the transit moisture and temperature within a bean and thus draw concrete conclusions about the relationship between these variables and cracking. For the present we must be satisfied with a quantitative description of the phenomena.

The extent of grain damage is directly related to the relative humidity of drying air. The temperature of air and hence the rate of drying has little effect on the quality of the final product. On the other hand, the rate of drying is directly related to the temperature of drying air. This means that a high rate of drying can be achieved by using temperatures around 60° C without damage to the grain if the relative humidity of air is kept above 25%. This can be achieved by recirculating part of the air used for drying. This principle may be applicable to drying other kernels such as peanuts, soybeans and other legumes.

From this study it appears that bean variety may be a significant factor affecting bean damage. Further investigations are required to verify the correlation between variety and damage, and to assess the relationship between shrinkage and surface moisture content.

Investigation is also required to determine the optimum harvesting and drying methods for high moisture content beans, which will reduce overall bean damage.

The scope of this investigation was limited to drying temperatures in the range of 32° to 62° C and relative

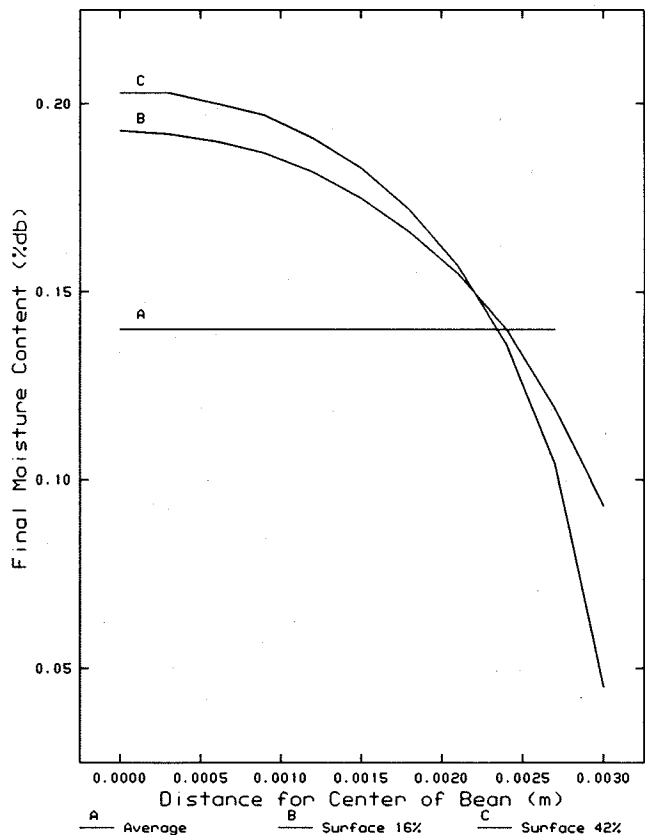


Figure 10—Profile of moisture content within the bean kernel after drying as predicted by the diffusion model.

humidities of 7.5% to 45%. As high drying rates can be achieved for temperatures in excess of 62° C, the effect of these temperatures and hence relative humidity on bean damage needs to be investigated.

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NOTATIONS

- A parameter in equation 13
- B parameter in equation 13
- C_r percentage of bean damage (%)
- d diameter (m)
- D diffusion coefficient (m^2/h)
- E parameter in Henderson's EMC equation
- F parameter in Henderson's EMC equation
- G parameter in Henderson's EMC equation
- h_c heat transfer coefficient ($W m^{-2} K^{-1}$)
- h_m mass transfer coefficient ($kg m^{-2} s^{-1}$)
- k_f thermal conductivity of film condition ($W m^{-2} ^\circ C^{-1}$)
- K parameter in exponential equation 1
- M moisture content d.b.
- M_a average moisture content d.b.
- M_e equilibrium moisture content d.b.
- M_o initial moisture content d.b.
- M_r moisture ratio M_t
- N parameter in exponential equation 1
- r kernel coordinate (m)
- r_o kernel radius (m)
- R_h relative humidity (decimal)
- t time (min)
- T_d drying temperature ($^\circ C$)
- T_k drying air temperature ($^\circ K$)
- T_s saturation temperature ($^\circ K$)
- v free stream velocity ($m s^{-1}$)
- Y_r local moisture fraction
- Y_s surface moisture fraction
- Z parameter in equation 10
- α parameter in equation 9
- β parameter in equation 9
- ρ density of air (kg/m^3)
- Θ time (s)
- v thermal diffusivity ($m^2 s^{-1}$)

