Cereal Chemistry

The Absorption of Water by Ground Barley Malt

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ABSTRACT

Measurements have been made of the uptake of water vapor by malt particles. The diffusivities determined for the vapor system are not highly temperature-dependent. Diffusion coefficient, $D = 1.6 \times 10^{-8}$ cm.^{2} sec.$^{-1}$ at 20°C. and activation energy, $E = 6.22$ kcal. mole^{-1}. Measurements have also been made of the rate of absorption of liquid water by malt particles. The rapid initial uptake of liquid water seems to be a combination of surface capillary absorption and rapid diffusion into surface excrescences which provide relatively high surface areas. The diffusion coefficient for liquid water, $D = 3.6 \times 10^{-7}$ cm.^{2} sec.$^{-1}$ while the activation energy was zero. The data of Fan, Chu, and Shellenberger for popcorn were recalculated and gave almost identical results to those obtained with sieved malt fractions.

In the system of extraction of malt with water, diffusion processes can be rate-limiting when the malt is coarsely ground. Therefore, it is desirable to determine the rate of uptake of water by malt particles. The process of absorption or desorption of liquids by vegetable tissue has been described as a diffusional process (1,2). Fish (3) obtained a value of 2.4×10^{-7} cm.^{2} sec.$^{-1}$ at 25°C. for the diffusion coefficient of water in starch gel. Lawrence and Scott (4) gave values of the order of 10^{-6} cm.^{2} sec.$^{-1}$ for the diffusivity of water in raw potato at 25°C., which may be compared with the diffusion coefficient for self diffusion of water, 2.04×10^{-5} cm.^{2} sec.$^{-1}$ determined by Graupner and Winter (5). Measurements of the diffusivity of water in cereal grain tissue have been limited to whole grains, with particular emphasis on the relatively low moisture conditions experienced in the processes of tempering or drying grain. Becker and Sallans (6,7) obtained for the drying of wheat kernels diffusion coefficients from 0.069×10^{-6} up to 2.77×10^{-6} cm.^{2} sec.$^{-1}$ in the temperature range from 20° to 80°. Energies of activation of 12,920, 14,600, and 16,300 calories per mole were calculated from their data and that of Jones (8). Becker (9) also applied the model of diffusion into a slab for shorter exposure times. In considering the absorption of water by wheat kernels he found (10) that following a small initial rapid absorption of water by the pericarp of the grain, the subsequent absorption could be described by the slab model up to a moisture gain of 0.75 g. per g. of wheat. Diffusion coefficients for a number of wheat varieties were in the range 1.8 to 3.3×10^{-8} cm.^{2} sec.$^{-1}$ Fan et al. (11,12)

measured diffusion coefficients over a wide range of moisture contents and temperatures for wheat, corn, and sorghum, arriving at substantially the same values as Becker (10).

No diffusion coefficient is available for the movement of water through barley malt endosperm. This paper reports measurements for absorption of water vapor and of water.

MATERIALS AND METHODS

Barley malt grains were dehusked according to the procedure of Pollock et al. (13). Detailed preparation of the specimens is reported by Meddings (14). Coleoptiles, husk layers, and testa were removed with minimum damage to the endosperm. Slicing down the valley of the ventral furrow provided two endosperm pieces of almost cylindrical shape which required little further slicing to produce cylinders. The aleurone layer was removed in its entirety. After shaping, the cylinders were dried over silica gel. The dimensions were measured from a magnified image.

Measurement of Water Vapor Absorption

Rate of uptake of water was measured in an automatic electrobalance in a vacuum chamber housed in an incubator with temperature controlled to $\pm0.02°C$. After calibration of the balance, the sample was suspended on a wire over silica gel, the chamber closed, and the temperature maintained at the desired value. It was assumed that after equilibration the moisture content of the sample was approximately zero. After equilibrium was reached — usually about 24 hr. — the silica gel was replaced by saturated potassium sulfate solution (15), the partial pressure of water vapor over such solutions being very nearly the same as for pure water, and the chamber evacuated. In some experiments, photographs were taken to correlate change in size with moisture content. Evacuation was not in fact necessary. Changes in weight of 0.01% of the endosperm weight were readily estimated.

Initial Water Uptake by Sieved Malt Fractions

A known weight of malt was stirred in a beaker with water for a definite time, then poured rapidly onto a filter paper in a Büchner funnel and filtered. The stage at which interstitial water between malt particles disappeared could be observed, usually between 5 and 10 sec. after commencing filtration. At this stage, the malt bed, which was no more than one particle deep, was blotted lightly on top with another filter paper to remove excess surface moisture. It was then rapidly scraped onto a watch glass and dried at 105°C. to constant weight. The contact time with liquid water was regulated to 30 sec. The above experiments were repeated in a vacuum system so that the particles were gas-free.

Water Absorption by Sieved Fractions of Ground Malt

Barley malt grains were dehusked according to the procedure of Pollock et al. (13) and ground in a domestic coffee mill. Coleoptiles were removed by winnowing in a stream of warm air. The ground particles were sieved to the required fractions in a gyratory sifter and the fractions were then allowed to equilibrate to a uniform moisture content in sealed containers. It was observed that the above procedure did

reduce the α-amylase activity of the malt and subsequently the degree of conversion during mashing. Although fortuitous this was desirable because it reduced the influence of leaching during the final stages of water absorption, thus allowing the latter to be studied meaningfully over a longer period.

RESULTS

Water Vapor

Curves indicating the weight of cylinders of malt endosperm suspended in an atmosphere of controlled humidity at different temperatures were obtained from the data listed in Appendix B. The equilibrium moisture content C_∞ cannot be obtained by employing long times due to factors such as endogenous biochemical activity or contaminative fungal activity. The volume of the endosperm increased as shown in Fig. 1. The results qualitatively confirm Becker's observation for wheat that the increase in volume caused by water absorption is proportional to the amount of water absorbed.

The characteristics of water vapor absorption varied from sample to sample. In Fig. 2 it is clear that different equilibrium moisture content applied in experiments 3(a) and 3(b) even though the runs were conducted at the same temperature. Also Fig. 2 illustrates that the rate of water absorption after 20 hr. varied between samples. The reason for these variations is believed to be the variability of the malt grains — in some grains where little growth occurs during malting, the starch and protein remain virtually unchanged, whereas in well-grown grains a large proportion of the starch and protein is converted into dextrins, sugars, and peptides. Some of
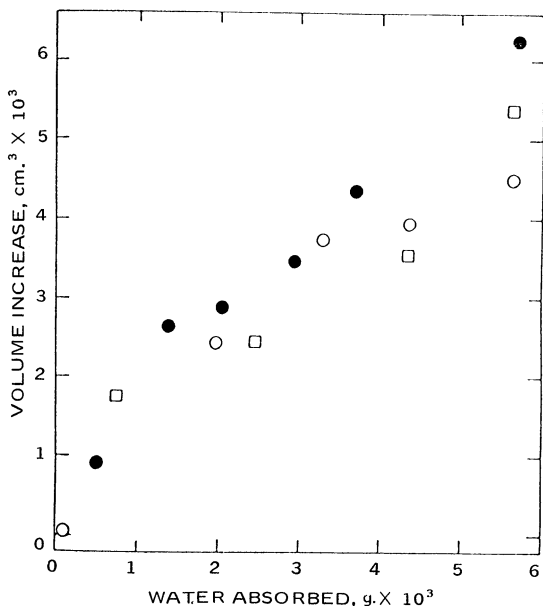

Fig. 1. Increase in volume of three samples of malt endosperm cylinders during water absorption.
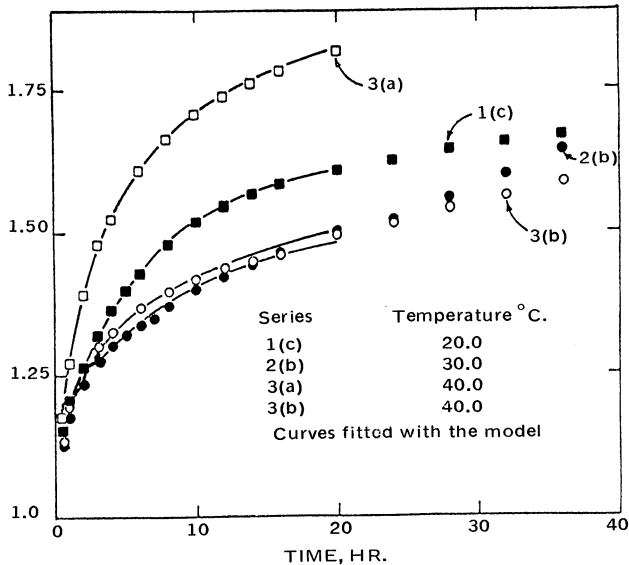
Fig. 2. Water absorption by cylinders of malt endosperm. The numerals 1, 2, and 3 refer to the three different temperatures employed, whereas (a), (b), and (c) refer to separate runs at a particular temperature.

these materials are hygroscopic and it was noticed that with some samples after long times the components of the endosperm dissolved in the water absorbed and the cylinders lost their shape.

Method of Calculating Diffusivity from the Data

There were two possibilities available. The one chosen was to proceed to calculate D on the initial dimensions of the particle, i.e., neglecting the swelling. A more correct value of D would take account of the swelling by describing in detail the local swelling rates at any particular state of the system. This more correct value of D would then be dependent on an accurate knowledge of the swelling phenomenon before the rate of uptake of water could be calculated. This difficulty is overcome by ignoring the swelling in the calculation of D, so that, given D, the rate of uptake of water can be simply calculated without resort to a detailed knowledge of the phenomenon of swelling.

A further problem is that in the long run the particles became liquid masses, so that the equilibrium concentration could not be obtained by allowing long times. At longer times the effect of hygroscopic components becomes evident. Also endogenous biochemical activity, e.g., hydrolysis of starch and dextrins by amylases, occurs at higher moisture contents. In addition, there was evidence of contaminative fungal activity. Hence C_∞ was one of the parameters to be extrapolated from the data. In fact a nonlinear least squares algorithm (14) was employed to determine simultaneously the values of D and C_∞ which best fitted the data.

As discussed briefly above, the water absorption at long times, say 40 hr., could

TABLE I.   DIFFUSION COEFFICIENTS FOR MALT ENDOSPERM
SUSPENDED IN WATER VAPOR

Experi-ment	Temp. °C.	C_∞ % of Dry Weight	D cm.^{2} sec.$^{-1}$ $\times 10^8$	Standard Deviation of D[a] $\times 10^8$	% of Variance Explained by Model
1(a)	20.0	74	1.3	0.2	99.0
1(b)	20.0	55	2.3	0.3	97.3
1(c)	20.0	81	1.4	0.6	99.8
2(a)	30.0	87	2.5	0.2	99.0
2(b)	30.0	52	3.4	0.3	99.4
2(c)	30.0	60	1.8	0.3	98.3
2(d)	30.0	60	2.4	0.3	96.1
3(a)	40.0	88	4.4	0.6	97.4
3(b)	40.0	45	5.4	0.5	99.2
3(c)	40.0	76	2.8	0.4	95.3
3(d)	40.0	41	3.1	0.6	98.1
4(a)	50.0	73	3.0	0.6	97.6
4(b)	50.0	64	3.7	0.6	96.4
5(a)	67.0	51	5.8	0.6	95.6
5(b)	67.0	46	10.3	0.8	98.3

[a] Linear approximation.

not be employed. It was found that if only the initial 10 hr. were used, insufficient information was available to obtain a reliable estimate of C_∞. It was found that the first 20 hr. of an experiment gave sufficient information to evaluate satisfactorily both D and C_∞. One can approach this differently and suppose the regression for D and C_∞ to be carried out using the data for different experimental times. Then for very short times the errors are large because the number of experimental points is few, and also for very long times for the reasons discussed. There is then some optimum time for the experiment at which errors are least. It is considered that this optimum time is about 20 hr. for the experiments described here.

This standard time of 20 hr. was used to calculate D and C_∞ for all sets of data and the assumption was made that the additional effect experienced at longer times had no influence at times less than 20 hr., or alternatively that D represents an effective diffusivity which empirically describes all mechanisms of water absorption during the first 20 hr.

TABLE II.   SENSITIVITY OF D TO VARIATION OF PARAMETERS

Parameter(s)	Value 1	Value 2	Change, % of Parameter	D 1	D 2	Change in D %
C_∞	75%	100%	33	1.85	1.10	−42
	75%	64%	−14.7	1.85	3.50	84
R_c	0.095	0.085	−10.5	1.85	1.54	−16.7
	0.095	0.105	10.5	1.85	2.18	17.8
R_c and L	R_c, 0.095	0.085	−10.5	1.85	1.64	11.4
(constant	L, 0.1770	0.2210	+24.9			
volume)	R_c, 0.095	0.105	10.5	1.85	1.99	7.6
	L, 0.1770	0.1448	−18.2			

Results - Water Vapor

The results obtained for D and C_∞ are given in Table I. Shown also is the percentage of the variance that is explained by the model and the estimate, by linear approximation, of the standard deviation. The model is particularly sensitive to variations in C_∞. This was shown by using the set of data from experiment 1(a) and estimating D for different values of C_∞, R_c, and L, where R_c and L are the radius and half-length respectively of the cylinder. Results are given in Table II and indicate that the most significant influence is that of changes in C_∞.

The activation energy was obtained by assuming a relationship of the form

$$D = D_0 \exp(-E/R_g T) \qquad (1)$$

where   E = energy of activation
                R_g = the gas constant
                T = absolute temperature

and determining the best fit using weighted least squares in a graph of *ln* D vs. 1/T. This gave:

$$D_0 = 6.76 \times 10^{-4} \text{ cm.}^2 \text{ sec.}^{-1}$$

$$E = 6.215 \text{ kcal. mole}^{-1}$$

and the best values of D were determined as

Temperature °C.	D cm.^{2} sec.$^{-1}$ $\times$ 10^8
20	1.6
30	2.4
40	3.4
50	4.7
67	8.0

Absorption of Liquid Water by Ground Malt

The initial stage of water absorption by ground malt is very rapid, corresponding to the type of behavior that Becker described as possibly due partly to capillary action and partly to the penetration of water along cracks and flaws in the endosperm. To obtain some idea of the nature and size of possible flaws in the endosperm of barley malt, photographs were taken of 4μm. sections through barley malt grain. The contents of the grain are quite compacted and there is noo evidence of cracks or crevices down to a size of 5 μm. The cell walls of the endosperm are still clearly defined. In Fig. 3 are reproduced a number of photographs of particles of ground malt that were dropped into I_2/KI solution for 15 sec., dried, and sliced. It can be seen that the liquid front is relatively even and there is no sign of deep penetration through "cracks"; the ground malt particle (f) was in two pieces only loosely attached before absorption occurred.

In defining the model, it was assumed that the malt particles were spherical, radius R, homogeneous, isotropic, and with fixed boundaries. The initial absorption
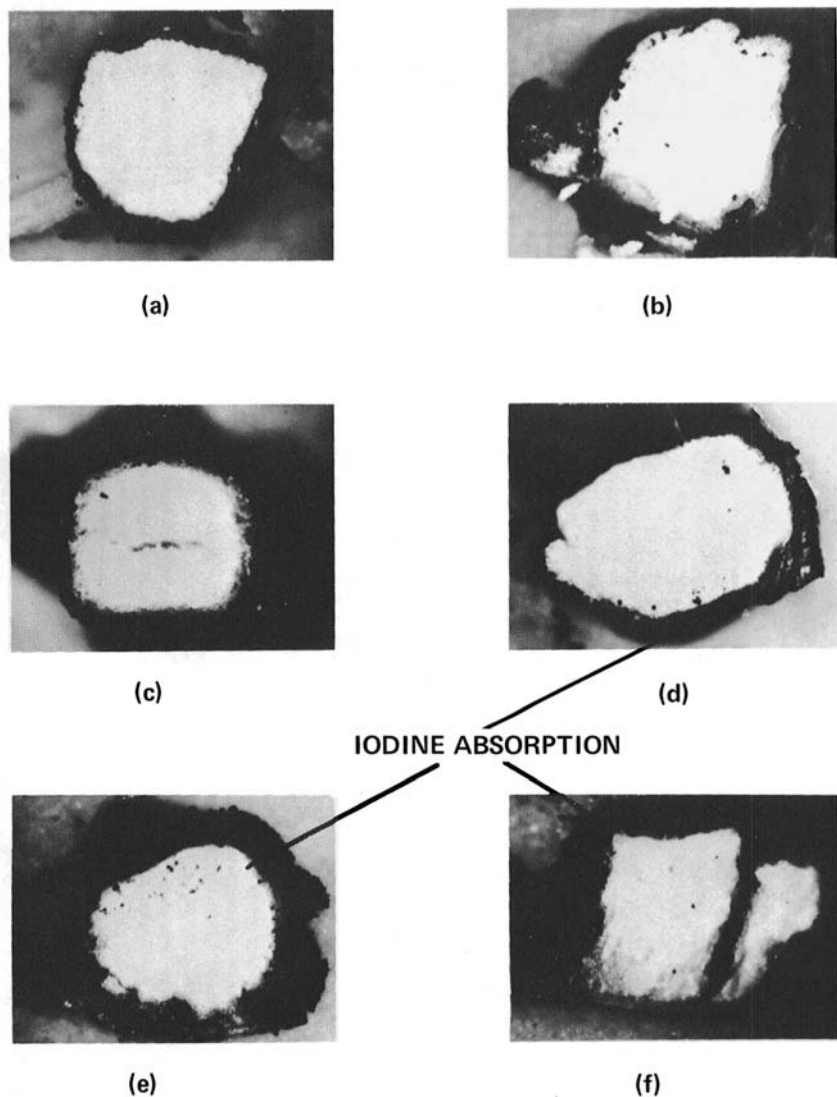
(a)

(b)

(c)

(d)

IODINE ABSORPTION

(e)

(f)

Fig. 3. Absorption of iodine solution by ground malt. Particles after immersion for 15 sec. (20 ×). Initial moisture content = 0.069 g. per g. dry malt.

stage was considered to produce rapidly an annulus of wetted malt, inner-radius R_d with a moisture content equal to the equilibrium moisture content C_∞ of the malt under the conditions being studied. After the initial absorption stage, further absorption was assumed to obey the diffusion equation.

Method of Assessing Diffusivity and Initial Absorption

Water absorption experiments were conducted with a number of sieved fractions
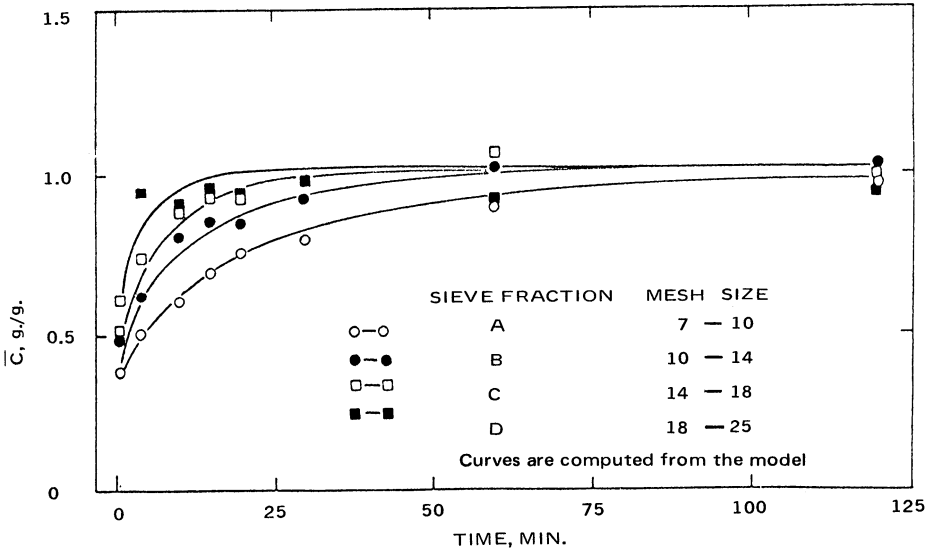
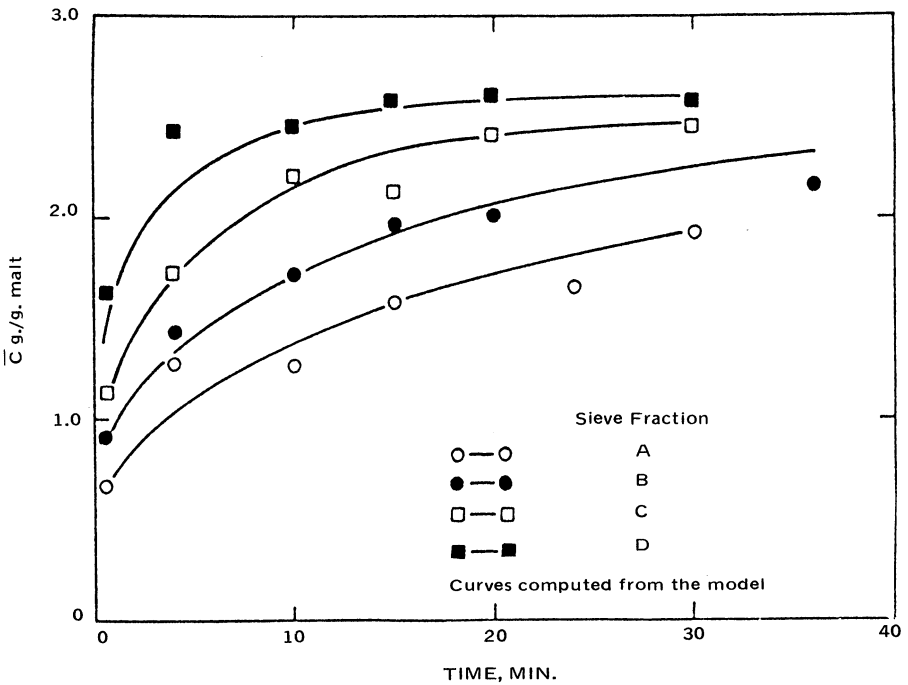**Fig. 4. Average water absorption (C̄) by ground malt at 18.0°C. Initial moisture content = 0.069 g. per g. dry malt.**

Fig. 5. Average water absorption (C̄) by ground malt at 67.0°C. Initial moisture content = 0.069 g. per g. dry malt.
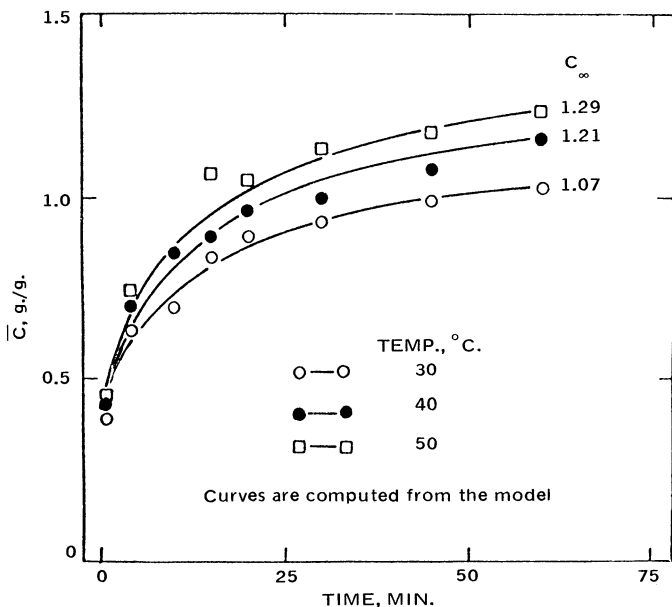
Fig. 6. Average water absorption by grind B at different temperatures. Initial moisture content = 0.069 g. per g. dry malt.

of ground malt at $18°$ and $67°C$. and for one fraction also at $30°$, $40°$, and $50°C$. (see Appendix C).

The calculation of D depends on the value assumed for C_i, the concentration of water in the whole sphere after the initial instantaneous absorption, so in evaluating D_0 and E a nonlinear least squares multi-variable computer program was employed. The computed best-fit values for all the experimental data gave:

$D_0 = 3.6 \times 10^{-7}$ cm.^{2} sec.$^{-1}$ S.D. $= 0.13 \times 10^{-7}$

$E = 0.0$ kcal. mole^{-1} S.D. $= 0.07$

i.e., using estimates of C_∞ from the water absorption data at long times the effective diffusivity calculated from the theoretical model is independent of temperature.

Figures 4, 5, and 6 show that the calculated results obtained from the model are a reasonably good fit for the experimental data and that the model provides an adequate description of water absorption by particles of different sizes.

Becker and Sallans (16) suggest that in wheat drying there is a large increase in the diffusion coefficient in passing through moisture contents of 10 to 12%, dry basis. In the present work no discontinuity or change of character appeared but moisture contents of this order were reached so rapidly that this work cannot strengthen or deny Becker and Sallans' finding.

Initial Absorption of Water

Values of $\overline{C}_{1/2}$, the average concentration of water in the sphere after absorption
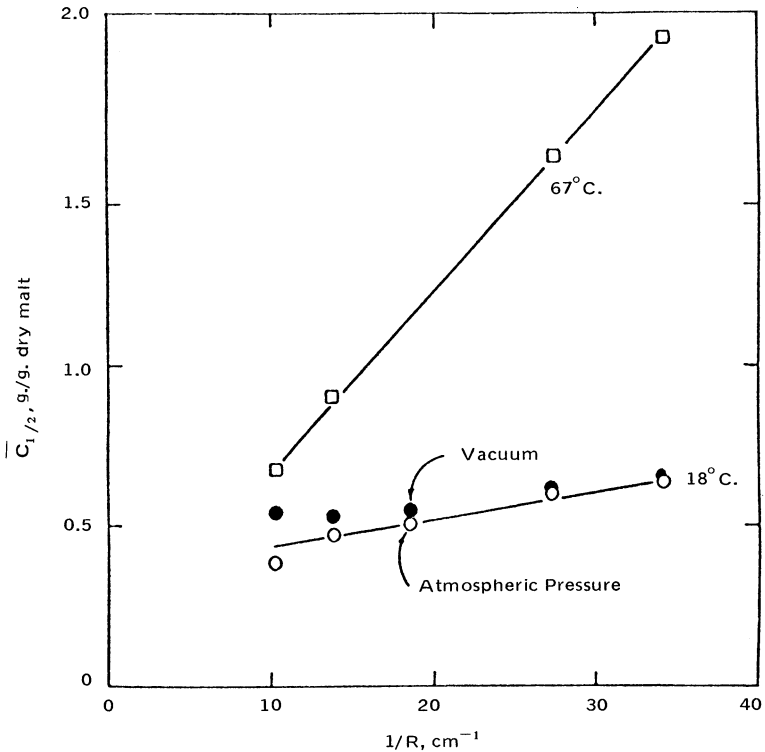
Fig. 7. The effect of particle size on water absorption during the first half-minute of wetting $C_{1/2}$**. Initial moisture content = 0.069 g. per g. dry malt.**

for 0.5 min., are plotted in Fig. 7 for all sieved fractions at 18° and 67°C. Indicated also are the results obtained at 18°C. when the 0.5-min. measurements of water absorption were conducted in a vacuum chamber so that the malt particles were initially under vacuum and water was then added to them under vacuum. The use of evacuated particles yielded results only fractionally higher than for experiments conducted at atmospheric pressure.

Data of Fan, Chu, and Shellenberger

The original data of Fan et al. (11) have been recalculated by the methods employed here, estimating C_∞ from the weight of samples after long periods of immersion. At the higher temperature, 71°C., C_∞ was chosen arbitrarily as 1.30. D_O and E were estimated to be:

D_O 3.5×10^{-7} cm.^{2} sec.$^{-1}$ S.D. = 0.08×10^{-7}

E   0.0 kcal. mole^{-1} S.D. = 0.08

The curves calculated from the model appear in Fig. 8, which shows the data of Fan et al. (11). The fit is good, suggesting that the equilibrium moisture content is temperature-dependent and the effective diffusivity is independent of temperature (in the narrow temperature range investigated).
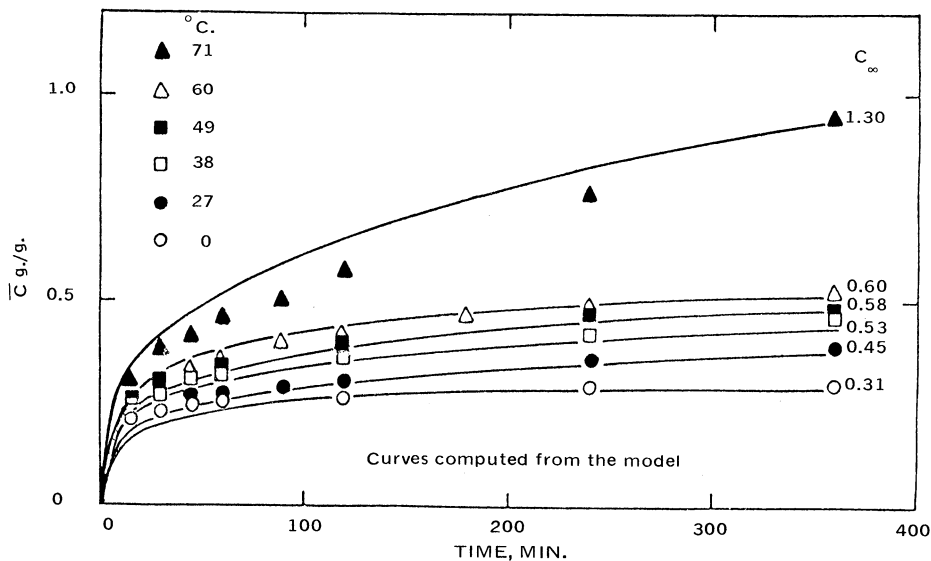
Fig. 8. Data of Fan et al. (11) for water absorption by popcorn. $D_o = 3.5 \times 10^{-7}$ cm.^{2} sec.$^{-1}$.

TABLE III.   WATER ABSORPTION BY COARSELY
GROUND MALT, 67°C.

Time min.	Water Absorption g./g. Dry Malt	
	Experimental	Calculated
0.4	1.05	1.18
4	1.58	1.60
10	1.61	1.89
15	1.81	2.02
20	1.84	2.11
30	2.00	2.25

Water Absorption by Ground Malt

If the particle-size distribution of unsieved ground malt is known, water absorption can be calculated by summing the contribution of the different sized fractions. The size analysis of a coarsely ground malt was determined and the water absorption estimated from the foregoing. Experimental and predicted results agreed reasonably well: after 4 min. to less than 2%, after 30 min. to 12.5%. Some differences might have been expected, because the coarsely ground malt contained the husk, whereas the calculated results are for dehusked grain. The results are given in Table III.

CONCLUSIONS

The effective diffusivity of water in malt endosperm suspended in water vapor can be computed by fitting the appropriate model to the experimental data using a least squares algorithm. The most satisfactory method is to fit D and C_∞ simultaneously.

The diffusivities determined for the vapor system are not highly temperature-dependent—$E = 6.22$ kcal. mole^{-1}.

The liquid front observed during water absorption from liquid by irregularly shaped ground malt particles was relatively more even than the surface of the particles, with no evidence of single-point penetration due to large crevices or flaws.

The rapid initial absorption of liquid water by ground malt seems to be a combination of surface capillary absorption and rapid diffusion into surface excrescences which provide relatively high surface areas.

A mathematical model, based on spherical geometry which assumed that the initial uptake occurred in an annulus in which the moisture content reached C_∞ rapidly and that thereafter the absorption obeyed diffusion laws, satisfactorily fitted the experimental data for different particle sizes and temperatures.

Diffusivities determined for the ground malt-liquid water system were temperature-independent, whereas C_∞ increased with temperature. Literature data (11) suggesting a high activation energy were recalculated and gave almost identical values to those obtained with sieved malt fractions.

Using the model and the values of diffusivity determined, the predicted water absorption by coarsely ground malt at $67°C$. agreed reasonably well with experimental results over the period when leaching of solubles had not significantly changed the physical and chemical nature of the malt.

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APPENDIX A

The unsteady-state diffusion in a finite cylinder can be expressed in dimensionless form as:

$$\overline{C}^* = 8 \sum_{i=1}^{\infty} \sum_{j=1}^{\infty} \frac{Bi_s^2 \, Bi_c^2 \, e^{-yt}}{m_j^2 \, (m_j^2 + Bi_s + Bi_s^2) n_i^2 \, (n_i^2 + Bi_c^2)}$$

where $\overline{C}^* = \dfrac{\overline{C} - C_\infty}{C_0 - C_\infty}$

$\overline{C}$ = average concentration of diffusing species at time t, g./cm.^{3}

C_0 = initial uniform concentration, g./cm.^{3}

C_∞ = concentration at infinite time, g./cm.^{3}

m_j, n_i = eigen-values from the equations

$$Bi_s = m_j \tan (m_j)$$

$$Bi_c = \frac{n_i \, J_1 \, (n_i)}{J_0 \, (n_i)}$$

k_x = mass transfer coefficient cm. sec.$^{-1}$

D = diffusion coefficient cm.^{2} sec.$^{-1}$

L = half-length of cylinder, cm.

R_c = radius of cylinder, cm.

K = ratio of the concentration of the diffusing species in the fluid and in the solid.

$$\eta = D \left(\frac{n_i^2}{R_c^2} + m_j^2 / L^2 \right)$$

Assuming no transfer resistance at the surface of the cylinder or $Bi_c, Bi_s \to \infty$

$$\overline{C}^* = 8 \sum_{i=1}^{\infty} \sum_{j=1}^{\infty} \frac{1}{m_j^2} \, \frac{1}{n_i^2} \, e^{-\eta t}$$

In similar terms, diffusion in a sphere (with no transfer resistance at the surface) is given by:

$$\overline{C}^* = \frac{6}{\pi^2} \sum_{i=1}^{\infty} \frac{e^{-i^2 \pi^2 \Phi}}{i^2}$$

where $\Phi = t \, D/R^2$

R = radius of sphere.

APPENDIX B

Weight Increase of Malt Endosperm Samples Suspended in an Atmosphere of Controlled Humidity

RESULTS OF WATER ABSORPTION EXPERIMENTS ON THE MICROBALANCE

	Weight of Sample, mg.						
Time hr.	Expt. 1(a) 20.0°C. R_c, 0.994 L, 0.1616	Expt. 1(b) 20.0°C. R_c, 0.0799 L, 0.1867	Expt. 1(c) 20.0°C. R_c, 0.0734 L, 0.2028	Expt. 2(a) 30.0°C. R_c, 0.0937 L, 0.1598	Expt. 2(b) 30.0°C. R_c, 0.0898 L, 0.1548	Expt. 2(c) 30.0°C. R_c, 0.0816 L, 0.1525	Expt. 2(d) 30.0°C. R_c, 0.0688 L, 0.2130
0	8.124	8.571	7.400	7.800	8.500	7.900	6.560
0.5	8.912	9.240	8.520	8.612	9.540	8.492	7.600
1.0	9.376	9.708	8.932	9.306	9.984	9.040	8.040
1.5	9.760	10.040	9.156	9.815	10.276	9.444	8.284
2.0	10.016	10.268	9.340	10.215	10.500	9.744	8.480
2.5	10.216	10.480	9.440	10.522	10.656	9.972	8.640
3.0	10.400	10.652	9.771	10.777	10.808	10.128	8.792
3.5	10.564	10.776	9.929	10.982	10.936	10.284	
4.0	10.704	10.904	10.080	11.086	11.052	10.396	8.996
5.0	10.920	11.096	10.347	11.323	11.224	10.592	9.152
6.0	11.104	11.236	10.571	11.604	11.356	10.724	9.272
7.0	11.248	11.360	10.763	11.849	11.488	10.860	9.376
8.0	11.380	11.452	10.939	12.052	11.628	10.968	9.464
9.0	11.548		11.097	12.241		11.080	9.556
10.0	11.664	11.600	11.238	12.414	11.864	11.180	9.624
12.0	11.832	11.736	11.436	12.690	12.060	11.380	9.752
14.0	11.976	11.776	11.575	12.919	12.240	11.576	9.868
16.0	12.112	11.836	11.721	13.117	12.400	11.780	9.984
18.0	12.236		11.827	13.284			10.112
20.0	12.360	11.928	11.902	13.435	12.688	12.048	10.240
24.0	12.528	12.012	12.034	13.711	12.940	12.160	10.480
28.0	12.748	12.088	12.166	13.932	13.248		10.925
32.0	12.920	12.140	12.260		13.592		11.303
36.0	13.092	12.184			13.964		11.607
40.0	13.224	12.236	12.408		14.332		11.884

	Weight of Sample, mg.						
Time hr.	Expt. 3(a) 40.0°C. R_c, 0.0990 L, 0.1616	Expt. 3(b) 40.0°C. R_c, 0.0939 L, 0.1939	Expt. 3(c) 40.0°C. R_c, 0.0828 L, 0.1585	Expt. 3(d) 40.0°C. R_c, 0.0612 L, 0.2442	Expt. 4(a) 50.0°C. R_c, 0.0789 L, 0.1541	Expt. 5(a) 67.0°C. R_c, 0.0631 L, 0.1386	Expt. 5(b) 67.0°C. R_c, 0.0683 L, 0.1635
0	7.900	10.664	6.800	6.240	7.000	3.160	6.160
0.5	9.287	12.080	7.908	7.084	8.360	3.790	7.524
1.0	10.049	12.760	8.392	7.324	8.868	4.140	7.660
1.5	10.648	13.168	8.696	7.480	9.208	4.350	7.756
2.0	11.000	13.440	8.916	7.604	9.472	4.490	7.840
2.5	11.464	13.688	9.120	7.700	9.692	4.568	7.932
3.0	11.700	13.880	9.308	7.780	9.868	4.640	8.040
3.5	11.916	14.000	9.464	7.852	10.036	4.690	8.168
4.0	12.018	14.120	9.608	7.920	10.184	4.720	8.276
5.0	12.440	14.368	9.844	8.044	10.460	4.740	8.476
6.0	12.700	14.568	10.080	8.156	10.764	4.768	8.640
7.0	12.948	14.724	10.380	8.256	10.960	4.782	8.796
8.0	13.148	14.884	10.588	8.340	11.180	4.792	8.924
9.0	13.320	15.012	10.772	8.428	11.392	4.800	9.040
10.0	13.492	15.116	10.948	8.504	11.596	4.802	9.136
12.0	13.724	15.320	11.260	8.656	11.968		9.332
14.0	13.921	15.500	11.536	8.788	12.320		9.476
16.0	14.079	15.644	11.787	8.912	12.648		9.569
18.0	14.200	15.792	12.014	9.012	12.960		
20.0	14.352	15.956		9.120	13.256		
24.0		16.212		9.308	13.816		
28.0		16.456		9.520			
32.0		16.692		9.692			
36.0		16.924		9.832			
40.0		17.132		9.984			

MEDDINGS and POTTER

APPENDIX C

Results of Water Absorption by Ground Malt

G. 1.　WATER ABSORPTION BY SIEVED
FRACTIONS OF GROUND MALT—18°C.[a]

Time min.	Adjusted Water Absorption (g./g. Dry Malt)[b]			
	Grind A	Grind B	Grind C	Grind D
0.5	0.389	0.478	0.501	0.610
4.0	0.502	0.614	0.740	0.945
10.0	0.596	0.800	0.878	0.895
15.0	0.693	0.852	0.924	0.960
20.0	0.752	0.844	0.923	0.948
30.0	0.793	0.920	...	0.975
60.0	0.893	1.025	1.069	0.921
120.0	0.966	1.025	0.994	0.934
180.0	0.992	0.937	0.936	0.899

[a]Initial moisture content = 0.069 g./g. dry malt.
[b]Average of duplicate determinations.

G. 2.　WATER ABSORPTION BY
SIEVED FRACTIONS OF GROUND MALT—67°C.[a]

Time min.	Adjusted Water Absorption (g./g. Dry Malt)[b]			
	Grind A	Grind B	Grind C	Grind D
0.5	0.675	0.907	1.134	1.643
4.0	1.276	1.433	1.727	2.442
10.0	1.266	1.718	2.202	2.450
15.0	1.589	1.962	2.124	2.578
20.0	1.655	2.008	2.400	2.603
30.0	1.923	(36)2.061	2.440	2.558
60.0		2.324	2.243	2.616

[a]Initial moisture content = 0.069 g./g. dry malt.
[b]Average of duplicate determinations.

G. 3.　WATER ABSORPTION BY GRIND B
AT DIFFERENT TEMPERATURES[a]

Time min.	Adjusted Water Absorption (g./g. Dry Malt)[b]		
	30°C.	40°C.	50°C.
0.5	39.3	42.8	44.9
4.0	63.2	70.7	74.8
10.0	68.9	84.0	...
15.0	84.5	89.2	106.2
20.0	89.7	96.4	105.0
30.0	93.3	98.5	114.0
45.0	96.7	107.5	118.2
60.0	102.5	116.2	123.5

[a]Initial moisture content = 0.069 g./g. dry malt.
[b]Average of duplicate determinations.