A Theoretical Approach to the Tempering of Grains[1,2]

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ABSTRACT

Tempering of grains consists of two distinct periods: (1) absorption of water by grains and (2) distribution of the absorbed water within the kernels. Mathematical models based on Fick's law of diffusion in spherical bodies were developed to describe water movement in grains during these two periods. These models were used to simulate the effects of kernel size, initial moisture content, and water diffusivity, both individually and collectively, on the tempering requirement of grains. Results showed that tempering time increases with increase in kernel size and decreases with increase in initial moisture content and water diffusivity. Unless all factors are considered simultaneously, the tempering results obtained can be inconclusive. These results explained why some literature values have seemed contradictory.

The purpose of tempering is to optimize the physical condition of the grain so that a clean separation of germ, bran, and endosperm can be achieved during milling (Larsen 1970, Scott 1936, Simon 1930). Specific effects of tempering on break release, flour ash content, flour yield, power consumption, and flour amylose number during the milling of wheat were examined in a review by Bradbury et al (1960). Tempering toughens the bran and reduces the bran friability, thus rendering a better separation during sieving; tempering also softens the endosperm and allows the endosperm to be reduced without creating an excess amount of damaged starch.

Tempering is usually achieved by adding water to grain and allowing the moistened grain a period to rest (Larsen 1970). Tempering involves two distinct periods of moisture movement: absorption and distribution or equilibration. Hence, any factor that influences the rate of water absorption and distribution affects the rate of tempering. Various studies have reported that temperature, kernel size, kernel structure, and initial moisture content affect the rate of moisture absorption and distribution (Abdelrahman and Farrell 1981, Farrell 1935, Frazer and Haley 1932, Haltmeier 1934, Herd 1937, Hinton 1955, Jones 1949, Nuret 1930, Schafer 1950, Stenvert and Kingswood 1977). There are, however, seeming contradictions in the results of these reports. Farrell (1935) reported that equilibration of moisture was reached sooner in soft wheats than in hard wheats. Herd (1937), however, observed a slower rate of water adsorption by soft wheats in comparison with hard wheats. Other results showed that variations in the time for water absorption existed within hard and soft wheat classes (Schafer 1950). Still others suggested that differences in the initial moisture content, not the texture, was responsible for the observed discrepancy in the rate of absorption (Nuret 1930). These contradictions might have been caused by the failure to take into account all the factors at the same time. There is a need to quantitatively analyze the movement of water during tempering so that the effects of all these factors can be properly assessed.

Quantitative analysis of moisture diffusion in grains during absorption was first introduced by Becker (1960). A solution for solids of arbitrary shape was derived from Fick's diffusion equation, from which Becker determined the diffusivity of moisture in wheat. Quantitative analyses of water uptake have also been performed for other cereals and legumes (Bakshi and Singh 1980, Fan et al 1962, Hsu 1983a). Analysis of moisture movement during tempering, however, has not been developed.

The purpose of this study was to develop a theoretical model for the prediction and analysis of the water movement in grains during tempering and to investigate the response of the model to changes in the parameters.

THEORY

Fick's law of diffusion has been used successfully to describe water movements in seeds during absorption (Becker 1960). The diffusion equation in spherical coordinates is provided by Crank (1975) as

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

where C is the moisture concentration, g of H_2O/g of solid; t is the time, sec; r is the radial distance, cm; and D is the diffusion coefficient, cm^2/sec. Other symbols are explained in Table I. If the diffusion coefficient can be taken as a constant, then, equation (1) can be simplified to

$$\frac{\partial C}{\partial t} = D \left(\frac{\partial^2 C}{\partial r^2} + \frac{2}{r} \frac{\partial C}{\partial r} \right) \tag{2}$$

Tempering can be considered a period of water absorption followed by a period of equilibration. One can treat each period separately. Because both absorption and equilibration of moisture depend on the same diffusion mechanism for water movement, equation (2) should be descriptive during these two periods. The boundary conditions for these two periods, however, are different. Usually, water is added directly to grains in a mixing conveyer or in the washer. This practice often results in an accumulation of surface water in the initial stage of tempering. Thus, one can assume that the concentration of surface moisture during absorption is raised to that of saturation instantaneously upon wetting. Assuming also that the initial moisture of grains is evenly distributed and that the moisture concentration at the center of the grain in finite, the boundary and initial conditions for the absorption period can be expressed as

$$C = C_1, \text{ for all } r, @ \ t_1 = 0;$$
$$\frac{\partial C}{\partial r} = 0, @ \ r = 0, t_1 > 0; \text{ and} \tag{3}$$
$$C = C_0, @ \ r = a, t_1 > 0$$

where C_1 is the initial moisture concentration, g of H_2O/g of solid; C_0 is the saturation concentration, g of H_2O/g of solid; and a is the radius of the seed, cm.

During the equilibration period, the surroundings immediate to the grain can be expected to be near saturation, and little moisture movement is expected between the grain and its surroundings. Under the circumstances, the surface of the grain can be assumed impermeable such that moisture movement is restricted to within the grain only. The initial concentration distribution will be the same as that at the end of the absorption period. Thus, the boundary and initial conditions for the equilibration period are

$$C = f(r), @ \ t_2 = 0;$$
$$\frac{\partial C}{\partial r} = 0, @ \ r = 0, t_2 > 0; \text{ and} \tag{4}$$
$$\frac{\partial C}{\partial r} = 0, @ \ r = a, t_2 > 0$$

where f(r) is the moisture profile at the end of the absorption period.

The solution to equation (2), subject to the boundary conditions as presented in equation (3), was presented by Crank (1975) as

$$\frac{C - C_1}{C_0 - C_1} = 1 + \frac{2a}{\pi r} \sum_{n=1}^{\infty} \frac{(-1)^n}{n} \cdot \sin \frac{n\pi r}{a} \cdot \exp(-Dn^2\pi^2 t_1/a^2), \text{ for } r > 0 \quad (5)$$

where t_1 is the time of absorption, sec equation (5) is valid for all r except at $r = 0$. Taking the limit as $r \to 0$, equation (5) becomes

$$\frac{C - C_1}{C_0 - C_1} = 1 + 2 \sum_{n=1}^{\infty} (-1)^n \exp(-Dn^2\pi^2 t_1/a^2), \text{ for } r = 0 \quad (6)$$

One can also integrate equation (5) over the volume of the spherical seed to get (Crank 1975)

$$\frac{M_{t_1}}{M_\infty} = 1 - \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp(-Dn^2\pi^2 t_1/a^2) \quad (7)$$

where M_{t_1}/M_∞ is the fraction of the total absorbable water absorbed after time, t_1.

A general solution to equation (2), subject to the equilibration period boundary conditions as presented in equation (4), has also been derived (Crank 1975)

$$C = \frac{3}{a^3} \int_0^a r^2 f(r) dr + \frac{2}{ar} \sum_{n=1}^{\infty} \exp(-D\alpha_n^2 t) \cdot \frac{\sin\alpha_n r}{\sin^2\alpha_n a} \cdot \int_0^a r' f(r') \sin\alpha_n r' dr' \quad (8)$$

where α_ns are positive roots of

$$a\alpha_n \cot a\alpha_n = 1 \quad (9)$$

Since equation (5) is the moisture profile in seed at the end of an absorption period, it should also be the profile at the initial stage of the equilibration period. Substituting equation (5) into equation (8), one gets

$$C = \frac{3}{a^3} \int_0^a r^2 \cdot [C_0 + (C_0 - C_1) \frac{2a}{\pi r} \sum_{n=1}^{\infty} \frac{(-1)^n}{n} \sin \frac{n\pi r}{a} \cdot \exp(-Dn^2\pi^2 t_1/a^2)] dr$$

$$+ \frac{2}{ar} \sum_{n=1}^{\infty} \exp(-D\alpha_n^2 t_2) \cdot \frac{\sin\alpha_n r}{\sin^2\alpha_n a} \cdot \int_0^a r' \cdot [C_0 + (C_0 - C_1) \frac{2a}{\pi r} \sum_{m=1}^{\infty} \frac{(-1)^m}{m}$$

$$\sin \frac{m\pi r'}{a} \exp(-Dm^2\pi^2 t_1/a^2)] (\sin\alpha_n r') dr' \quad (10)$$

where t_2 is the time of equilibration, sec. This substitution allows one to link together the two periods. By integrating equation (10), the specific solution for the equilibration period is obtained

$$\frac{C_0 - C}{C_0 - C_1} = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp(-Dn^2\pi^2 t_1/a^2) + \frac{4}{ar} \sum_{n=1}^{\infty} \exp(-D\alpha_n^2 t_2) \cdot$$

$$\frac{\sin\alpha_n r}{\sin\alpha_n a} \cdot \sum_{m=1}^{\infty} \frac{1}{\frac{m^2\pi^2}{a^2} - \alpha_n^2} \cdot \exp(-Dm^2\pi^2 t_1/a^2), r > 0 \quad (11)$$

Again, taking the limit as $r \to 0$, equation (8) becomes

$$\frac{C_0 - C}{C_0 - C_1} = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp(-Dn^2\pi^2 t_1/a^2) + \frac{4}{a} \sum_{n=1}^{\infty} \exp(-D\alpha_n^2 t_2) \cdot$$

$$\frac{\alpha_n}{\sin\alpha_n a} \cdot \sum_{m=1}^{\infty} \frac{1}{\frac{m^2\pi^2}{a^2} - \alpha_n^2} \cdot \exp(-Dm^2\pi^2 t_1/a^2), r = 0 \quad (12)$$

Equations (11) and (12) are unique in that moisture distribution during the equilibration period is being described as a function not only of the equilibration time, t_2, and radial position, r, but also of the time elapsed during absorption, t_1. These expressions signify the effect of absorption on equilibration.

The equations presented are useful in the following situations:

(a) The effect of each parameter on water movement in the grain

can be studied by varying one parameter at a time, while holding the others constant and observing the changes induced. This practice allows one to make a better assessment of the relative importance of the parameters.

(b) If the constants C_0, C_1, D, and a, as well as the desired final moisture are known, equation (7) can be used to determine the time, t_1, required for the added water to be absorbed into the grain. Equations (11) and (12) then can be employed to simulate the moisture profile in the grain with respect to equilibration time, t_2. Moisture profiles during absorption are given by equations (5) and (6). Furthermore, if the termination criterion for tempering is provided, the equilibration time, t_2, needed to reach that specific condition can be determined by equations (11) and (12). The total tempering time, θ, can then be taken as

$$\theta = t_1 + t_2.$$

RESULTS AND DISCUSSION

The tempering process starts with the addition of water. In the beginning, the added water tends to accumulate on the surface, and as time passes the water is absorbed into the grain. This period is what is referred to as the absorption period. The moisture profile during this period, as predicted by equations (5) and (6), was shown by Crank (1975) and is not repeated here. The moisture distribution or equilibration period begins at the instant when the last free water on the surface is being absorbed into the grain. Figure 1 depicts the moisture profiles in a kernel during the distribution period with the

TABLE I
Explanation of Symbols

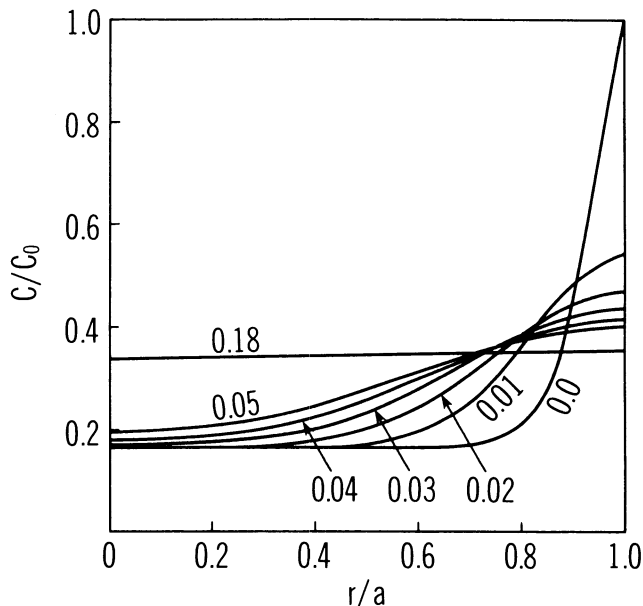| Symbol	Definition
a	Radius, cm
C	Moisture concentration, g H_2O/g solid
C_0	Saturation moisture concentration, g H_2O/g solid
C_1	Initial moisture concentration, g H_2O/g solid
D	Diffusivity, cm^2/sec
M_{t_1}/M_∞	Fractional absorption after time, t_1
r	Radial distance, cm
t	Time, hr
t_1	Absorption time, hr
t_2	Equilibration time, hr
θ	Tempering time, hr

Fig. 1. Concentration profiles during the equilibration period. Numbers on curves are values of dimensionless time, Dt_2/a^2.

dimensionless time, D_2/a_2, as the parameter. The values of the constants C_0 and C_1 used for this simulation were 0.6 g of H_2O/g of solid and 0.1 g of H_2O/g of solid, respectively. In addition, the final moisture was at 0.2 g of H_2O/g of solids. Under this condition, the surface water will be completely absorbed when the dimensionless time, Dt_1/a^2, reaches $3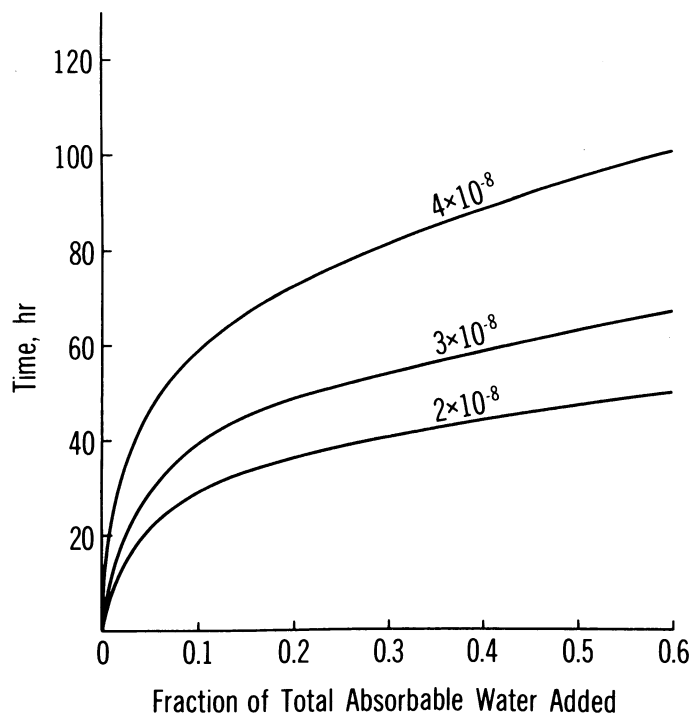.9 \times 10^{-3}$. The moisture profile in this instance is the same as that at the beginning of the equilibration period, which is depicted in Fig. 1 by the curve that shows Dt_2/a^2 equal to zero. It is obvious that, at the beginning of the distribution period, most of the moisture is located at or near the kernel surface. As time passes, the moisture near the surface diffuses toward the center of the kernel where the moisture concentration is low. This diffusion results in a gradual equilibration of moisture in the kernel. At a point at which the dimensionless time, Dt_2/a^2, reaches 0.18, the concentration at the center of kernel is within 0.01 g of H_2O/g of solid of that at the surface. Using D and values typical of hard wheats of 3×10^{-8} cm^2/sec and 0.168 cm (Becker 1960, Chung et al 1961), respectively, the tempering time is calculated to be roughly 48 hr, which is reasonable for hard wheat. Of the 48 hr, absorption takes only 1 hr; the rest is for equilibration.
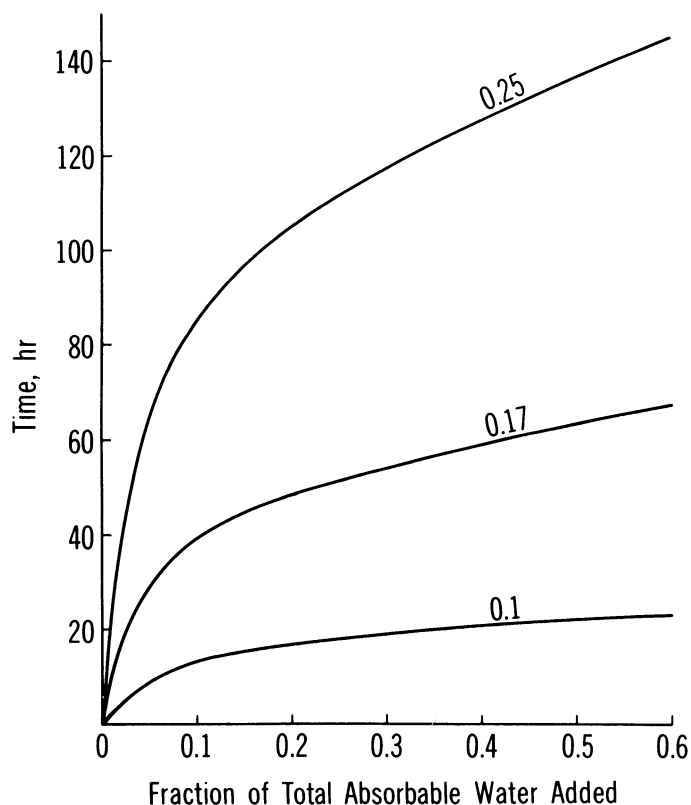
Kernel structure, size, and initial moisture content are some factors reported to affect tempering (Frazer and Haley 1932, Haltmeier 1934, Jones 1949, Nuret 1930, Stenvert and Kingswood 1977). The effects of these factors are investigated by using the developed model. Figures 2, 3, and 4 summarize the simulated effects of diffusivity, kernel radius, and initial moisture content on tempering time, respectively. The termination criterion for tempering was taken as when the moisture content at the center of kernel reaches within 0.01 g of H_2O/g of solid of that at the surface. Evidently, everything else being equal, the greater the diffusivity, the less time is required for tempering (Fig. 2). Notice that diffusivity rather than kernel structure is the parameter in Fig. 2. This practice does not contradict previous reports (Frazer and Haley 1932, Stenvert and Kingswood 1977) because diffusivity is very much determined by the kernel structure. The correlation between the two, however, is not well established and will be the subject of further study.

Figure 3 shows that, as the size of the kernel decreases, the tempering time also decreases. This is obvious because, the smaller the kernels, the shorter the distance for the diffusing water to travel. The effect of kernel size on tempering time is greater than that of diffusivity; eg, doubling the radius, a, quadrupled the tempering
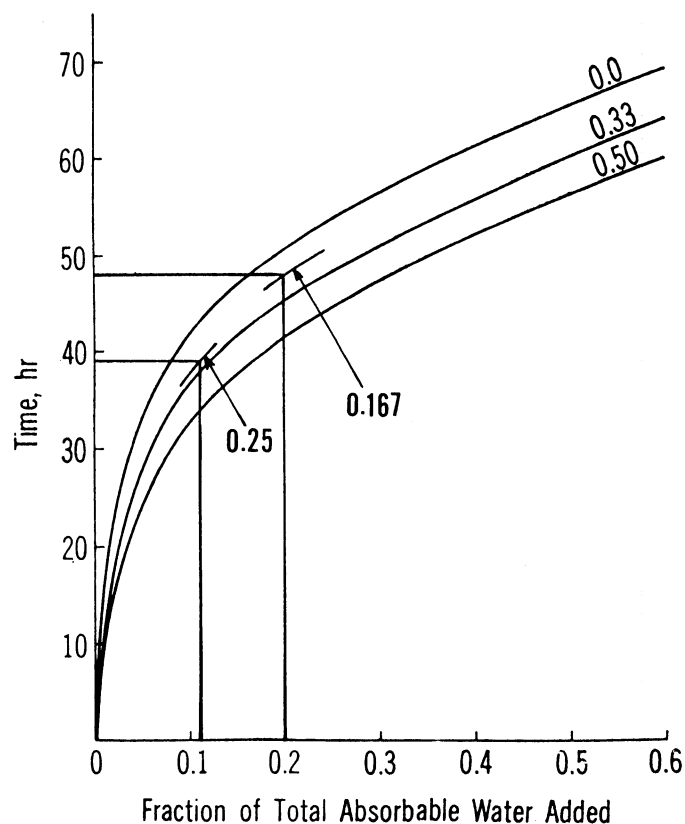

Fig. 2. Effect of diffusion coefficient on tempering time. Numbers on curves are values of D.

Fig. 3. Effect of kernel size on tempering time. Numbers on curves are values of a.

Fig. 4. Effect of initial moisture content on tempering time. Numbers on curves are values of C_1/C_0.

time, whereas doubling the diffusivity resulted only in halving the tempering time.

The lower the initial moisture content of the grain, the longer the time required for tempering (Fig. 4). This effect of initial moisture content may seem small at first glance; however, a closer examination proves otherwise. An increase in the initial moisture content of the grain not only shifts the curve in Fig. 4 to the right, but it also reduces the fraction of water absorbed. These two effects combined can result in a substantial reduction in tempering time. For example, the tempering time for a grain with $C_1 = 0.1$ g of H_2O/g of solid, $C_0 = 0.6$ g of H_2O/g of solid, $D = 3 \times 10^{-8}$ cm^2/sec, and a = 0.168 cm. That is, being tempered to a moisture content of 0.2 g of H_2O/g of solid can be determined on Fig. 4 by first calculating the fraction of total absorbable water added as

$$\frac{C - C_1}{C_0 - C_1} = \frac{0.2 - 0.1}{0.6 - 0.1} = 0.2 \qquad (13)$$

Locating the point on the X-axis and drawing a vertical line upward until it intersects with the curve for $C_1/C_0 = 0.167$ gives a value of 48 hr for tempering on the Y-axis. If the initial moisture content, C_1, is increased to 0.15 g of H_2O/g of solid, the fraction of absorption will be decreased to

$$\frac{C - C_1}{C_0 - C_1} = \frac{0.2 - 0.15}{0.6 - 0.15} = 0.11 \qquad (14)$$

The intersection of a line drawn vertically from this point and the curve for $C_1/C_0 = 0.25$ gives a tempering time of 39 hr, a value substantially less than 48 hr.

Temperature has also been reported by various workers to have a great effect on tempering (Jones 1949, Haltmeier 1934, Swanson and Pence 1930). The effect of this factor is not shown directly in the equation. However, previous analyses of water uptake by cereals and legumes have established that temperature affects the diffusivity of moisture in grains according to the Arrhenius law, with activation energies ranging from 3 to 12 Kcal/mole, depending upon the type and variety of the grain (Bakshi and Singh 1980, Becker 1960, Chung et al 1961, Hsu 1983b). Thus, as
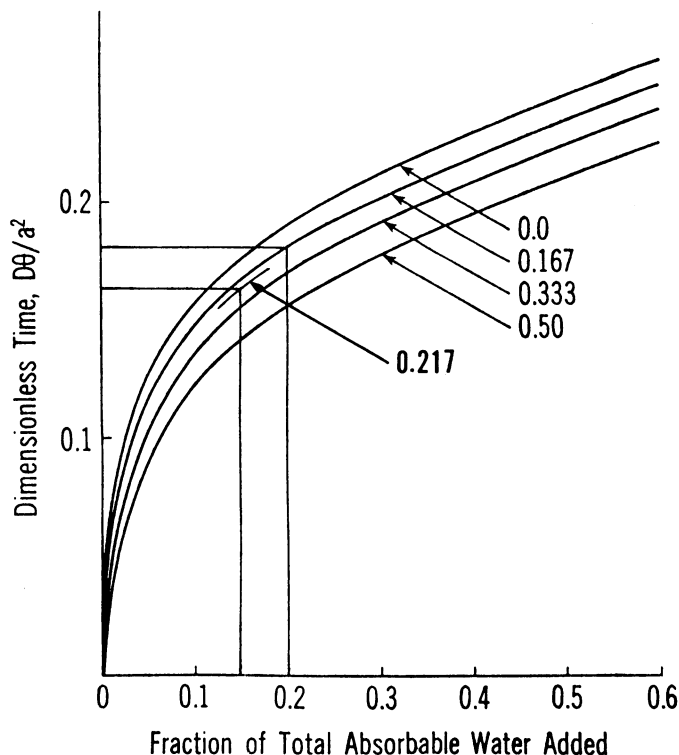
temperature changes, the diffusivity change in a grain can be calculated, and its effect on tempering can then be determined from Fig. 2.

Results in Figs. 2, 3, and 4 clearly show the effect of each individual parameter on tempering. However, since these effects occur simultaneously, the cumulative outcome is sometimes difficult to see. This problem is solved by Fig. 5, which combines all effects, thus providing a convenient means for determining the tempering requirement of a grain. Because tempering is affected by many factors, it is possible for two grain samples with different diffusivity, size, and initial moisture content to have the same tempering requirement. This can be demonstrated by Fig. 5. Suppose hard wheat A with $C_1 = 0.1$ g of H_2O/g of solid, $C_0 = 0.6$ g of H_2O/g of solid, $D = 3 \times 10^{-8}$ cm^2/sec, and a = 0.168 cm is to be tempered to 0.2 g of H_2O/g of solid. One can calculate from this information the fraction of absorption

$$\frac{C - C_1}{C_0 - C_1} = \frac{0.2 - 0.1}{0.6 - 0.1} = 0.2$$

and the dimensionless initial moisture concentration

$$\frac{C_1}{C_0} = 0.167.$$

So in Fig. 5, one can find

$$\frac{D\theta}{a^2} = 0.184$$

which results in a tempering time, θ, of 48 hr. If another hard wheat B with the same saturation moisture content, C_0, but with a higher initial moisture, $C_1 = 0.13$ g of H_2O per solid, a more vitreous kernel, $D = 2 \times 10^{-8}$ cm^2/sec, and a smaller kernel size, a = 0.15 cm, is also to be tempered to a final moisture of 0.2 g of H_2O/g of solid. In this case, the calculated values for $C - C_1/C_0 - C_1$ and C_1/C_0 would be 0.149 and 0.217, respectively. Using Fig. 5 again, one can determine $D\theta/a^2$ to be equal to 0.154, which reflects a tempering time of 48 hr, also. It is now clear that, unless all parameters are strictly controlled, the tempering results obtained will be inconclusive, at best. This might be why various results in the literature seem contradictory (Farrell 1935, Herd 1937, Schafer 1950).

CONCLUSION

A theoretical model based on Fick's law of diffusion has been developed to describe moisture movement during tempering and to predict the tempering requirement. This model demonstrates how variations in diffusivity, kernel size, and initial moisture content, individually or in combination, affect the tempering time. Although this model provides the theoretical basis to evaluate the effect of parameters on tempering, it requires experimental verification to be of practical use. For instance, in this study, one used a termination criterion for tempering as when the center concentration reaches within 0.01 g of H_2O/g of solid of that at the surface. Is this reasonable? One would guess that the termination criteria will be different for different grains, but they can only be determined experimentally. Furthermore, how accurately can the model predict the tempering time? Is it sensitive enough to differentiate between small and large grains, or between grains of hard and soft texture? Experimental work is underway to answer these questions and will be reported subsequently.

Fig. 5. A summary of factors affecting tempering. Numbers on curves are values of C_1/C_0.

LITERATURE CITED

ABDELRAHMAN, A. A., and FARRELL, E. P. 1981. Use of an electrical conductance moisture meter to study tempering rates in grain sorghum. Cereal Chem. 58:307.

BAKSHI, A. S., and SINGH, R. P. 1980. Kinetics of water diffusion and starch gelatinization during rice parboiling. J. Food Sci. 45:1387.

BECKER, H. A. 1960. On the absorption of liquid water by the wheat kernel. Cereal Chem. 37:309.

BRADBURY, D., HUBBARD, J. E., MacMASTER, M. M., and SENTI, F. R. 1960. Conditioning wheat for milling. A survey of the literature. Misc. Publ. 824. U.S. Department of Agriculture, Washington, DC.

CHUNG, D. S., FAN, L. T., and SHELLENBERGER, J. A. 1961. Volume increase of wheat kernels accompanying absorption of liquid water. J. Biochem. Microbiol. Technol. Eng. 3:377.

CRANK, J. 1975. The Mathematics of Diffusion, 2nd ed. Oxford University Press, London.

FAN, L. T., CHU, P. S., and SHELLENBERGER, J. A. 1962. Volume increase of kernels of corn and sorghum accompanying absorption of liquid water. Biotechnol. Bioeng. 4:311.

FARRELL, E. P. 1935. Tempering time and rate of water absorption in wheat. Am. Miller 63(1):28.

FRAZER, C. W., and HALEY, W. L. 1932. Factors that influence the rate of absorption of water by wheat. Cereal Chem. 9:45.

HALTMEIER, O. 1934. Water penetration in the wheat kernel. Am. Miller 62(5):35.

HERD, C. W. 1937. Wheat washing and conditioning. Miller (London) 63:714.

HINTON, J. J. C. 1955. Resistance of the testa to entry of water into the wheat kernel. Cereal Chem. 32:96.

HSU, K. H. 1983a. A diffusion model with a concentration-dependent diffusion coefficient for describing water movement in legumes during soaking. J. Food Sci. 48:618.

HSU, K. H. 1983b. Effect of temperature on water diffusion in soybean. J. Food Sci. 48:1364.

JONES, C. R. 1949. Observations on the rate of penetration of water into the wheat grain. Milling 113:80.

LARSEN, R. A. 1970. Milling. Page 6 in: Cereal Technology. S. A. Matz, ed. Avi Publ. Co., Westport, CT.

NURET, H. 1930. Concerning the absorption of water by grain. Z. Ges. Muhlenw. 6(12):193. Cited by Bradbury et al 1960.

SCHAFER, W. 1950. Investigation concerning the absorption of water by kernels of cereal grains. Getreide Mehl Brot. 4:192. Cited by Bradbury et al 1960.

SCOTT, J. H. 1936. The behavior of moisture in wheat. Page 63 in: Flour Milling Processes. D. Van Nostrand Co., New York.

SIMON, E. D. 1930. Conditioning—The practical problem. Page 101 in: The Physical Science of Flour Milling. Northern Publ. Co., Liverpool, England.

STENVERT, N. L., and KINGSWOOD, K. 1977. Factors influencing the rate of moisture penetration into wheat during tempering. Cereal Chem. 54:627.

SWANSON, C. O., and PENCE, R. O. 1930. The penetration rate of water in wheat during tempering as disclosed by college mill trials. Am. Miller 58:435.