Diffusion Coefficients of Glucose, Potassium, and Magnesium in Maine Russet Burbank and Maine Katahdin Potatoes from 45 to 90°C

ABSTRACT

Experimental data for the leaching of glucose, potassium and magnesium from French fry cut Maine Russet Burbank and Maine Katahdin potatoes were modeled over the temperature range 45–90°C, using a one-parameter diffusion equation based on Fick's second law. Correlations for the dependence of the resulting effective diffusion coefficients on temperature were determined. At temperatures greater than 60°C, plots of the diffusion coefficients as a function of temperature showed a change in slope or a discontinuity in the slope of the curve. This reflected the change in the diffusion matrix which occurred when the starch began to gelatinize. The effect of cultivar differences on values of the diffusion coefficients might be linked to the concentrations of starch and electrolytes in the potato.

INTRODUCTION

A CRITICAL STEP in the processing of vegetables is hot water blanching. Blanching deactivates enzymes which cause browning and undersirable flavors. In the processing of potatoes for French fries, mashed potato flakes, and occasionally potato chips, the hot water blanch is also used to remove reducing sugars and other components which participate in the Maillard reaction. Blanching also gelatinizes the starch. Unfortunately, in the leaching of reducing sugars from the potato, hot water blanching also results in the loss of nutrients.

Commerical hot-water blanchers are typically of the screw-conveyor type with direct steam injection. The temperature of the water used in blanching potatoes typically ranges from 60°C to 82°C with residence times of up to 20 min for the processing of mashed potato flakes (Cording et al., 1955). The optimum temperature and blanching time for the leaching of reducing sugars have been reported to depend on the cultivar, cultural practices and low-temperature storage history, where an increase in reducing sugars is noted with long-term storage. Handling and temperature changes during transit have also been implicated in the increase in reducing sugars after harvest (Talburt and Smith, 1987). Because of the effects of these varied phenomena on the leaching of sugars, the experience of the processor often determines the optimum processing conditions. A knowledge of the mass transfer which occurs during blanching expressed through a suitable mathematical model would aid the processor in the calculation of the rate of leaching of reducing sugars as a function of temperature and time.

Several mathematical models have been proposed for this purpose. The adjustable parameter in all the models is the effective diffusion coefficient and in case of laminar flow, a mass transfer coefficient is utilized. Effective diffusion coefficients for glucose in potato have already been tabulated by Kozempel et al. (1981) from pilot-plant data, Califano and Calvelo (1983) and Garrote et al. (1984). Kozempel et al. (1981, 1982) also presented diffusion coefficients for some minerals and vitamins. Garrote et al. (1986) determined diffusion coefficients of Vitamin C in potatoes.

Data for the effects of potato cultivar on the values of the effective diffusion coefficients of sugars and minerals in potato are limited. Loncin (1979) reports that diffusion coefficients are a function of temperature for cyclohexanol tracer in potato and that the diffusion coefficients for potato depend on cultivar and consequently on the water content. Cultivars of high water content have effective diffusion coefficients whose values approach those in pure water.

This work was undertaken to: (1) develop a mathematical model which relates uptake by the blanch water of a component leached from a French fry cut of potato to the blanch time; (2) show a simple experimental method for the determination of effective diffusion coefficients which relies only on the determination of the concentration of the component in the blanch water, and not in the potato; (3) determine the influence of cultivar on values of the effective diffusion coefficients using Maine Russet Burbank and Maine Katahdin potatoes; and, (4) investigate the temperature dependence of the diffusion coefficients.

Mathematical model

The French fry strip of potato was assumed to consist of an insoluble and isotropic matrix of starch, the major solid component of the potato, and other solid components of the potato, such as pectin, and water through which the solutes leached from the potato matrix diffuse. The starch of the potato is composed mainly of amylose and amylopectin. The solutes are distributed uniformly throughout the strip. The French fry strip of potato approximates a solid of constant thickness bounded by two planes. Negligible diffusion takes place through the ends of the strip.

The mathematical equations used here are similar to those of Crank (1967) for the case of diffusion from a well-stirred solution of limited volume to a sheet. In this study, the solution for the complementary problem of diffusion from a sheet to a well-stirred fluid was used. The unsteady state diffusion in the potato is given by Fick's second law

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} \tag{1}$$

where C is the concentration of solute in the potato; D is the effective diffusion coefficient; x is distance measured from the center of the piece and t is time. D is an effective diffusion coefficient because its value is influenced by other diffusing components of the potato and the diffusional path.

C is related to the concentration of the solute leached from the potato, C_2, by the expression

$$C_2 = C_1 - C \tag{2}$$

where C_1 is the initial concentration of the solute in the potato.

Eq. (1) may be solved through substitution of Eq. (2) with the initial conditions

$$C = C_1 \qquad -\ell < x < \ell; \qquad t = 0 \qquad (3)$$
$$C_2 = 0$$

and the boundary condition

$$a\frac{\partial C}{\partial t} = \mp D\frac{\partial C}{\partial x} \qquad x = \pm\ell, t > 0 \qquad (4)$$

where a is the length of the solution outside the sheet. Eq. (4) indicates that at the surfaces of the potato piece, the concentration of the solute in the solution is equal to the concentration of the solute just within the sheet.

The solution to Eq. (1), (3) and (4) is given by Eq. (5), which is reported in terms of the uptake ratio of the solution, R. R expresses the ratio of the amount of solute in solution at time t, M_t, as a fraction of the amount of solute in the solution at infinite time, M_∞.

$$R = \frac{M_t}{M_\infty} = 1 - \sum_{n=1}^{\infty} \frac{2\alpha(\alpha + 1)e_n^{-Dq^2t/\ell^2}}{1 + \alpha + \alpha^2 q_n^2} \qquad (5)$$

α is the ratio of the volume of the fluid, V_L, to the volume of the solid, V_S. The q_n are the non-zero positive roots of the equation

$$\tan q_n = -\alpha q_n \qquad (6)$$

In the case of an infinite amount of solution, $\alpha = \infty$, $q_n = (n + 1/2)\pi$ and Eq. (5) becomes

$$R = \frac{M_t}{M_\infty} = 1 - \frac{8}{\pi^2}\sum_{n=0}^{\infty} \frac{e^{-D(2n+1)^2\pi^2t/4^2\ell^2}}{(2n + 1)^2} \qquad (7)$$

MATERIALS & METHODS

MAINE RUSSET BURBANK (sp gr = 1.086) and Maine Katahdin (sp gr = 1.083) potatoes with average moisture contents of 81% and 82%, respectively, stored at 3°C were used in the experiments. The average initial concentrations of glucose, potassium and magnesium in Maine Russet Burbank potatoes were 5000, 3700 and 200 ppm, respectively. The average initial concentrations of these components in Maine Katahdin potatoes were 7700, 4200, and 210 ppm, respectively. The potatoes were hand-peeled and cut into nominal 1 cm × 1 cm × 9 cm pieces. Only two strips from the center of the potato were used.

In a typical run, a covered preweighed 2000 milliliter beaker containing about 500 g of deionized water was immersed in a larger water bath heated to the desired temperature. The experiments were carried out at 45°, 50°, 55°, 60°, 65°, 74°, 80°, 85°, and 90°C. The contents of the beaker were well-mixed using a stream of nitrogen. The temperature control of the bath was maintained to ±0.2°C. When the temperature of the water in the beaker was that of the bath, a preweighed French fry strip of potato at 25°C, secured by a string, was lowered into the beaker and a timer started. The strip generally attained the bath temperature in less than 6 min. The other strip was weighed and freeze-dried for later analysis. Five milliliters of the water was removed every 15 min, weighed and analyzed for glucose, magnesium and potassium, using the methods described below. The experiment was continued until the glucose concentration in the beaker was steady.

Water analyses

Glucose was determined immediately using a YSI Model 27 (Yellow Springs Instrument Co., Yellow Springs, OH 45387) Glucose Analyzer. Potassium and magnesium were determined using the Perkin-Elmer 1100B Atomic Absorption Spectrophotometer. The samples were diluted and acidified with nitric acid before analysis.

Solid analyses

The freeze-dried strips were ground to a powder. Glucose was extracted from a sample of the powder with 80% methanol and then dried under nitrogen to a brown syrup. The syrup was then dissolved with hot distilled water. Potassium and magnesium were extracted from the sample with water and nitric acid (20:1) over a steam bath for 16 hr, filtered and then diluted with water. Glucose, potassium and magnesium were then determined for the potato using the methods outlined for the liquid.

Calculations

The experimental value of R was calculated from the following equation

$$R_{exp} = \frac{C_L W_L}{C_S W_S} \qquad (8)$$

where C_L is the concentration of solute in the solution at time t; C_S is the concentration of solute in the solid initially; and W_L and W_S are the weights of blanch water in the beaker and of the French fry strip, respectively. R_{exp} may also be evaluated based on the weight of solute in the blanch water at infinite time instead of the weight of solute in the potato initially. However, this weight is difficult to obtain when the experiment is performed at low temperatures since the potato strip usually degrades before this time is reached.

Eq. (7) was used in most calculations since the volume of water was sufficiently larger than the volume of the potato piece resulting in a value of α approaching infinity. In the cases where Eq. (5) and (6) were used, the q_n were calculated using a modified Newton-Raphson (Scarborough, 1962) procedure.

Calculations were carried out using the experimental data for either Maine Russet Burbank or Maine Katahdin potatoes at a particular temperature and a Fibonacci Search program (Kuester and Mize, 1973) to determine the value of the diffusivity that minimized the following objective function:

$$Q = \sum_{i=1}^{n} ((R_{exp} - R_{cal})/R_{exp})_i 2 \qquad (9)$$

The summation is over all experimental data points. R_{cal} is the calculated ratio of M_t/M_∞ given by either Eq. (5) or (7). Up to twenty terms of Eq. (5) and (7) were used in the calculation of the diffusion coefficients. The assumption of negligible diffusion through the ends of the French Fry piece was verified using Eq. (7) and the Newman (McAdams, 1954) method.

RESULTS & DISCUSSION

TYPICAL EXPERIMENTAL and calculated results of the uptake ratio of the solution, R, for glucose, potassium and magnesium as a function of blanch time are shown in Fig. 1 using Maine Katahdin potatoes at 65°C as an example. The scatter in the experimental values of R was due to differences in the relative concentrations of glucose, potassium and magnesium in the raw sample potatoes. At a fixed time, the fractional uptake by the solution of potassium was greater than that of magnesium or glucose. This trend was observed in all the experiments and indicated that the diffusion coefficients and, therefore, the rate of diffusion of potassium in potato were greater than those of magnesium and glucose. The diffusion coefficients of glucose (Wilke-Chang, 1955; Hayduk and Laudie, 1974) and salts of potassium and magnesium in dilute aqueous solutions exhibit the same trend (Robinson and Stokes, 1959).

The effective diffusion coefficients of glucose, potassium and magnesium in Maine Russet Burbank and Maine Katahdin potatoes were obtained from a fit of the data in Eq. (5) or (7). The natural logs of the effective diffusion coefficients are plotted in Fig. 2, 3 and 4, respectively, as a function of reciprocal temperature. The diffusion coefficients of these components in dilute aqueous solution, calculated from the Wilke-Chang (1955) equation in the case of glucose and the Nernst-Haskell (Reid et al., 1977) equation in the case of potassium and magnesium

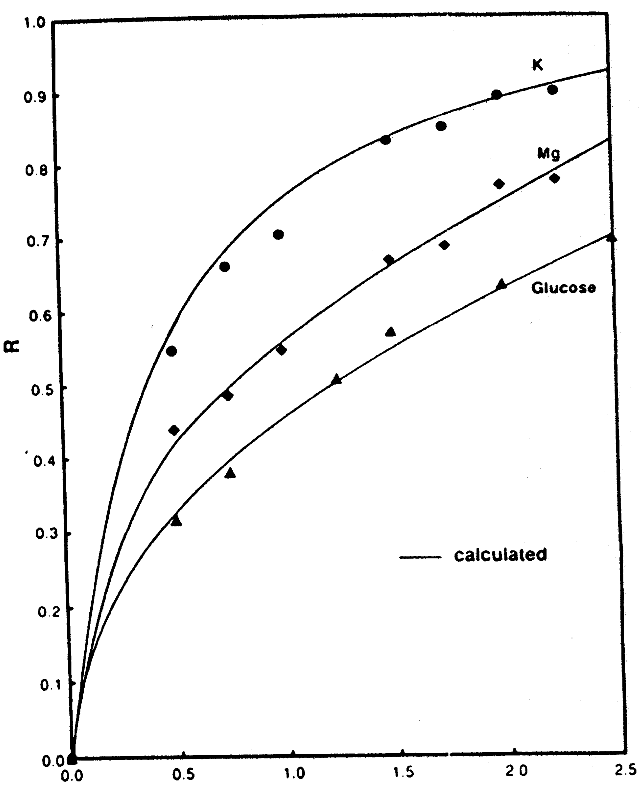

Fig. 1—Comparison of experimental and calculated data for Maine Katahdin potatoes, t = 65°C.

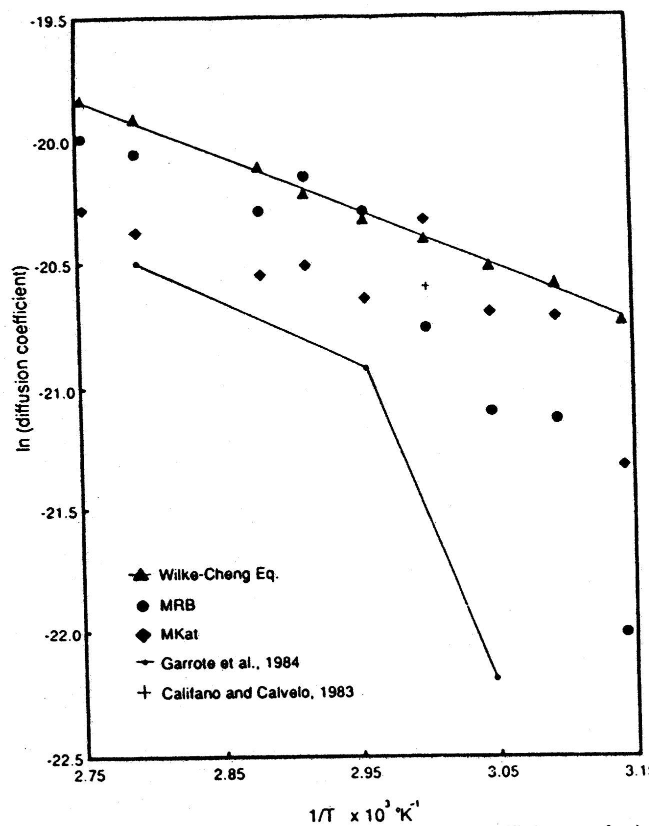

Fig. 2—Variation of the effective diffusion coefficients of glucose with temperature.

ions are plotted for comparison. The Nernst-Haskell equation yields values of diffusion coefficients for salts only and not the individual ions. It was assumed in this study, for purposes of demonstration, that most of the potassium and magnesium in the potato existed as the chloride salt since the chloride ion was the predominant negative ion in the potato. No data are available in the literature for the diffusion coefficients of potassium, magnesium and glucose in dilute aqueous solution or methods available to estimate their values.

The effective diffusion coefficients for glucose are presented in Fig. 2. The diffusion coefficients for Maine Russet Burbank potatoes increased with temperature to approximately 70°C after which a break in the curve of the plot was observed. The value of the diffusion coefficient of glucose at 74°C was less than that at 70°C. As the temperature increased further, the diffusion coefficients increased with temperature again but at a slower rate. Similar trends were observed for Maine Katahdin potatoes but the break in the curve of the effective diffusion coefficients of glucose occurred at 60°C. The diffusion coefficients of glucose obtained by Califano and Calvelo (1983) and Garrote et al. (1984) for Kennebec potatoes are also plotted for comparison. Those obtained by Kozempel et al. (1981) are not plotted because their diffusion coefficients were obtained from pilot-plant data and reflect some of the nonidealities of this system. The diffusion coefficient at 60°C obtained by Califano and Calvelo (1983) (Kennebec potatoes with a moisture of 79.9%) is within 20% of but less than the diffusion coefficients obtained here for Maine Russet Burbank and Maine Katahdin potatoes. The diffusion coefficients obtained by Garrote et al. (1984) are less than those obtained in this study; but, with the exception of the diffusion coefficient at 55°C, they are also within approximately 20% of the values obtained here. The moisture content of the Kennebec potatoes used was not indicated. Also, since Garrote et al. (1984) only determined three diffusion coefficients, it is possible that the break in the diffusion coefficient with temperature was not observed.

The diffusion coefficients of potassium are presented in Fig. 3. The diffusion coefficients for both cultivars increased sharply as the temperature increased from 45°C to 60°C. A break in the curve was observed for Maine Russet Burbank potatoes. The value of the diffusion coefficient dropped at 65°C and then increased again with temperature. The diffusion coefficients of potassium for Maine Katahdin potatoes changed slope at this temperature.

The diffusion coefficients of magnesium for Maine Russet Burbank and Maine Katahdin potatoes as a function of temperature are presented in Fig. 4. The break in the curve of diffusion coefficient with temperature and the subsequent drop in the value of the diffusion coefficients occurred for both cultivars with the break occurring at approximately 60°C. From 65°C to 90°C, the diffusion coefficients increased with temperature for the Maine Russet Burbank potatoes. For the Maine Katahdin potatoes, there was an increase in the diffusion coefficients from 65°C to 74°C, and then a leveling off of the diffusion coefficients with further increases in temperature.

As the data in Fig. 2, 3 and 4 demonstrate, the diffusion coefficients are essentially linear with temperature over the temperature range 45°C to 55°C. They obey the Stokes-Einstein equation in that they were inversely proportional to the viscosity of water. At 60°C, the diffusion coefficients for both cultivars approached their values in pure water.

The break in the diffusion coefficient curves or the change in slope of the curves signified a change in the diffusion matrix of the potato. At low temperatures, the potato matrix consisted of intact starch granules of various sizes. As the temperature of the potato increased, and above a certain temperature known

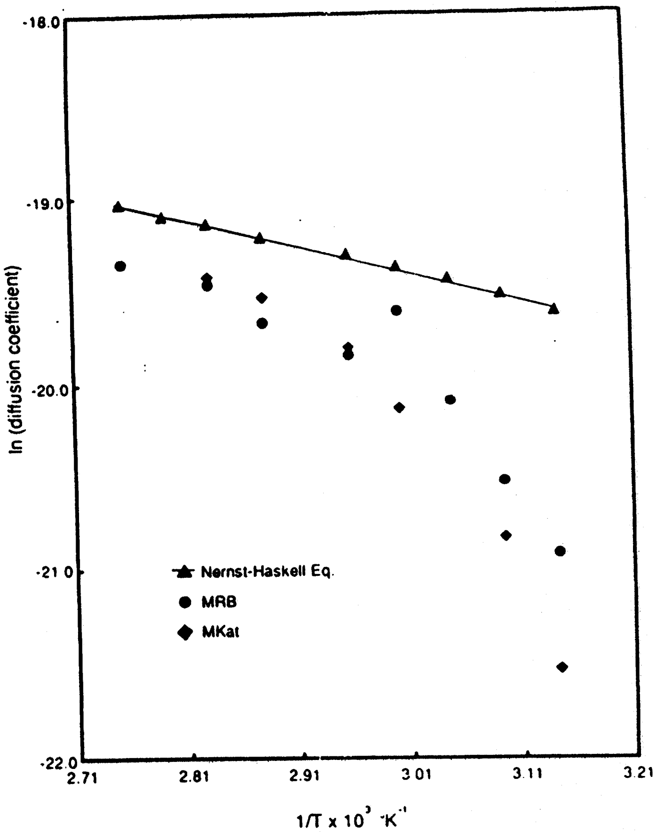

Fig. 3—Variation of the effective diffusion coefficients of potassium with temperature.

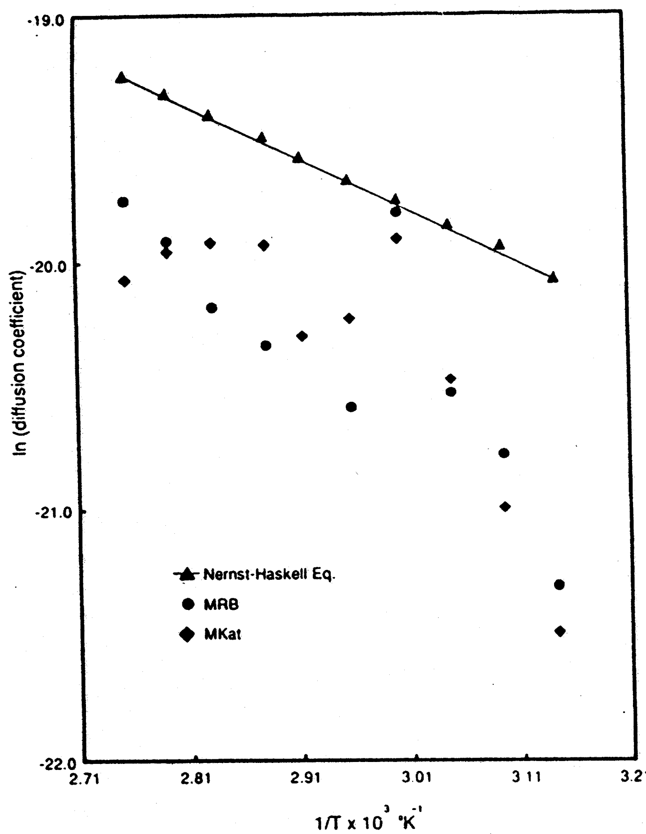

Fig. 4—Variation of the effective diffusion coefficients of magnesium with temperature.

as the gelatinization temperature (Potter et al. 1959), the starch granules absorb water and begin to swell. Reeve (1977) indicates that the swelling of the starch typically occurs over the temperature range from 58°C to 70°C. Shiotsubo (1983) has shown that starch swelling occurs in starch-water solutions at temperatures as low as 52.5°C. As the granules swell, amylose leached out and formed a gel composed of starch granules embedded in an amylose matrix. The path for diffusion at temperatures above 70°C was through a gel of higher viscosity. The increased viscosity results in a lowering of the diffusion coefficient of the component (Schwartzberg, 1982). In addition, the decrease in the rate of diffusion and the diffusion coefficients with increasing temperature might also result from the change in the diffusional path upon formation of the gel, i.e., many diffusional paths are now blocked and there is an increased drag on the molecules due to the smaller walls of the diffusional path. Apparently, continued heating from this point decreases the viscosity of the water phase and weakens the cell integrity and results in a rise of the diffusion coefficient with temperature. The diffusion coefficients for both cultivars again approach their values in pure water.

The effective diffusion coefficients for Maine Russet Burbank and Maine Katahdin potatoes, shown in Fig. 2, 3, and 4, were correlated with reciprocal temperature over three temperature ranges using an Arrhenius type equation (Eq. 10) and a polynomial expression (Eq. 11).

$$\ln D = A - B(1/T) \quad (10)$$

and

$$\ln D = C + D(1/T) + E(1/T)^2 \quad (11)$$

The correlations were over the temperature ranges: 45–90°C, which included all the experimental data; 45–60°C, which included all data up to the break in the curve or the change in slope of the curve; and 65–90°C, which included data after the break or change in slope of the curve. Eq. 11 was only used for correlation if more than three data points were available in the temperature range.

The parameter values, correlation coefficients and the average absolute percent error in diffusion coefficient are shown in Table 1 for Eq. 10 and Table 2 for Eq. 11. Eq. 10 and 11 correlated the data well in the temperature ranges 45–60°C and 65–90°C. The correlation of the data over the entire temperature range with Eq. 10 was poor for both cultivars because the data was nonlinear. If a single equation is needed to correlate the data, for example, in a computer simulation program, it is recommended that Eq. 11 be used. However, more accurate predictions of the diffusion coefficients are obtained with Eq. (10) for the two temperature ranges, 45–60°C and 65–90°C.

CONCLUSIONS

THE PROPOSED MATHEMTICAL MODEL and experimental method can be used to validly determine effective coefficients in potatoes. The diffusion coefficients for both cultivars showed a change in slope or a discontinuity in the slope of the curve at 60°C when the diffusion coefficients were plotted as a function of temperature indicative of a change in the diffusion matrix with increasing temperature. The equation presented for the calculation of the effective diffusion coefficients can be used in computer programs which simulate the blanching of potatoes.

NOMENCLATURE

a = length of solution outside the sheet, m
cal = calculated value

Table 1—Constants of Eq. (10)

Component	Cultivar	Temperature range °C	A	B	r^2	Avg Abs %Error
Glucose	MRB[a]	45-90	−6.9463	4637.7	0.84	21.8
	MK[b]		−13.9568	2266.2	0.69	14.5
	MRB	45-60	1.7993	7382.6	0.98	12.3
	MK		1.7330	7484.2	0.94	9.6
	MRB	65-90	−13.2433	2445.1	0.99	1.1
	MK		−15.7226	1661.1	0.94	2.6
Potassium	MRB	45-90	−9.1298	3646.9	0.81	16.6
	MK		−4.1108	5411.9	0.90	21.9
	MRB	45-60	7.8934	9175.2	1.00	2.5
	MK		8.6709	9580.5	0.97	9.4
	MRB	65-90	−12.4137	2512.1	0.97	2.8
	MK		−9.8355	3394.4	0.96	6.6
Magnesium	MRB	45-90	−11.7278	2928.7	0.63	19.1
	MK		−13.4056	2372.5	0.45	29.0
	MRB	45-60	10.3473	10076.4	0.97	8.6
	MK		13.5653	11161.3	1.00	4.0
	MRB	65-90	−8.3610	4146.9	0.98	2.3
	MK		−17.7295	805.1	0.24	9.5

[a] Maine Russet Burbank
[b] Maine Katahdin

Table 2—Constants of Eq. (11)

Component	Cultivar	Temperature range °C	C	D	$E\times10^{-7}$	r^2	Avg abs %Error
Glucose	MRB[b]	45-90	−137.9	84389.2	−1.511	0.96	11.0
	MK[c]		−88.1	48168.5	−0.856	0.82	13.3
	MRB	45-60	−126.1	77023.0	−1.396	0.95	11.1
	MK		188.1	−128789.4	1.977	0.99	9.6
	MRB	65-90					
	MK		0.2329	−12855.0	0.196	0.95	2.5
Potassium	MRB	45-90	−114.9	68200.9	−1.218	0.93	10.4
	MK		−110.8	67555.5	−1.244	0.99	7.5
	MRB	45-60	112.5	−77322.8	1.109	1.00	0.9
	MK						(a)
	MRB	65-90					(a)
	MK						(a)
Magnesium	MRB	45-90	−75.0	40115.3	−0.731	0.67	21.3
	MK		−177.0	109745.9	−1.916	1.00	12.5
	MRB	45-60	232.2	−154548.1	2.351	0.98	7.3
	MK		108.7	−73104.8	1.008	1.00	1.5
	MRB	65-90	59.9	−51940.4	8.365	0.99	1.9
	MK		−206.5	131461.7	−2.315	0.99	6.7

[a] Insufficient data for correlation
[b] Maine Russet Burbank
[c] Maine Katahdin

C = concentration of solute in the potato, ppm
C_1 = initial concentration of solute in the potato, ppm
C_2 = concentration of solute leached from the potato, ppm
C_L = concentration of solute in the solution at time t
C_S = concentration of solute in the French fry initially
D = effective diffusion coefficient, m^2/sec
exp = experimental value
ℓ = half - thickness of the potato piece, m
MKat = Maine Katahdin potatoes
MRB = Maine Russet Burbank potatoes
M_t = amount of solute in solution at time t
M_∞ = amount of solute in solution at infinite time
n = number of data points
q_n = roots of equation 6
Q = objective function
R = M_t/M_∞
t = time, sec
T = temperature, Kelvin
V_L = volume of liquid surrounding the potato peice
V_S = volume of the French fry strip
W_L = weight of blanch water in the experimental vessel, kg
W_S = weight of the French fry strip, kg
x = distance measured from the center of the strip

Greek letters

α = $V_L/V_S = a/\ell$
η = dimensionless length, x/ℓ

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—Continued on page 1046

DIFFUSION COEFFICIENTS OF GLU, K + Mg IN POTATOES. . . From page 989

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