# Modeling the Hydration of Foodstuffs: Temperature Effects

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*To assess the impact of hydration kinetics of dried foodstuffs on their sensory property and release of functional molecules, it is necessary to be able to predict the temperature effect. Based on the dynamics of capillary flow in partially saturated porous media, a finite-element model is developed to directly predict the infiltration of water into dried food materials as a function of temperature. The transfer properties are derived from physically based constitutive relationships of water adsorption and permeation. This is in contrast to the semiempirically fitted transfer properties often used in the heat- and mass-transfer models of foods based on Fick's diffusion theory. Rehydration of green tea at different temperatures has been measured using the NMR method. The rehydration process also has been simulated using the capillary model, and the predictions are in good agreement with experimental data.*

## Introduction

Dried foodstuffs often need to be rehydrated before they are consumed. It is desirable for the dried foodstuffs to hydrate as fast as possible and show adequate structural and chemical characteristics. Examples of foodstuffs that need rehydration include dried vegetables (carrots, peas, broccoli, celery), tea, coffee, rice, beans, and cereal grains. Information about water absorption as a function of temperature of those food materials is of critical importance to their shelf life and product usage. Rehydration of food materials also has an important impact on their nutritional and sensorial properties.

A number of studies have been reported to model the hydration kinetics of foodstuffs and different types of models have been used. Two main approaches can be identified. One approach uses the empirical and semiempirical models, for instance, the Peleg and the Weibull equation (Machado et al., 1999; Machado et al., 1998; Lim et al., 1995; Sopade et al., 1992; Sopade and Obekpa, 1990; Peleg, 1988). The other approach employs the diffusive models based on Fick's second law of diffusion (Sanjuan et al., 1999, 2001; Thorvaldsson and Janestad, 1999; Simal et al., 2000; Hsu, 1983). Despite numerous studies using Fick's law to model liquid water transport in porous foodstuffs, the hydration of food materials cannot be simply defined as a diffusion process. Hydration occurs by capillary flow, driven by an energy-potential gradient, rather than by diffusion. One of the main limitations of the diffusion model is that it does not take into account the fundamental properties of water adsorption and permeation. As a result, the transport properties in the diffusion model are often fitted empirically. The other disadvantage of the diffusion model is that it does not include the gravity effect. This can cause problems for high-porosity food materials.

Some studies using the capillary-flow approach to model hydration and/or drying of foodstuffs have been reported recently (Ni et al., 1999; Feng et al., 2001; Irudayaraj and Wu, 1999; Turner and Jolly, 1991; Lian et al., 1997). The capillary flow model takes into account the matrix interaction by using physically based constitutive relationships of water in partially saturated porous media. However, these rigorous constitutive relationships of water retention and permeation are not readily available for most food materials. As a result, the capillary-flow approach is still not widely used.

The objective of this work is to show the feasibility of modeling the rehydration process of foodstuffs using the capillary-flow approach. In particular, the effect of temperature is modeled. We first demonstrate that the transport properties in the capillary model can be derived from the constitutive relationships of water activity that are widely used and readily available for most food materials. We then demonstrate

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that the effect of temperature on hydration can be directly taken into account in the constitutive properties of water adsorption and permeation. This is in contrast to the empirical parameter fittings for the diffusion model. As a model system of porous foodstuff, we use dried green tea leaf material (Sencha). Hydration behavior of green tea at various temperatures is investigated using time-domain NMR. A finite-element model is then proposed to model the hydration process. Consequently, we compare our model predictions with the experimental data of green leaf tea hydration. For the range of temperatures studied, we find good agreement between the model prediction and the experimental data.

## Theory

### *Capillary-flow model*

For fluid flow in a capillary body, we can write the continuity equation as follows (Celia et al., 1990)

$$\nabla\cdot \rho_w J + \rho_w \frac{\partial \theta}{\partial t} = 0 \tag{1}$$

where $J$ is the volumetric mass flux, and $\theta$ is the volumetric moisture (water) content. Normally in capillary-flow theory the flux of water is considered to be governed by Darcy's law

$$J = -\frac{kk_r}{\mu_w}(\nabla P_c - \rho_w g) \tag{2}$$

where $k$ is the intrinsic permeability (m$^2$) and $P_c$ is commonly referred to as the capillary pressure, capillary suction, or matrix potential; $k_r$ is the relative water permeability; $\rho_w$ is the density of water (1,000 kg/m$^3$); $g$ is gravity ($-9.81$ m$^2$/s); and $\mu_w$ (Pa$\cdot$s) is the viscosity of water. The concepts of volume averages over a representative elementary volume (REV) (Whitaker, 1977) are assumed to apply.

The capillary pressure should be thought of as the energy potential of the water, and is negative for partially saturated porous media. The flux is proportional to the gradient of the capillary potential. When the effect of gravity is included, Eq. 1 can be expanded as

$$\frac{\partial \theta}{\partial t} = \nabla\cdot\left(\frac{kk_r}{\mu_w}\nabla P_c\right) - \nabla\cdot\frac{kk_r}{\mu_w}\rho_w g \tag{3}$$

We can further change the unit of capillary potential from Pa to m. Introducing the conductivity, $K$ (m/s)

$$K = \frac{kk_r \rho_w g}{\mu_w} \tag{4}$$

we derive the following more convenient form of water transfer equation in partially saturated porous media

$$\frac{\partial \theta}{\partial t} = \nabla\cdot(K\nabla h) - \nabla\cdot(K\sin\varphi) \tag{5}$$

where $h$ is the pressure head (m), or pressure in equivalent water column, and $\varphi$ is the angle away from the horizontal.

Equation 5 is called the "mixed form" (Celia et al., 1990) of the unsaturated flow equation because of the presence of both $\theta$ and $h$. This mixed form has been implemented in various finite different and -element models for single and multiphase transport (Tiktak and Bouten, 1992; Celia and Binning, 1992; Celia et al., 1990), including solute transport (Simunek et al., 1994) in porous media. It also can be easily extended to include heat transfer (Leech, 2002). Its advantages have not been realized in coupled heat and mass transfer in variably saturated porous media where normally the potential form is used (Chen and Pei, 1989; Irudayaraj and Wu, 1994; Thomas and King, 1992). The potential form suffers from a lack of mass conservation. The mixed form has the advantage of being perfectly mass conservative when implemented numerically. Readers are directed to Celia et al. (1990) for an in-depth discussion of the mixed vs. the potential form and its advantages.

### *Constitutive relationships*

To solve the equation of water transfer in partially saturated porous media, constitutive relationships describing the relative water permeability and capillary potential are needed. Heat- and mass-transfer models developed for foods often assume that simple Fick's diffusion theory applies. As a result, empirically fitted weak constitutive relationships are often used. Here, the constitutive relationships adopted are physically based and characteristic to porous media. We first introduce the water-retention curves most often used in soil physics and hydrology. The water-retention curve describes the capillary potential of a porous medium as a function of moisture content and temperature. Several types of water-retention curves have been proposed (Rossi and Nimmo, 1994; van Genuchten, 1980). One of the commonly used equations is given by van Genuchten et al. (1980).

$$\frac{\theta}{\theta_s} = \frac{1}{[1+|\alpha h|^n]^m} \tag{6}$$

where $h$ is the pressure head (m), $\theta$ is the volumetric water content (m$^3$/m$^3$), $\theta_s$ (m$^3$/m$^3$) is the saturated water content assumed to be equal to the porosity $\phi$; $\alpha$ (m$^{-1}$) and $n(>1)$ are two parameters defining the shape of the water activity curve; and $m = 1-(1/n)$. The water-retention curve can be related to the water-activity curve (Campbell et al., 1993; Gee et al., 1992) by using the Kelvin equation

$$h = \frac{RT}{\rho_w g M_w}\ln(A_w) \tag{7}$$

where $A_w$ is the water activity, $R$ is the gas content, and $M_w$ is the molecular mass of water. The value of $R/M_w$ is 0.461 MPa/K.

According to Mualem (1976), the relative permeability can be modeled by the following relationship as a function of water content and porosity

$$k_r = \left(\frac{\theta}{\theta_s}\right)^{0.5}\left(1-\left(1-\left(\frac{\theta}{\theta_s}\right)^{1/m}\right)^m\right)^2 \tag{8}$$

The viscosity of water depends on temperature. The relationship can be approximately described as follows (Thomas and King, 1992)

$$\mu_w = 661.2(T-229)^{-1.562} \times 10^{-3} \pm 0.5\% \qquad (9)$$

where $T$ is the temperature in Kelvin.

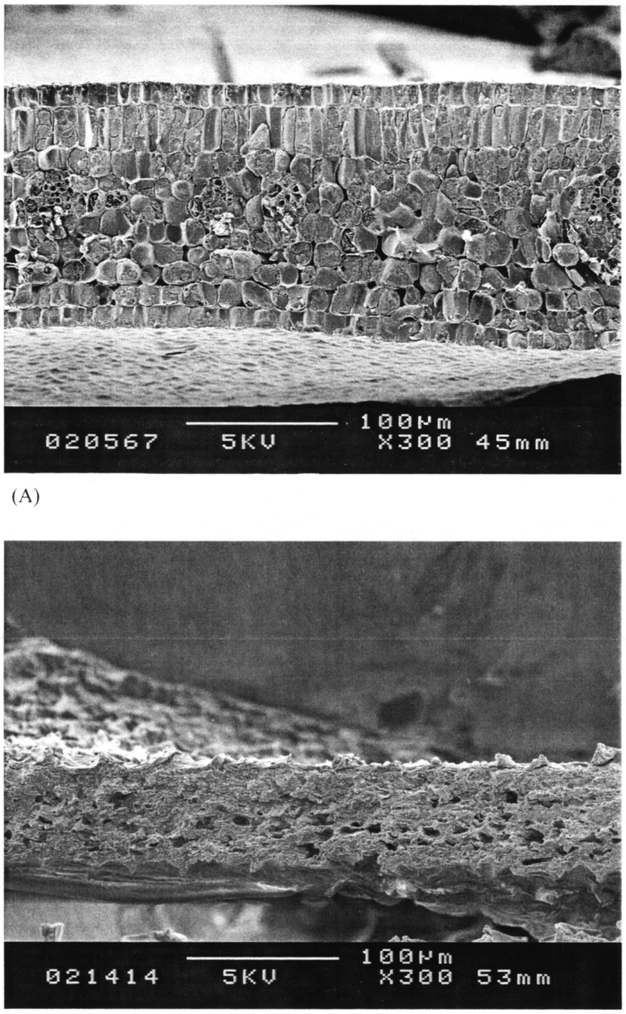
Note that the constitutive relationships of both water retention and hydraulic conductivity just described are strongly dependent on temperature. Thus, the effect of temperature is directly accounted for. This is apparently an advantage of the physically based constitutive relationship over the empirically based weak constitutive relationships widely adopted in food science and engineering. We further demonstrated this advantage in the following example.

## Material and Methods

### *Leaf tea hydration data*

Isothermal hydration experiments have been performed on green tea using time-domain NMR, which is a well-established technique for the measurement of rehydration kinetics of porous systems such as dried foods (Hills, 1998). All NMR measurements were made on a Resonance Instruments (R.I.) MARAN spectrometer operating at 23 MHz. Sample temperature was controlled via a standard R.I. temperature unit, calibrated against an external thermocouple and was found to be stable to $\pm 1$°C. To ensure a more homogeneous system during the rehydration experiments, a simple stirring device was used, enabling measurements to be made while stirring. The stirring device consists of a central plastic rod with perpendicular cross members that fits inside a standard 18-mm-OD NMR tube. The rod was connected to a general lab stirrer running at 30–50 rpm. The motor was clamped to a frame around the magnet, as described elsewhere (Ablett et al., 1999). This work also showed that the action of shear (stirring) has negligible effect on the acquired NMR signal. Up to 200 mg of dry tea leaf was placed in a clean dry tube within the spectrometer and warmed to the appropriate measurement temperature. Between 2 and 2.5 g of prewarmed water was then added and data acquisition immediately started.

Data was acquired by measuring NMR spin-spin relaxation times ($T_2$) as a function of hydration time. These were measured using the CPMG (Carr and Purcell, 1954; Meiboom and Gill, 1958) pulse sequence with up to 8192 echoes and an interpulse spacing of 200 $\mu$s. Normally two transients were recorded with a recycle delay of 1 s. This recycle delay was found to be sufficient to quantify the fast relaxing component, but too short for the slower relaxing component. A final scan was, therefore, recorded with a recycle delay of 20 s in order to quantify the volume of water added. All the resulting CPMG relaxation decays were fitted to a number of discrete exponential components using the R.I. software WinFit. It was assumed that the total signal intensity was due solely to the added water, and no account was taken of the initial moisture content of the leaf. It was also assumed that the fastest relaxing component was due to the water within the tea leaf. The intensity of this component was, therefore, corrected to give the mass of water uptake per gram of dry leaf and plotted as a function of time.



(A)

(B)

**Figure 1. Field emission scanning electron microscope (FESEM) picture of (A) frozen fresh tea leaf, and (B) frozen dried tea leaf.**

### *Tea leaf model*

The hydration of green tea was measured at different temperatures (288, 298, 308, 318, 328, 338, and 348 K). Computer simulations of hydration also have been performed at these temperatures. Figure 1 shows pictures of a frozen fresh and a dried tea leaf. The tea leaf is modeled as a two-dimensional block of 0.0002 m by 0.0025 m, representing the average thickness and size of tea leaves. The model tea leaf was then meshed to a 3,200 triangular finite-element mesh with 1,681 nodes. The initial moisture content at each node was set to 0.012 $m^3/m^3$, about 3% of dry weight. The boundary condition is that the capillary potential for all the nodes at the surface has to be zero.

### *Water activity model parameters*

From the hydration data, we estimate that the saturated water content of the tea leaf is about 0.8 $m^3/m^3$, equivalent to moisture content of 300% (d.b.), assuming a dry bulk den-

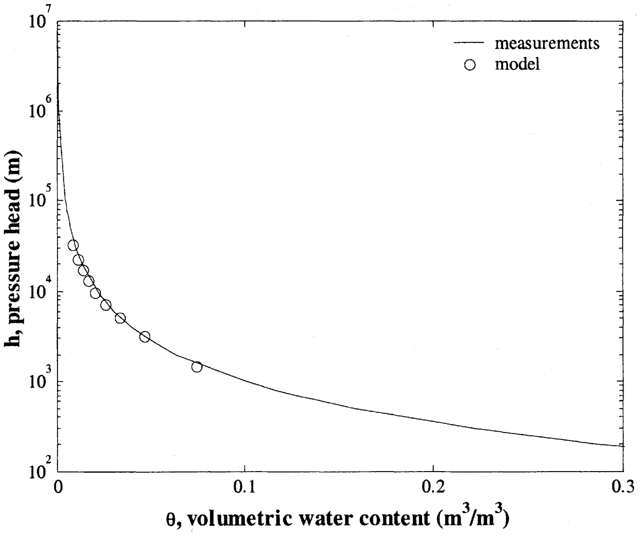


**Figure 2. Measured water activity data (Panchariya et al., 2001) and fitted water retention function as a function of water content at $T = 298$ K.**

sity of 290 kg/$m^3$ and matrix inert density of ±1450 kg/$m^3$. Water activity curves of tea were taken from Panchariya et al. (2001). Using the least-square method, the data were fitted to Eq. 6 to obtain the values of $\alpha$ and $n$. Extrapolation and interpolation between these water-retention parameters as a function of temperature yielded the water-retention curves at the temperatures of the hydration data.

### *Hydraulic conductivity*

From our study on the hydration of black tea as a function of tea leaf size (Weerts et al., 2003), we known that the hydraulic conductivity in the horizontal direction (from the cut edges of the leaf) is much greater than that in the vertical direction (top-bottom), about 100–250 times. Here we assumed that the hydraulic conductivity in the horizontal directions is 125 times greater than that in the vertical direction. The hydraulic conductivity at saturation is calibrated on the hydration data obtained at 25°C, the only temperature at which the water activity curve was also measured. The hydraulic conductivity as a function of water content is calculated using Eqs. 8. Hydraulic conductivity at other temperatures was directly predicted by substituting the viscosity equation (Eq. 9) into Eq. 4.

## Results and Discussion

Figure 2 shows the measured water activity data compared with the fitted water-retention equation proposed by van Genuchten et al. (1980) at $T = 298$ K. The model fits the data well. Results at the other temperatures are similar. The fitted shape parameters of the water-retention curves are given in Table 1 for the different temperatures at which the measurements of the water activity were taken.

**Table 1 Obtained Water Retention Parameters as a Function of Temperature**

| Temp. (K) | $\alpha$ (L/m) | $N$ |
|---|---|---|
| 298 | 0.022 | 1.68 |
| 313 | 0.018 | 1.72 |
| 333 | 0.016 | 1.74 |
| 353 | 0.011 | 1.82 |

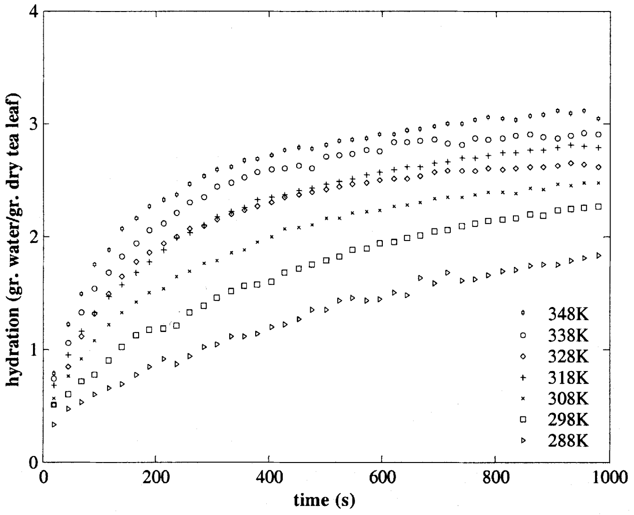


**Figure 3. Measured hydration of green tea as a function of temperature.**

The temperatures are indicated in the legend.

Figure 3 shows all measured hydration curves of green tea for a range of temperatures from 288 K to 348 K. Generally, as the temperature increases, the hydration rate increases. Similar behavior of hydration as a function of temperature was observed for broccoli stems and florets (Sanjuan et al., 2001, 1999), red beans (Abu-Ghannam, 1998), blueberries (Lim et al., 1995), and carrots (Lin et al., 1998).

Figure 4 shows a comparison of the modeled and measured rehydration data at $T = 298$ K. The data at this tem-

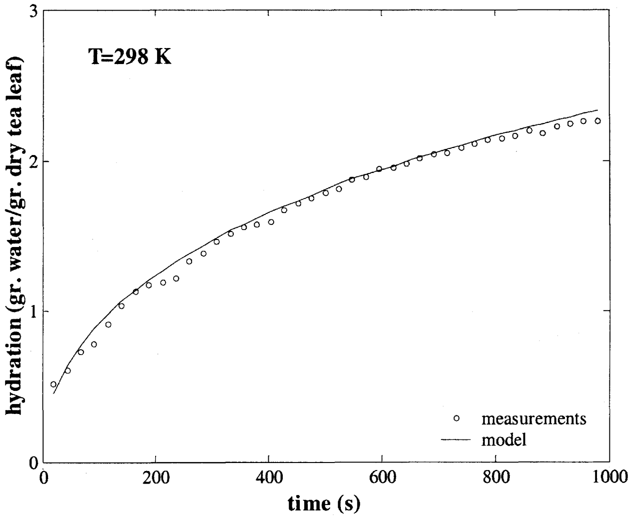


**Figure 4. Modeled (dots) vs. measured (circles) rehydration data on green tea at $T = 298$ K as a function of time; temperature is indicated in the graph.**

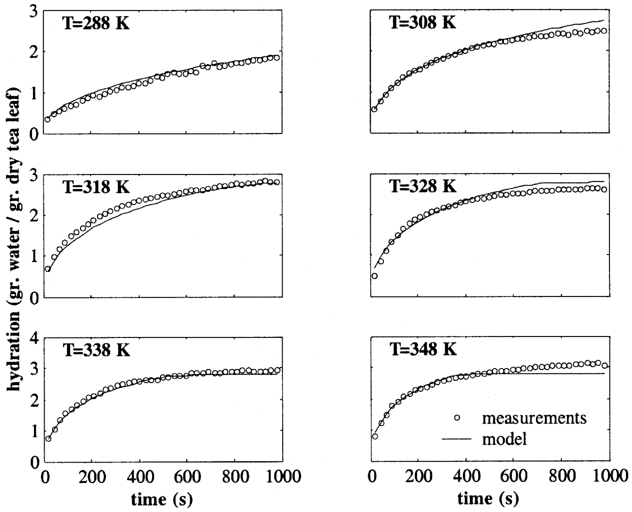


**Figure 5. Model predicted (dots) vs. measured (circles) rehydration data on green tea at $T = 288$ K and $T = 308–348$ K as a function of time.**

Temperature is indicated in each graph.

perature were used to calibrate the values of the hydraulic conductivity. The modeled hydration curve compares well with the measured data. The calibrated value of the hydraulic conductivity (in the horizontal direction) at saturation is $10^{-11}$ m/s. This value of hydraulic conductivity is comparable to the value obtained by Weerts et al. (2003) for black tea.

Figure 5 shows the predicted hydration of green tea at $T = 288$ and $T = 308$, 318, 328, 338, and 348 K. The measured data are also given in the figure for comparison. The predicted hydration curves agree well with the experimental measurements, suggesting that, by using the physically based constitutive relationships, the effect of temperature can be directly predicted with good accuracy. The only model parameters that varied with temperature are the viscosity and activity (that is, surface tension) of water. Their variations with temperature are well documented and are given by simple equations.

The experimental data of leaf tea hydration showed moderate variations in the equilibrium moisture content. There is no clear trend in terms of temperature effect. In the model, we assumed that the equilibrium moisture content was constant for all temperatures. This has resulted in some under- and overpredictions in the equilibrium moisture uptake at some temperatures. However, the differences are very small ($< 10\%$). Experimental studies on other foodstuffs showed that the equilibrium moisture content varied (decreased) as a function of temperature (Abu-Ghannam, 1998; Lim et al., 1995; Sanjuan et al., 1999). From the current hydration data of leaf tea, the effect of temperature on the equilibrium water uptake is not clear. One has to remember that tea is a very heterogeneous material. The tea used in the hydration study was not size-fractionated. The water activity curves used in the modeling study were from the data of black tea. Furthermore, some physical processes such as swelling are not properly taken into account. Nevertheless, the effect on hydration by temperature can be accounted for by the viscosity and activity of water when the physically based constitutive relationships of water transfer in porous media are employed.

## Conclusions

Hydration of foods and biomaterials is greatly influenced by temperature. A mixed form of the unsaturated flow equation based on the capillary flow in porous media is presented in this article. Using this approach, the hydration of green tea at a range of temperatures has been successfully modeled. The predicted hydration curves agree well with the experimental data of NMR. The hydraulic conductivity of green tea was estimated to be $10^{-11}$ m/s at 298 K in the horizontal direction (from the cut edges of the leaves). The hydraulic conductivity in the vertical direction is $8.0 \times 10^{-14}$ m/s.

The mixed-form capillary flow model presented in this article directly predicts the effect of temperature on hydration. The increase in the hydration rate with temperature is mainly due to the viscosity and surface tension of water. The current model is apparently advantageous over the models based on the so-called Fick's second law of diffusion. The current model can easily be applied to model the hydration and dehydration of foodstuffs. Moreover, this approach can easily be extended to include the coupling with heat and solute transport.

## Acknowledgments

This research was funded by the European Union (EU) under the Industry Host Marie Curie Postdoc Fellowship scheme (contract No. HPMI-CT-1999-00046). C. A. Leech is thanked for useful discussions on modeling heat and mass transport in porous media using finite-element techniques. Peter Cleall and Professor Howard Thomas are also thanked for useful discussions on modeling heat and mass transport in porous media.

## Notation

$A_w$ = water activity
$g$ = gravity, m/s$^2$
$h$ = pressure head, m
$J$ = volumetric mass flux of water, m/s
$k$ = intrinsic permeability, m$^2$
$K$ = water permeability, m/s
$k_r$ = relative water permeability
$M_w$ = molecular mass water, kg
$m$ = 1-1/$n$
$n$ = water retention (shape) parameter
$P_c$ = capillary pressure, Pa
$R$ = gas constant, J/mol·K
$t$ = time, s
$T$ = temperature

### *Greek letters*

$\alpha$ = water retention (shape) parameter, m$^{-1}$
$\theta$ = water content, m$^3$/m$^3$
$\theta_s$ = saturated water content, m$^3$/m$^3$
$\phi$ = porosity
$\rho_w$ = density of water, kg/m$^3$
$\mu_w$ = water viscosity, Pa·s

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*Manuscript received May 22, 2002, and revision received Oct. 30, 2002.*