Rehydration Kinetics of High-Pressure Pretreated and Osmotically Dehydrated Pineapple

N.K. RASTOGI, A. ANGERSBACH, K. NIRANJAN, AND D. KNORR

ABSTRACT: Rehydration kinetics of high-pressure pretreated (100, 300, and 500 MPa for 10 min) and osmotically dehydrated pineapple (Ananas comus) cubes (2 × 2 × 1 cm) were studied at different temperatures (5, 25, and 35 °C), and compared with ordinary osmotically dehydrated samples. The effective diffusion coefficients for water and solute were determined, assuming the rehydration process to be governed by Fickian diffusion. Diffusion coefficients for water absorption into the tissue and as well as for solute diffusion out of the tissue were found to be lower in the samples subjected to high-pressure treatment. Further, the diffusion coefficients decreased with increase in treatment pressure. A possible explanation for the observed decrease in diffusion coefficients can be attributed to the permeabilization of cell membranes, the release of cellular components, and structural changes of the cell materials. The diffusion coefficients were correlated with rehydration temperature (T) and treatment pressure (P) by an Eq. of the form $D = A \exp\left[-(B \cdot P + C/T)\right]$, where A, B, and C are constants.

Key Words: rehydration, high pressure, osmotic dehydration, mass transfer, diffusivity, pineapple

Introduction

PINEAPPLE FRUIT, LARGELY GROWN IN THE TROPICAL REGIONS, is distributed worldwide. An earlier study reported that the mass transfer rates in high-pressure treated pineapples (100 to 700 MPa) during osmotic dehydration are significantly higher than those observed in ordinary pineapples (Rastogi and Niranjan 1998). The effective diffusion coefficients for water and sucrose reportedly increased 4- and 2-fold, respectively. This enhancement in diffusion coefficient was attributed to cell rupture and increase in tissue permeability caused by the application of high pressure. While the enhancement in mass transfer rates is a desirable outcome, it is well known that cell disintegration can impair rehydration (Rastogi and Niranjan 1998). Absorption of water into the tissue and leaking out of solutes both occurred concurrently during rehydration. Increase in mass is a net result of these 2 processes. The amount of water absorbed as well as the rates of absorption are adversely affected if cell disintegration occurs. A study of rehydration kinetics can be used to ascertain the net extent of injuries sustained by any material during dehydration and any other processing steps prior to it. Although, considerable published information is available on the drying of fruits and vegetable using different methods, there is a lack of information relating to rehydration. Further, there is no consistency in studying rehydration characteristics with regard to food to water mass ratio, temperature of rehydration, level of agitation, and procedure for the determination of moisture content (Lewicki 1998). It has been reported in literature that high-pressure processed green beans, carrots, potato (Eshtigahi and others 1994), and pineapple (Rastogi and Niranjan 1998) samples rehydrated poorly due to lack of cell integrity. This work was undertaken to investigate this aspect further. The effective diffusion coefficients for water infusion and solute loss during rehydration of high-pressure treated and osmotically dehydrated pineapple were experimentally determined using rectangular parallelepiped shaped pieces. The proportion of the cell damaged after high-pressure pretreatment was estimated in terms of the cell disintegration index using an electrophysical measurement technique.

Results and Discussion

Effect of high-pressure pretreatment on rehydration kinetics

The moisture and solids content of the samples during rehydration were measured with time at high-pressure treatment of 5, 25, and 35 °C. Plots for the variation of moisture and solid contents with time (Fig. 1a and 1b) show that the moisture and solute diffusion rates decreased with each increase pretreatment pressure. Thus at given time, the control took up more water and consequently had a lower solute content than the pressure-treated samples. This was true for the 3 rehydration temperatures used.

The cell disintegration indices ($Z_p$) of control and high-pressure treated samples are compared in Fig 2. It may be noted that control samples are those that are not subjected to high-pressure treatment. $Z_p$ values were found to increase almost in direct proportion to the applied pressure, indicating that a high-pressure treatment of 10 min irreparably damaged the cells. Pressure treatment other than 10 min was not studied.

The rate of change of moisture ($dm/dt$) as well as solid ($ds/dt$) content (obtained from Fig. 1a and 1b) were plotted against average solid and moisture content (Fig. 3a and 3b), respectively, and the equilibrium moisture and solid contents ($m_e$, $s_e$) as well as moisture and solid mass transfer coefficients ($k_{m_p}$, $k_{s_p}$) were inferred from these plots. These values together with the diffusion coefficients for different combinations of high-pressure pretreatment and rehydration temperatures are given in Table 1.

It is evident from Table 1 that the diffusion coefficient for water absorption was lower in high-pressure pretreated samples, mainly due to cell permeabilization caused by high pressure. At the same time, the diffusion coefficient for solute loss during rehydration was also lower. This suggests that high-pressure pretreatment can be used to reduce solute loss during rehydration.
could be attributed to structural changes caused by high-pressure pretreatment (Eshtiaghi and others 1994) due to compactness of cellular structure and the formation of gel-network with divalent ions binding to de-esterified pectin (Basak and Ramaswamy 1998).

**Table 1—Effective diffusion coefficients of water ($D_{w}$) and solute ($D_{s}$) at different pressures using a 10-min hold**

<table>
<thead>
<tr>
<th>Treatment Pressure (MPa)</th>
<th>Treatment Temperature (°C)</th>
<th>$D_{w} \times 10^9$ (m²/s)</th>
<th>$D_{s} \times 10^9$ (m²/s)</th>
<th>$k_w \times 10^3$ (1/s)</th>
<th>$k_s \times 10^3$ (1/s)</th>
<th>$m_w$ (kg/kg)</th>
<th>$s_w$ (kg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>5</td>
<td>0.892</td>
<td>1.286</td>
<td>0.130</td>
<td>0.187</td>
<td>1.151</td>
<td>0.353</td>
</tr>
<tr>
<td>100</td>
<td>5</td>
<td>0.783</td>
<td>1.142</td>
<td>0.114</td>
<td>0.166</td>
<td>0.968</td>
<td>0.379</td>
</tr>
<tr>
<td>300</td>
<td>5</td>
<td>0.560</td>
<td>1.015</td>
<td>0.081</td>
<td>0.148</td>
<td>0.909</td>
<td>0.425</td>
</tr>
<tr>
<td>500</td>
<td>5</td>
<td>0.470</td>
<td>0.941</td>
<td>0.068</td>
<td>0.137</td>
<td>0.820</td>
<td>0.473</td>
</tr>
<tr>
<td>Control</td>
<td>25</td>
<td>0.960</td>
<td>1.460</td>
<td>0.140</td>
<td>0.214</td>
<td>2.066</td>
<td>0.255</td>
</tr>
<tr>
<td>100</td>
<td>25</td>
<td>0.830</td>
<td>1.270</td>
<td>0.121</td>
<td>0.181</td>
<td>1.642</td>
<td>0.282</td>
</tr>
<tr>
<td>300</td>
<td>25</td>
<td>0.660</td>
<td>1.110</td>
<td>0.095</td>
<td>0.163</td>
<td>1.557</td>
<td>0.303</td>
</tr>
<tr>
<td>500</td>
<td>25</td>
<td>0.510</td>
<td>1.001</td>
<td>0.089</td>
<td>0.150</td>
<td>1.504</td>
<td>0.323</td>
</tr>
<tr>
<td>Control</td>
<td>35</td>
<td>1.250</td>
<td>1.340</td>
<td>0.182</td>
<td>0.195</td>
<td>1.949</td>
<td>0.144</td>
</tr>
<tr>
<td>100</td>
<td>35</td>
<td>1.070</td>
<td>1.250</td>
<td>0.156</td>
<td>0.182</td>
<td>1.695</td>
<td>0.191</td>
</tr>
<tr>
<td>300</td>
<td>35</td>
<td>0.852</td>
<td>1.057</td>
<td>0.124</td>
<td>0.160</td>
<td>1.525</td>
<td>0.245</td>
</tr>
<tr>
<td>500</td>
<td>35</td>
<td>0.675</td>
<td>0.955</td>
<td>0.098</td>
<td>0.139</td>
<td>1.462</td>
<td>0.251</td>
</tr>
</tbody>
</table>

**Data correlation**

A correlation similar to the combination of the well-known Arrhenius and Erying Eq. can be proposed to relate the effect of high-pressure treatment and rehydration temperature on effective diffusion coefficients:
Rehydration Kinetics of High-pressure Treated Pineapple . . .

\[ D_w = 2.51 \times 10^{-4} \left[ e^{-2 \left( 15 \times 10^{-4} \cdot P \cdot 0.29 \cdot T \right) / (T + 273)} \right] \quad (R^2 = 0.936) \quad (5) \]

\[ D_s = 0.26 \times 10^{-4} \left[ e^{-0.67 \cdot 10^{-7} \cdot P \cdot 0.2 \cdot 10^9 / (T - 273)} \right] \quad (R^2 = 0.931) \quad (6) \]

where \( P \) is absolute pressure in MPa, and \( T \) is temperature in degrees Celsius. The diffusion coefficients decrease markedly with pressure up to 300 MPa. Further increase in pressure does not result in the diffusion coefficients changing significantly. This confirms the earlier observation that major changes in the tissue microstructure occur below 300 MPa, and potential benefits of higher pressures are minimal (Rastogi and Niranjan 1998).

**Materials and Methods**

**Materials**

Ananas de Cote d’Ivoire variety of pineapples (Ananas comosus) were procured from a local supermarket. The pineapple, after peeling and decoring, was cut into rectangular parallelepiped shaped pieces (20 mm \( \times \) 20 mm \( \times \) 10 mm). The average moisture content of fresh pineapple, determined by vacuum drying at 70 °C, was found to be 85% on a wet weight basis. Commercial sucrose was used as the osmotic agent.

**High-pressure pretreatment**

The pineapple pieces were subjected to high hydrostatic pressures in an isostatic pressure vessel (National Forge Europe, Belgium). The unit had a working volume of 700 ml, and its maximum recommended working pressure was 600 MPa. Maximum pressure could be reached within 2 min, and the decompression time was about 10 s. Pineapple samples were vacuum-sealed in double polyethylene pouches and subjected to pressures of 100, 300, and 500 MPa, for an arbitrarily chosen time period of 10 min. The maximum temperature experienced by the sample during pressurization was 35 °C, and it cooled to about 15 °C during decompression. A mixture of distilled water and press oil (97:3 \( \text{v/v} \)) was used as a medium for transmitting pressure.

**Osmotic dehydration**

High-pressure treated samples and nontreated controls were taken from the same pineapple, blotted with tissue to remove external moisture, and then subjected to osmotic dehydration in sugar solution (50 °Brix) maintained at 30 °C. The temperature was controlled using a constant temperature stirred water bath. The ratio of the volume of the pieces to that of the medium was maintained at 1:25. The pieces were weighed and then subjected to rehydration. The dry matter was estimated after rehydration by drying the rehydrated sample in a vacuum oven at 70 °C for 18 h. The moisture and solid content after rehydration was expressed in terms of kg of water (or solids)/kg of initial dry solids. All the experiments were done in triplicate, and average values are reported.

**Determination of water and solute diffusivities during rehydration**

The solution of Fick’s second law for diffusion from a rectangular parallelepiped of sides \( a \), \( b \), and \( c \) results in the following well-known equation for the transfer of water and solute, respectively (Crank 1975):

\[ M_r = \frac{m_0 - m_n}{m_0 - m_s} = \sum_{n=1}^{\infty} C_n \exp\left[-D_{tw} \left(1 + \frac{a^2}{a^2} \right) \right] \quad (1) \]

and

\[ S_r = \frac{s_0 - s_n}{s_0 - s_s} = \sum_{n=1}^{\infty} C_n \exp\left[-D_{ts} \left(1 + \frac{b^2}{a^2} \right) \right] \quad (2) \]

where \( M_r \) and \( S_r \) are the moisture and solute ratio; the subscripts \( o \), \( s \), and \( t \) represent the relevant concentrations initially, at equilibrium, and at any time; \( D_{tw} \) and \( D_{ts} \) are the effective diffusivity of water and solute, respectively; and \( C_n \) is equal to \( 2a(1 + \alpha)/(1 + \alpha + a^2 q_n^2) \) where, \( q_n \) are the non-zero positive roots of the equation \( q_n^2 = a^2 \). Here, \( \alpha \) is the ratio of volume of solution to that of each piece, and \( 1/A^2 = (1/a^2) + (1/b^2) + (1/c^2) \).

Defining the fourier numbers for moisture (\( F_{ow} \)) and solute diffusion (\( F_{os} \)) as \( D_{ow}/A^2 \) and \( D_{ts}/A^2 \), respectively, an approximate form of Eq. 1 and 2, which neglected terms involving \( n \) > 1, was graphically represented by plotting log (\( M_r \) or \( S_r \)) against fourier number (Fig. 4). The slope of this line gave \( d\log(M_r)/dF_{ow} \) and \( d\log(S_r)/dF_{os} \).

The slopes of the corresponding experimental lines for moisture and solid diffusion \( (d\log(M_r)/dt) \) and \( (d\log(S_r)/dt) \) were obtained by fitting the experimental data to the solution of mass transfer equation for moisture and solid mass.
transfer during rehydration:

\[
\frac{dm}{dt} = k_m (m - m_a)
\]

and

\[
\frac{ds}{dt} = k_s (s - s_a)
\]

where \(k_m\) and \(k_s\) are the moisture and solid mass transfer coefficients. Integration of the Eq. 3 and 4, with the appropriate initial condition, resulted in the following equation:

\[
\ln \left( \frac{m - m_a}{m_c - m_a} \right) = \ln M_r = k_m t
\]

and

\[
\ln \left( \frac{s - s_a}{s_c - s_a} \right) = \ln S_r = -k_s t
\]

The experimental data (\(M_r\) and \(S_r\) against \(t\)) were fitted to Eq. 5 and 6 to yield \(k_m\) and \(k_s\), which in turn gave the slopes:

\[
\frac{d}{dt} \left( \log M_r \right) = \frac{k_m}{2.3025}
\]

and

\[
\frac{d}{dt} \left( \log S_r \right) = -\frac{k_s}{2.3025}
\]

\(D_{cv}\) and \(D_{cs}\) values were estimated from the following Eq., which hold good when rehydration time is sufficiently large. (Perry and others 1984; Rahman and Lamb 1991; Rastogi and Raghavarao 1997):

\[
D_{cv} = \left[ \frac{d(dM_r)/dt}{d(dS_r)/dF_{cv}} \right] A^2
\]

Determination of cell disintegration index (\(Z_p\))

The conductivity–frequency spectra (Fig. 5) of high-pressure treated and control samples of pineapple were obtained (Angersbach and others 1997, 1999; Knorr and Angersbach 1998). The cell integration index (\(Z_p\)) was defined as:

\[
Z_p = 1 - \frac{k_i}{k_h}; \quad 0 \leq Z_p \leq 1
\]

where \(b = \frac{k_n}{K_{i}}; K_h\) and \(K_i\) are the electrical conductivity of control and treated samples measured in a low-frequency field (1 to 5 kHz), and \(K_n\) and \(K_i\) are the electrical conductivity of control and treated samples measured in a high-frequency field (3 to 50 MHz). The cell disintegration index characterizes the proportion of cells with highly permeable cell walls. \(Z_p\) takes values between 0 and 1 corresponding to 100% intact cells and total cell disintegration, respectively. The conductivity of control and treated samples was determined with impedance measurement equipment (Electronic Manufacture Company, Mahlsdorf, Germany) between parallel disc electrodes (9.7 mm dia) spaced 10 mm apart. The phase voltages were of equal amplitude (between 1 to 5 V, peak to peak), and the frequency changed between 3 kHz to 50 MHz.

Fig. 4—Theoretical diffusion curve for parallelepiped (as per the Eq. 1 and 2)

Fig. 5—Frequency dependent electrical conductivity spectra of control (0.1 MPa) and high-pressure treated pineapple samples

References


Rastogi NK, Raghavarao KSMS. 1997. Mass transfer during osmotic dehydration of carrot:

\[ D_{cs} = \left[ \frac{d(dM_r)/dt}{d(dS_r)/dF_{cs}} \right] \cdot A^2 \]


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