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15 Mass Transport and Deformation Relaxation Phenomena in Plant Tissues

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**Abstract**

Mass transfer in the dehydration process of plant tissues promotes a great sample volume reduction due to cell water loss. As a consequence, cells deform greatly while linked through bonding zones, giving a shrunken cell network. This network may store a great amount of mechanical stress, depending on the elastic-viscous properties of cell walls and bonding zones. In osmotic dehydration, water loss and solute gain define the total volume of product liquid phase (LP) lost throughout the process and the final ratio between LP and solid matrix phase (MP); the higher the ratio, the lower the sample volume loss. In highly porous tissues, the gas phase (GP) volume collapse will also affect the sample volume development. LP and GP volume changes are greatly affected by sample shape.
After sample deformation as a result of water loss, the free energy stored in the sample as mechanical stress can be liberated, leading the system to true equilibrium. Then, the sample volume relaxes, and the product recovers volume and, if it is immersed in an external liquid phase, mass. Hydrodynamic mechanisms promoted by internal pressure gradients associated with volume relaxation imply a gain in the external liquid phase. Kinetics of volume relaxation and volume-mass recovery degree are greatly affected by particular characteristics of the plant tissues and by the osmotic dehydration process conditions. The control of these phenomena may be a useful tool to reformulate fruit and vegetable products in processes focused on improving their quality, stability, and nutritional or health properties.

15.1 INTRODUCTION

In the processing of fruits and vegetables, the solid-fluid systems (SFSs) are very frequent in different fields of food technology, such as osmotic dehydration, rehydration, candy processing, boiling and cooking, etc. The heat and mass transfer processes in such systems have usually been modeled considering the food solid as a continuous phase. Nevertheless, the tissue cellular structure (intercellular spaces and cell compartmentation) plays an important role in the definition of mechanisms involved in the process and, therefore, in process kinetics. Recently, several works have been carried out in determining the influence of product porosity in the response of the fruit tissue to solid-liquid operations. In this sense, hydrodynamic mechanisms (HDMs) have been described as fast mass transfer phenomena occurring in process operations in SFS when changes in temperature or pressure take place. During HDM action, the occluded gas inside the product pores is compressed or expanded according to pressure or temperature changes, while the external liquid is pumped into the pores in line with the gas compression. An effective exchange in the product (internal gas for the external liquid) can be promoted by vacuum impregnation (VI). In such an operation, a vacuum pressure \( p_v \) is imposed on the system for a short time \( t_v \) and afterward, the atmospheric pressure \( p_a \) is reestablished, while the product remains immersed in the liquid for a time \( t_a \).

The pressure changes may cause deformation of the sample volume, and, consequently, HDM usually occurs coupled with deformation-relaxation phenomena (DRP) of the sample structure. The role of DRP is relevant when the sample behaves as a viscoelastic structure, and characteristic impregnation and relaxation times of the product are in the same order. The volume fraction of the initial sample impregnated by the external liquid when mechanical equilibrium is achieved in the sample \( \chi \) has been modeled as a function of the compression ratio \( \gamma \), sample effective porosity \( \varepsilon_{eff} \), and sample volume deformations \( \gamma \) at each step of the process. Vacuum impregnation implies a significant structural change of the product: volume deformation and great reduction of porosity with the introduction of external liquid in the pores. So, different mass transfer behavior has been observed for VI products.

Mass transfer in many processes (such as hydration or dehydration operations) implies important changes in the sample volume and shape, mainly in regard to the gain or loss of the major component (water). Cellular structures such as plant tissue deform to a great extent after osmotic or air dehydration (shrinkage) as well as after hydration (swelling). In such systems, the occurrence of pressure gradients also concerns both mass transfer and deformation-relaxation phenomena. Deformations will be greatly dependent on the cell network arrangement, the gas-phase volume trapped or contained in their porous structure and, in osmotic dehydration, on the facility of the tissue to allow the contradiffusion of external solutes to replace the water lost. After shrinkage, the elastic component of mechanical energy involved in the volume changes and the cellular deformations may be liberated, thus promoting volume recovery of the samples. The generated changes in the internal pressure associated with volume recovery will promote hydrodynamic fluxes and, consequently, mass gain.

In this chapter, the volume changes promoted by osmotic dehydration as affected by sample porosity and shape are analyzed. Likewise, the volume recovery capability of some osmoated fruits and its implication in promoting hydrodynamic flow after chemical equilibrium is discussed. Finally, the influence of the replacement of the sample gas phase by VI with an external liquid on sample volume changes and deformation-relaxation phenomena is analyzed.

15.2 FRUIT VOLUME CHANGES IN OSMOTIC TREATMENTS

Changes of the volume of a fruit or vegetable sample throughout an osmotic dehydration process may be considered in a simplified way as being made up of three phases: the fruit liquid phase (LP), the gas phase occupying pores (GP) and the insoluble solid matrix (MP). The first is constituted by water plus soluble solids (native or incorporated from the external solution). Volume or mass loss during an osmotic process may be explained in terms of the partial losses of each one of the phases. In samples where there is a gas phase, either losses or compression-expansion of gas will contribute to volume change. Equation (15.1) reflects the total volume variation in terms of the changes of each phase, all referring to the sample's initial volume. In practical terms, it is possible to assume that \( \Delta V_{MP} = 0 \), due to its very small initial value; thus, only changes in the liquid and gas phase will describe the volume development. The values of \( \Delta V_{LP} \) can be calculated, if sample composition (water and soluble solid content) and weight loss are known, by applying Equation (15.2), where the density of the LP \( \rho_{LP} \) can be estimated from its empirical relationship with the LP solute mass fraction \( \chi_e \). Equation (15.3) shows an example of a previously established equation for some fruits by Barat et al. At a determined level of LP concentrations, \( \Delta V_{LP} \) values will be lower when the solute gain is higher and the water loss lower.

\[
\Delta V = \Delta V_{LP} + \Delta V_{GP} + \Delta V_{MP} \tag{15.1}
\]

\[
\Delta V_{LP} = \left( \frac{\rho_{LP}^0}{M^0} \right) \left( \frac{M^0(x_e^0 + x_e^1) + M^1(x_e^0 + x_e^1)}{\rho_{LP}^0} \right) \tag{15.2}
\]
\[ \rho_{LP} = 141z_e^2 + 376z_e + 1000 \]  \hspace{1cm} (15.3)

In Figure 15.1, differences in sample volume development, in line with concentration of the LP, can be observed for the same product (Granny Smith apple) in osmotic treatments with 65° Brix sugar solutions. Total volume change of the samples is plotted as a function of the solid mass fraction of the LP \( z_e \) reached at different times. Volume pathway differences appear due to sample shape (2 x 2 cm cylinders, C, and 1 cm thick slices, S) and sample porosity reduction by previous V1 treatment with isotonic solutions of different viscosity (with and without 2% HM pectin: samples C-I-2 C-I-1, respectively). Comparison of cylinder and slice behavior throughout osmotic treatment shows that at a determined LP concentration, greater volume reduction was promoted in cylinders. This is because the greater solid gain-water loss ratio was reached in slices, as shown by the development of \( \Delta V_{LP} \), also plotted in Figure 15.1 for both samples. Sugar gain-water loss ratio is improved in slices because of their higher surface-volume ratio and their lower mass transfer characteristic dimension, both making the solid penetration into the tissue through the pores more effective.

In porous samples, the change in the gas-phase volume will also contribute to volume loss. Figures 15.2a and 15.2b show the comparison between \( \Delta V \) and \( \Delta V_{LP} \) for cylinders and slices, respectively. Total volume losses are greater than the corresponding \( \Delta V_{LP} \), although a linear correlation was observed for both magnitudes. In cylinders, \( \Delta V \) is 1.07 times the \( \Delta V_{LP} \), which, taking into account Equation (15.1), implies a gas volume loss in line with process progression of 0.065\( \Delta V \). In slices, gas volume losses contribute to the total volume loss to a greater extent, on the order of 0.19 \( \Delta V \). From these results, it can be deduced that sample shape plays an important role, not only in the relative water-solute transport rate, but also in the cell network collapse during dehydration and thus in porosity changes of the sample. Figure 15.3 shows the development of apple sample porosity throughout osmotic dehydration as a function of the reached \( z_e \) values. In both cases, porosity increases in line with sample concentration, as has been previously reported. Nevertheless, the greater gas phase collapse in slices is reflected in Figure 15.3, as the porosity increase is less marked than in cylinders.
Reduction of sample porosity by VI with isotonic solutions modifies the pathway of sample volume change, depending on the viscosity of the impregnating liquid. Apple cylinders impregnated with the low-viscosity solution (samples C-I-1 in Figure 15.1) show smaller volume losses, at a determined concentration level, than nonimpregnated cylinders or those impregnated with the higher viscosity solution (samples C-I-2 in Figure 15.1). For impregnated samples where practically no residual gas remains, total volume change will be equal to the $\Delta V_{LP}$ value, as shown in Figure 15.2a for samples C-I-1 and C-I-2. Therefore, differences in sample volume change behavior are explained in terms of the differences in sugar concentration profiles. As shown in Figure 15.2a, the close agreement between $\Delta V$ and $\Delta V_{LP}$ values for C-I-1 and C-I-2 samples can be observed. The presence of a low-viscosity liquid in the intercellular spaces promotes solute diffusion in these non-compartmented spaces, whereas this is more limited in samples containing a very viscous liquid in the pores. So, in low-porosity products, the compositional equilibrium may be reached in each case with different relative levels of sugar gain and water loss, defining the total volume change of the samples. The greater the LP/MP mass ratio, the higher the sample final volume.

In osmotic dehydration processes, sample porosity reduction occurs when a vacuum pulse is applied at the beginning of the process in the dehydration tank. This process has been called pulsed vacuum osmotic dehydration (PVOD), and differences in the sample volume change path may be obtained in these cases. In this operation, an osmotic solution is introduced into the fruit pores, replacing the initial gas, but sample volume compression may occur when atmospheric pressure is reestablished, if characteristic times of liquid penetration and sample deformation range in the same order. This takes place when sample pores are very narrow or liquid viscosity is high. In VI with highly concentrated osmotic solutions, both factors may be present: highly concentrated sugar solutions are viscous, and the surface pore entrance may be narrowed because of the fast water loss by surface cells. Sample volume changes vs. $\Delta V_{LP}$ for apple slices (1 cm thick) in PVOD treatments with 65°C Brix sucrose solutions are plotted in Figure 15.2b. A linear relationship is observed for both variables, but a significant value of the straight-line intercept was obtained. The slope of the straight line is not near 1, as in previously impregnated samples with isotonic solutions, but less than 1. In this case, Equation (15.4) shows the volume balances, where two additional terms appear: possible sample volume change due to compression-relaxation by the vacuum pulse $\Delta V_{C,R}$, and a liquid phase volume impregnating the pores ($\Delta V_{LP}$) that does not contribute to sample volume (Equation (15.4)), both terms replacing the initial $\Delta V_{LP}$ in Equation (15.1). These terms explain the straight-line intercept value. On the other hand, a sample volume relaxation when taken out of the viscous osmotic solution (and the subsequent GI recovery) may explain the slope deviation from 1.

$$\Delta V = \Delta V_{LP,VI} + \Delta V_{C,R} + \Delta V_{LP}$$ (15.4)

Table 15.1 shows the changes in mass and volume of cylindrical samples of some osmotically treated fruits, with different porosities, at time of chemical equilibration with the osmotic solution ($t_i$). The effects of previous impregnation of the sample with an isotonic solution of different viscosity on sample volume and mass, commented on above, can be observed at this time. On the other hand, values of change in mass and volume of some fruits equilibrated with 55°C Brix sucrose solution ($z_i = 0.55$) can be observed in Table 15.1. Fruits with low porosity show very close values of $\Delta V$ and $\Delta V_{LP}$, since the reduction of the gas volume phase is not appreciable due to its low initial value. Different feasibility of the fruit tissue to promote solid gain was observed through the $\Delta VLP$ values. In this sense, apple and kiwi fruit with very different initial porosities show the smallest LP loss and, thus, the highest sugar gain-water loss ratio. In all fruits, PVOD process implied lower values of $\Delta V_{LP}$ and, as expected, the higher the fruit porosity, the greater the difference, according to the LP gain in the sample due to the vacuum pulse.

15.3 CHANGES AT THE CELLULAR LEVEL

Sample volume loss in the osmotic process is the result of a great cell volume reduction because of water loss. Cell water loss implies the generation of an internal void and subsequent internal pressure reduction, which promotes hydrodynamic mechanisms. Internal pressure gradients also contribute to a different cell microstructural development depending on the kind of fluid (gas or liquid) in the tissue pores. Figures 15.4a and 15.4b show cryoSEM micrographs of osmosed apple tissue for two kinds of osmotic treatments, OD (carried out at atmospheric pressure) and PVOD, where a very different aspect can be observed. In this kind of micrograph, an insoluble matrix (MP) can be observed as the cell wall network and membranes. The fruit LP appears in the intracellular or extracellular volumes with a dentritic aspect, according to the description of Bomber and King, for aqueous phases in
the tissue containing soluble solids. GP volume can also be observed occupying the intercellular spaces (is) in the OD, treated samples. No GP is observed in the micrograph of the PVOD, treated sample, as this was quantitatively exchanged by external liquid during the vacuum pulse. Another difference between the microstructures of OD and PVOD samples concerns the behavior of the cell wall-plasmalemma ensemble throughout dehydration. When GP is present in the is, such as in OD treated apple, no cell wall-plasmalemma separation is observed, and the latter deforms together with the cell wall throughout the cell shrinkage. In the PVOD-treated sample, plasmalemma separates from the cell wall at the very beginning of the osmotic process in the cell, and the LP in the is flows through the permeable cell wall, flooding the volume between plasmalemma and wall. This feature can be observed in Figure 15.4b for apple PVOD treated with rectified-concentrated grape must. The well-preserved cell volume surrounded by the cell membrane during sample fracture after cryofixation is remarkable. This suggests a great firmness of the apparently undisrupted membrane.

The differences in behavior of the cell wall plasmalemma ensemble have been explained in terms of the different pressure drops of gas or liquid phases in the is during their flux toward the generated volumes when the cell shrinks. A force balance on both sides of the cell-cell wall layer during the cell dehydration can be created (Figure 15.5). The reaction forces to the shrinkage-associated force \( F_3 \) are
the deformation resistance of the layers \( F_p \), plus the resistance associated with the fluid pressure drop (\( \Delta P \)) when it flows in the is.] The module of action-reaction forces on the elastic double layer in dynamic equilibrium increases in line with the overall water loss (degree of layer deformation), and with the water loss rate (deformation rate) as well. When the is is occupied by gas (e.g., in OD), the force component \( \Delta P \) is negligible, and cw deforms bonded to p while the gas phase flows into the is. On the contrary, when a liquid phase occupies the is (e.g., in PVOD), the pressure drop of liquid is much greater, and the \( F_p \) value overcomes the cell wall-plasmalemma adherence force \( F_p \) quickly. In this situation, cell wall-plasmalemma separate, thus promoting the liquid flow through the permeable cw, whereas this remains less deformed. The water loss rate, which defines the cell deformation rate, will also affect the critical value of water loss at which cw-p separation occurs, due to the viscoelastic response of the bonding zones.\(^9\,11\)

Figure 15.4c shows a cryoSEM micrograph of an osmohydrated apple sample previously impregnated with an isotonic solution containing 2% HM pectin. The dendritic aspect of the intercellular liquid appears more compact due to the vitrifying effect of polymer in the impregnated liquid. Cell walls are more folded than in the sample impregnated with a less viscous solution (Figure 15.4b). Another notable difference with respect to this sample is that sample fracture after cryofixation does not show the entire cell volume surrounded by plasmalemma, but it shows a non-continuous membrane and vesicles. The different response of cell wall plasmalemma ensemble in this impregnated sample can be understood on the basis of the model of force balance explained above. When \( F_p \) increases in line with dehydration, the is liquid will pass through the cell wall, but pectin macromolecules will be retained in the cell wall as in a filtration membrane, as the process occurs with a very high pressure drop. Cells lose water (and volume) faster than the external liquid passes through the cell wall, and so this deforms to a greater extent than in the sample of Figure 15.4b. These great forces acting on the cw-p layer seem to break membranes that appear, in some cases, as small vesicles.

**15.4 CELL NETWORK RELAXATION AND HYDRODYNAMIC FLOW**

In long-term osmotic processes, sample mass and volume decrease in line with osmotic dehydration until a minimum value is reached at compositional equilibrium time \( t_e \). This is when the fruit LP and the osmotic solution have the same value of water chemical potential, which, in practical terms, implies the similar mass fraction of soluble solids of both liquid phases.\(^10\) From this point, sample mass and volume begin a slowly increasing pathway until the initial values are almost recovered in some cases. This was observed initially in apple samples\(^10\,16\) and has been confirmed for other fruits.\(^17\) Sample mass and volume recovery has been explained in terms of the relaxation of the shrunken cell wall network, greatly deformed in the initial dehydration step. A great amount of free energy was stored in the structure as mechanical energy during cell dehydration-shrinkage. The true equilibrium in the system implies the free energy reduction by release of stored mechanical stress. If the product remains immersed in the external solution, volume recovery will be coupled with liquid suction, and, therefore, with mass gain by hydrodynamic mechanism (HDM). The volume relaxation rate will be affected by the process driving force or stored mechanical energy in the sample, and also by the pressure drop of in-flowing liquid, because the system (fruit plus in-flowing liquid) behaves as a viscoelastic structure. The total recovery of volume or mass will be affected by the elastic character of the tissue cellular matrix, which will be greatly dependent on the integrity of bonding zones or cell middle lamella after chemical equilibrium in the osmotic process, as well as on the preservation of the laminar cell wall ultra-structure.

Figures 15.6 and 15.7 show the mass and volume recovery of several fruit cylinders after their chemical equilibrium with the osmotic solution at \( t_e \). Time scale was plotted in a reduced way \((t - t_e)\), and mass and volume recovery was calculated as the variation between \( t \) and \( t_e \) divided by the sample initial value, according to Equations (15.5) and (15.6). In Figure 15.6, the influence of previous impregnation of the sample with an isotonic solution on the relaxation pathway of apple samples can be observed, as well as the influence of the liquid viscosity of the impregnating solution. The impregnated sample volume relaxes faster than that of nonimpregnated samples. Nevertheless, when the impregnated solution has HM pectin (sample C-I-2), the relaxation rate slows down. Differences in volume relaxation rate may be due to different cell network microstructure reached in each case, as commented on above, which will imply a different level of stored mechanical energy. The different viscosity of the fruit LP will also affect relaxation rate, because internal LP will flow inside the sample throughout its volume recovery. As expected, mass and volume recovery undergoes parallel variations, although mass gain of a nonimpregnated sample is faster than volume gain, because a part of the external liquid flows into the empty is, reducing sample porosity at the same time as the cell network relaxes.\(^10\,11\)

\[
\Delta M(t) = \frac{M(t) - M^\infty}{M^\infty}
\] (15.5)
\[ \Delta V(t) = \frac{V(t) - V^*}{V^*} \]  

(15.6)

On the other hand, Figure 15.7 shows the pathway of initial volume relaxation and mass gain of some fruits OD and PVOD treated with 55° Brix sucrose solution. The volume of pear and kiwi fruit relaxes to a smaller degree than that of mango and apple, which relaxes quickly. The kind of treatment, OD or PVOD, appears to have no notable influence on volume relaxation of pear and apple, although the volume of PVOD-treated mango (and kiwi to a much lesser extent) relaxes faster than OD samples. Mass recovery is faster than volume recovery, especially for the more porous OD-treated fruit, due to the pore impregnation in line with cell network relaxation commented on above, as it has been described for apple in previous works. The roundness of osmosed cells at long-term relaxation time can be appreciated in Figure 15.4d for apple tissue PVOD treated with 65° Brix.
syrup concentration. The reduced volume of the cell membrane can be observed in the round cell cavity.

The effect of sample vacuum impregnation with a sugar solution on the cell network relaxation rate could be explained in terms of a reinforcement of cell walls during passing through of the external liquid in line with cell wall-plasmalemma separation. Solids of external liquid may positively interact with the cell wall polymeric arrangement giving a more elastic structure. Several works have reported the beneficial effect of PVOD treatments on the preservation of cell wall ultrastructure and its implications in fruit texture improvement as compared with OD-treated products with the same water activity reduction.18-20

The HDM flux in the matrix relaxation process has been modeled on the basis of the Peleg model1 for relaxation of viscoelastic structures (Equation (15.7)). In Equation (15.7), \( F_0 \) and \( F(t) \) are, respectively, the initial force acting on the sample at a given deformation, and the force at a determined relaxation time \( t \). The constants \( A \) and \( B \) represent, respectively, the total relative relaxation level and the relaxation rate. To fit Equation (15.7) to the experimental mass recovery data (\( \Delta M' \) vs. \( t - t_c \)), the next hypotheses were considered: the mechanical stress on the matrix is released as pressure gradients on the external liquid, which promote a determined flow pressure drop; likewise, a laminar flow was assumed. From these hypotheses, \( F(t) \) can be obtained from the relationship given in Equation (15.8), where \( L \) is the pore characteristic dimension, \( D_p \) the pore diameter, and \( \mu \) and \( \rho_g \) the viscosity and density, respectively, of the impregnating solution and \( m' \) the liquid flux. The latter can be obtained from the slope of the curve \( \Delta M' \) vs. \( t' \), according to Equation (15.9), \( t' \) being equal to \( t - t_c \).

\[
\frac{F_0 t}{F_0 - F(t)} = \frac{1}{AB} + \frac{t}{A} \quad (15.7)
\]

\[
\Delta p = \frac{32\mu L}{\rho_g D_p^2} = \frac{4F}{\pi D_p^2} \quad (15.8)
\]

\[
m' = \left( \frac{\partial \Delta M'(t')}{\partial t'} \right) \quad (15.9)
\]

From Equations (15.8) and (15.9), the relationship between \( F(t) \) and data \( \Delta M'(t) \) can be obtained [Equation (15.10)]. By substituting Equation (15.16) in Equation (15.7) at time \( t \) and 0, assuming constant \( L \), the volume relaxation equation is obtained in terms of the slopes of the curve \( \Delta M'(t) \) and parameters \( A \) and \( B \) [Equation (15.11)].

\[
F(t) = \frac{8\pi \mu L}{\rho_g} \left( \frac{\partial \Delta M'(t')}{\partial t'} \right) \quad (15.10)
\]

\[
\frac{(\partial \Delta M'(t')/\partial t')_0 - (\partial \Delta M'(t')/\partial t')_0}{(\partial \Delta M'(t')/\partial t')_0} = \frac{t}{AB} + \frac{t}{A} \quad (15.11)
\]

This model has been fitted to mass recovery data, throughout approximately two months, of apple cylinders OD and PVOD treated with sucrose solutions of different concentrations (ranging from 35 to 65° Brix) at 30, 40, and 50°C.17 To fit Equation (15.11) to the experimental data the function \( m'(t') \) was obtained by fitting a biexponential function to the experimental curve \( \Delta M'(t') \), and calculating the derivative equation and its values at each time.

Figure 15.8 shows the linear relationship between experimental points plotted as defined by Equation (15.11) for OD and PVOD treatments of apple, with 55° Brix sucrose solution, at each temperature. As can be observed in Figure 15.8, a slight influence of temperature and kind of treatment on the kinetics of HDM mass flux during mechanical relaxation of apple cylinders was detected. Table 15.2 shows the mean values obtained for \( A \) and \( B \) parameters for OD and PVOD treatments in the range 30-50°C. The values of \( A \) are near 1 in all cases, which indicates that the sample recovers about 100% of initial mass throughout the examined time, the relaxation rate being affected by the syrup concentration. Until 25° Brix, the lower the sucrose concentration, the faster the relaxation, in agreement with the lower viscosity values of the solutions.

15.5 FINAL REMARKS

Deformation-relaxation phenomena of plant tissue occur in line with osmotic dehydration processes, these contributing to define mechanisms involved in mass transfer.

Figure 15.8 Linearization of mass recovery data of osmosed apple cylinders in 55° Brix sucrose solution. Treatment temperatures: • = 30°C, ■= 40°C, ▲ = 50°C. Closed symbols = OD treatments, open symbols = PVOD treatments.
TABLE 15.2
Parameters A and B [Equation (15.11)] for Mass Recovery of OD and PVOD Treated Apple Cylinders in Sucrose Solutions of Different Concentration

<table>
<thead>
<tr>
<th>Osmotic solution, °Brix</th>
<th>OD</th>
<th></th>
<th></th>
<th>PVOD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>65</td>
<td>1.02</td>
<td>0.002</td>
<td>0.98</td>
<td>0.009</td>
</tr>
<tr>
<td>55</td>
<td>1.05</td>
<td>0.004</td>
<td>1.07</td>
<td>0.005</td>
</tr>
<tr>
<td>45</td>
<td>1.02</td>
<td>0.012</td>
<td>1.05</td>
<td>0.037</td>
</tr>
<tr>
<td>35</td>
<td>1.01</td>
<td>0.024</td>
<td>1.07</td>
<td>0.004</td>
</tr>
<tr>
<td>25</td>
<td>0.98</td>
<td>0.162</td>
<td>0.96</td>
<td>0.082</td>
</tr>
<tr>
<td>20</td>
<td>1.01</td>
<td>0.024</td>
<td>1.01</td>
<td>0.080</td>
</tr>
</tbody>
</table>

Plant tissue microstructure (cell network arrangement) and porosity, as well as sample shape, affect the sample volume pathway throughout the dehydration-deformation step. They also affect sample volume recovery in line with the release of stored mechanical energy. By understanding and modeling the action of all these mechanisms, better process control will be possible.

15.6 NOTATION

- $\mu$: Solution viscosity
- $\varepsilon$: Sample effective porosity
- $L$: Sample pore length
- $D_p$: Pore radius
- $\rho_0$: Density of the initial product (kg/m$^3$)
- $\rho_0':$ Density of the impregnating solution (kg/m$^3$)
- $x_i$: Mass fraction in the product of component $i$ at time $t$ of treatment
- $z_i$: Mass fraction of component $i$ in the liquid phase at time $t$ of treatment
- $M$: Mass of the sample at time $t$
- $\nu$: Sample volume at time $t$
- $\Delta V$: Relative volume change with respect to the product initial value, occurred between $t = 0$ and $t$
- $\Delta V':$ Relative volume change with respect to the product initial value, occurred between $t_1$ and $t$
- $\Delta M$: Relative mass change with respect to the product initial value occurred between $t_1$ and $t$
- $\rho_0'$: Mass flux of external liquid during the sample volume relaxation period
- $t$: Process time
- $t_E$: Time of chemical equilibrium (equal solute concentration in product liquid phase and osmotic solution)
- $t' = t - t_E$
- $F$: Force
- $A$: Parameter of volume relaxation equation (dimensionless)
- $B$: Parameter of volume relaxation equation (time$^{-1}$ dimension)

REFERENCES