A novel approach for numerical simulation of plant tissue shrinkage during drying

H.C.P. Karunasena,[1,2] W. Senadeera,*[1] R.J. Brown[1] and Y.T. Gu[1]

[1] School of Chemistry, Physics and Mechanical Engineering, Faculty of Science and Engineering, Queensland University of Technology, 2-George Street, Brisbane,QLD 4001, Australia.

[2] Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, University of Ruhuna, Hapugala, Galle, Sri Lanka.

*Corresponding author: w3.senadeera@qut.edu.au

ABSTRACT

Drying is a key processing techniques used in food engineering which demands continual developments on advanced analysis techniques in order to optimize the product and the process. In this regard, plant based materials are a frequent subject of interest where microstructural studies can provide a clearer understanding on the fundamental physical mechanisms involved. In this context, considering numerous challenges of using conventional numerical grid-based modelling techniques, a meshfree particle based model was developed to simulate extreme deformations of plant microstructure during drying. The proposed technique is based on a particle based meshfree method: Smoothed Particle Hydrodynamics (SPH) and a Discrete Element Method (DEM). A tissue model was developed by aggrading individual cells modelled with SPH-DEM coupled approach by initializing the cells as hexagons and aggregating them to form a tissue. The model also involves a middle lamella resembling real tissues. Using the model, different dried tissue states were simulated with different moisture content, the turgor pressure, and cell wall contraction effects. Compared to the state of the art grid-based microscale plant tissue drying models, the proposed model is capable of simulating plant tissues at lower moisture contents which results in excessive shrinkage and cell wall wrinkling. Model predictions were compared with experimental findings and a fairly good agreement was observed both qualitatively and quantitatively.

Keywords: Food drying, plant cells, SPH, moisture content, shrinkage

INTRODUCTION

Dehydration or drying is one of the most popular food preservation techniques used in the food industry. In drying process, the food materials subject to excessive moisture reductions which result in excessive structural deformations of the food material. In the literature, there is a comprehensive collection of the conventional empirical and theoretical models that relate different physical properties of the food materials during drying. But, based on the practical challenges and limitations of popular grid-based modelling techniques such as Finite Element Methods (FEM) and Finite Different Methods (FDM), numerical modelling has not been well explored on food materials under drying conditions. In this background, we have developed a meshfree based numerical modelling approach for microscale modelling of plant cells during drying

(Karunasena, Senadeera *et al.* 2014b)The fundamental difference between grid based methods and meshfree methods is the discretisation.

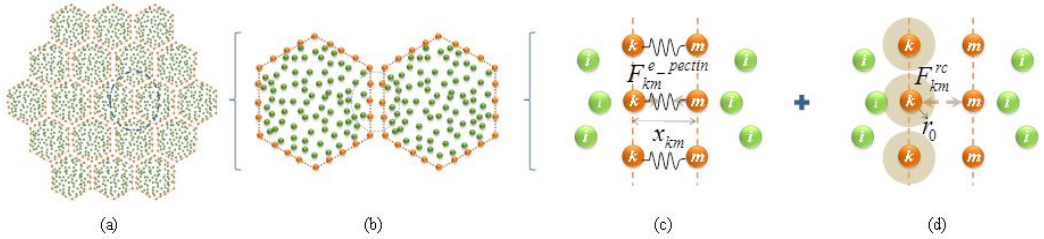


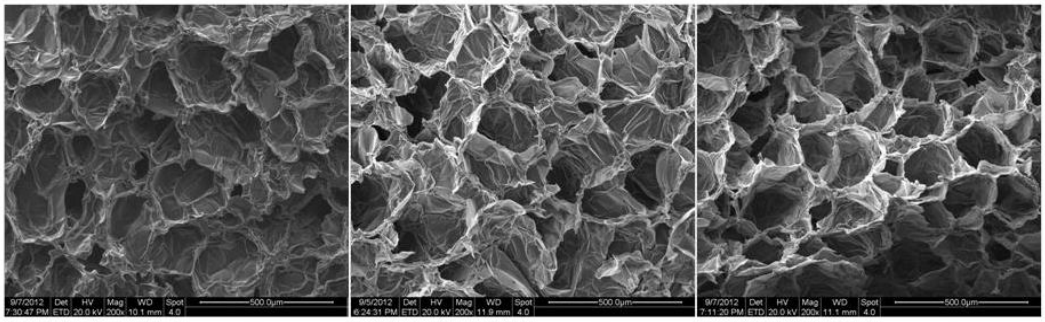
Fig. 1 Tissue model and cell-cell force interactions: (a) hexagonal shaped cells are used for tissue initialization with positive pectin layer gap. (b) Interacting wall particle pairs of adjacent cells. (c) Pectin layer stiff forces. (d) Cell-cell repulsion forces. (*i*: fluid particles; *k* & *m*: wall particles)

technique used. In meshfree methods, interconnected meshes or grids are not involved as in the case of FEM or DEM. The discretisation is achieved by representing the problem domain using non-connected particles that can time-evolve to produce new states. Due to the fundamental benefit of grid-free nature of these meshfree methods, they are more capable of handling problems that characterise excessive geometric deformations and multi phase systems. Our model is based on one of the most popular meshfree techniques: Smoothed Particle Hydrodynamics (SPH) (Gingold and Monaghan 1977, Liu and Liu 2003) and is coupled with a Discrete Element Method (DEM) to model plant cells. SPH is used to model cell protoplasm (cell fluid) and DEM is used to model the cell wall. In our previous works (Karunasena, Senadeera *et al.* 2012a; Karunasena, Senadeera *et al.* 2012b; Karunasena, Senadeera *et al.* 2014b), we have presented how a single cell can be modelled with this technique to study moisture content and turgor pressure driven structural deformations under drying conditions. In this work, we demonstrate how a tissue model can be developed using such a single cell drying model by incorporating several new improvements. Sections below describe how the model was developed and how the model predictions were compared with experimental findings on apple parenchyma cell drying (Mayor, Silva *et al.* 2005; Karunasena, Hesami *et al.* 2014a).

MATERIALS AND METHODS

Firstly the individual cells were modelled in two-dimension (2-D) according to the procedure introduced in our previous work (Karunasena, Senadeera *et al.* 2014b). Such individual cells were initiated as hexagons as shown in Fig. 1 and were bonded together by two fundamental force interactions: Pectin layer stiffness and Lenard Jones (LJ) type repulsion forces between them. Using this method, a sample tissue model of 37 cells was generated and drying conditions were established by varying the moisture content and turgor pressure. For this purpose we used a moisture-content-domain based approach which was introduced in our previous works (Karunasena, Senadeera *et al.* 2012b; Karunasena, Senadeera *et al.* 2014b). Further, based on the experimental evidence of moisture content dependent positive turgor pressure existence in cells when they are subjected moisture deficiencies (Barker, Sullivan *et al.* 1993; Neumann 1995; Hills and

Remigereau 1997; Marshall and Dumbroff 1999; Blum 2011), we simply assumed that the turgor pressure will remain positive during drying that would linearly reduce with the reduction of the cell fluid mass. Therefore, when 200 kPa is used as the fresh cell turgor pressure, the dried tissues of: X/X_0 = 0.8, X/X_0 = 0.6, X/X_0 = 0.4 and X/X_0 = 0.3 were simulated by initially setting the turgor pressures to: 160 kPa, 120 kPa, 80 kPa and 60 kPa in each cells. At the end of each tissue time evolution, the dry basis moisture content X = (kg water / kg dry material) was computed and related with steady state cell deformations which were quantified using a set of cellular geometrical parameters: cell area (*A*), ferret diameter1 (*D*), perimeter (*P*), roundness2 (*R*), elongation3 (*EL*) and compactness4 (*C*). Further, in order to facilitate analysis and comparison of the model performances, normalized parameters (X/X_0, A/A_0, D/D_0, P/P_0, R/R_0, EL/EL_0 and C/C_0) were involved used. For model validation, these results were compared with experimental data for apple cell drying obtained from our experiments (Karunasena, Hesami et al. 2014a) (see Fig. 2) and literature (Mayor, Silva et al. 2005).



(a) (b) (c)

Fig. 2 SEM images of apple cells at different states of dryness: (a) X/X_0= 1.0. (b) X/X_0 = 0.5. (c) X/X_0 = 0.2.

RESULTS AND DISCUSSION

When considering the 37-cell tissue as seen from Fig. 3 and Fig. 4 extensive shrinkage patterns can be observed with cell wall local wrinkling or warping. This is in close agreement with the wrinkled cell walls of realistic dried tissues (see Fig. 2(b) and (c)). To elaborate these trends quantitatively, the geometric parameters introduced were studied and as seen from Fig. 5, predictions are fairly in a good agreement with the experimental findings. Model predictions show a slightly rapid shrinkage during the latter part of drying (X/X_0 < 0.6) which replicates what is observed from the experimental curves. All these observations highlight the capability of the proposed tissue model to replicate realistic tissue deformations during drying.

[1] $\sqrt{4A/\pi}$
[2] $4\pi A/P^2$
[3] $\sqrt{4A/\pi}$/(major axis length)
[4] major axis length/minor axis length

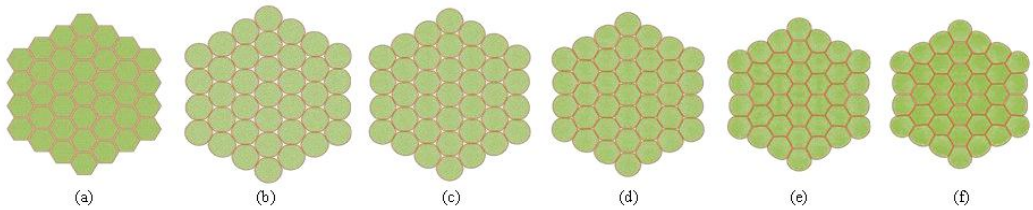


Fig. 3 37-cell tissue model: (*a*) Initial condition before simulations. (*b*) Turgid condition: X/X_0 = 1.0 & P_T = 200 kPa. Dried conditions: (*c*) X/X_0 = 0.8 & P_T = 160 kPa. (*d*) X/X_0 = 0.6 & P_T = 120 kPa. (*e*) X/X_0 = 0.4 & P_T = 80 kPa. (*f*) X/X_0 = 0.3 & P_T = 60 kPa.

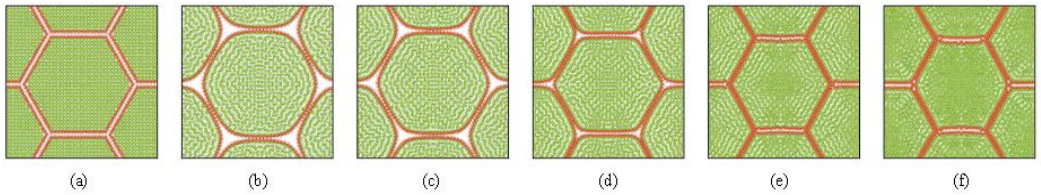


Fig. 4 37-cell tissue model (enlarged view): (*a*) Initial condition before simulations. (*b*) Turgid condition: X/X_0 = 1.0 & P_T = 200 kPa. Dried conditions: (*c*) X/X_0 = 0.8 & P_T = 160 kPa. (*d*) X/X_0 = 0.6 & P_T = 120 kPa. (*e*) X/X_0 = 0.4 & P_T = 80 kPa. (*f*) X/X_0 = 0.3 & P_T = 60 kPa.

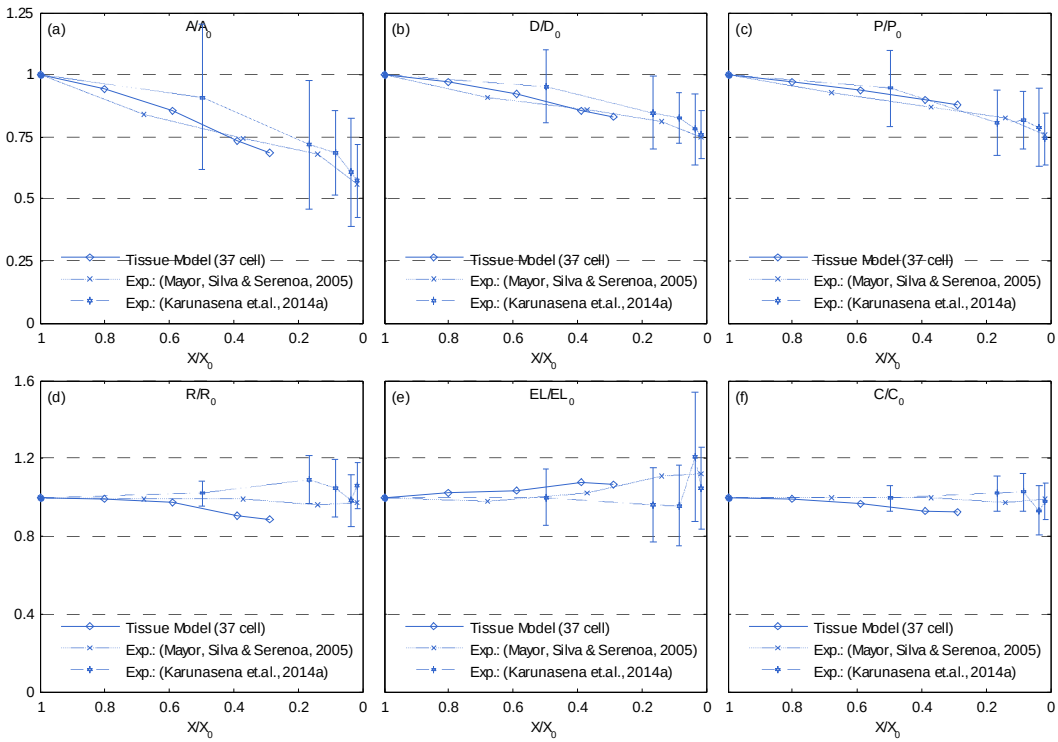


Fig. 5 Influence of moisture content reduction for cellular geometric property variations of tissues: (*a*) A/A_0. (*b*) D/D_0. (*c*) P/P_0. (*d*) R/R_0. (*e*) EL/EL_0. (*f*) C/C_0. (Error bars indicate one standard deviation).

REFERENCES

Barker DJ, CY Sullivan et al. (1993). Water Deficit Effects on Osmotic Potential, Cell Wall Elasticity, and Proline in Five Forage Grasses Agronomy Journal **85**(2): 270-275.

Blum A (2011). Plant Water Relations, Plant Stress and Plant Production. Plant Breeding for Water-Limited Environments, Springer New York**:** 26.

Gingold R A and JJ Monaghan (1977). Smoothed particle hydrodynamics - Theory and application to non-spherical stars. Monthly Notices of the Royal Astronomical Society **181**: 375-389.

Hills BP and B Remigereau (1997). NMR studies of changes in subcellular water compartmentation in parenchyma apple tissue during drying and freezing. International Journal of Food Science & Technology **32**(1): 51-61.

Karunasena H C P, P Hesami et al. (2014a). Scanning Electron Microscopic Study of Microstructure of Gala Apples During Hot Air Drying. Drying Technology **32**(4): 455-468.

Karunasena HCP, W Senadeera et al. (2012a). A particle based micromechanics model to simulate drying behaviors of vegetable cells. 4th International Conference on Computational Methods (ICCM 2012), Gold Coast, Australia.

Karunasena HCP, W Senadeera et al. (2012b). A Coupled SPH-DEM Model for Fluid and Solid Mechanics of Apple Parenchyma Cells During Drying. 18th Australian Fluid Mechanics Conference, Launceston - Australia, Australasian Fluid Mechanics Society.

Karunasena HCP, W Senadeera et al. (2014b). A Coupled SPH-DEM Model for Micro-scale Structural Deformations of Plant Cells during Drying. Applied Mathematical Modelling.

Liu G R and MB Liu (2003). Smoothed Particle Hydrodynamics : A Meshfree Particle Method. Singapore, World Scientific Publishing Co.

Marshall J G and E B Dumbroff (1999). Turgor regulation via cell wall adjustment in white spruce. Plant Physiology. **119**: 313-319.

Mayor L, MA Silva et al. (2005). Microstructural Changes during Drying of Apple Slices. Drying Technology. **23**(9-11): 2261-2276.

Neumann P M (1995). The Role of Cell Wall Adjustments in Plant Resistance to Water Deficits.Crop Science. **35**(5): 1258-1266.