International Journal of Thermal Sciences 117 (2017) 266–273

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Experimental investigation of bound and free water transport process during drying of hygroscopic food material

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ARTICLE INFO

Article history:
Received 15 July 2016
Received in revised form
30 March 2017
Accepted 4 April 2017

Keywords:
Bound water
Free water
Drying
Cell rupture
Transport

ABSTRACT

Hygroscopic food materials contain free (FW) and bound (BW) water in different cellular environments. In-depth understanding of the mechanisms of moisture migration from different cellular environments during drying is crucial for optimising heat and mass transfer as well as for obtaining better quality dried foods. Therefore, the main aim of the present work is to investigate the transportation mechanisms of FW and BW during drying. Experiments were performed on the potato tissue using ^{1}H-NMR T_2 relaxometry to uncover the mechanisms involved in FW and BW transportation. The results have confirmed the view that BW migrates after the rupture of the cell membranes. It is interesting to highlight that the cell membranes rupture at different stages of drying rather than collapsing at one time. The membrane collapse depends predominantly on the penetration rate of heat energy and the pressure gradient between intracellular and intercellular environments. All test results suggest that most of the cell membranes rupture at the middle stage of drying where the moisture content is about 2–4 kg/kg (db.). Furthermore, the moisture distribution profile confirmed that some moisture remained around the centre of the dried sample although the surface of the sample became dry.

1. Introduction

Drying is an excellent method of food preservation. However, the dehydration of foodstuffs is a very complex process because of its complexity in internal structure and simultaneous heat and mass transfer during drying [1]. Understanding of the actual heat and mass transfer during drying is crucial for optimising energy efficiency of the drying process and preserving the quality attributes of food materials [2]. Many physical and chemical changes take place in food tissue during drying and moisture and temperature distributions significantly contribute to these changes [3]. Therefore, understanding of moisture and temperature distributions and transport mechanism during drying is important. The rate of moisture transport depends on the size and orientation of cells as well as the types of cellular water in the samples [4]. Plant-based foods materials are hygroscopic and porous in nature and contain two types of water, namely free water (FW) and bound water (BW) [5]. FW is present in capillaries or intercellular spaces; whereas, the water in the intracellular space is referred to as BW [6], as shown in Fig. 1. The migration pathways of FW and BW are also different. It is assumed that most of the BW migrate after the collapse of the cells. When cells are collapsed, BW from cells moves to intercellular spaces and shows the characteristics of FW [7]. Due to insufficient knowledge about the migration pathways and characteristics of FW and BW during drying, the current food drying models consider bulk water transport mechanisms in the mathematical modelling [8–12].

Compared to single phase models, multi-phase models considering transport of liquid water, water vapour and air inside the food materials are more realistic [5]. These three phases (water, gas and solid matrix) inside plant-based food structures, as shown in Fig. 2, represent the domain which is commonly used in most multiphase drying models. According to the assumptions presented in Refs. [8–12], there is no water inside the solid matrix.

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http://dx.doi.org/10.1016/j.ijthermalsci.2017.04.006
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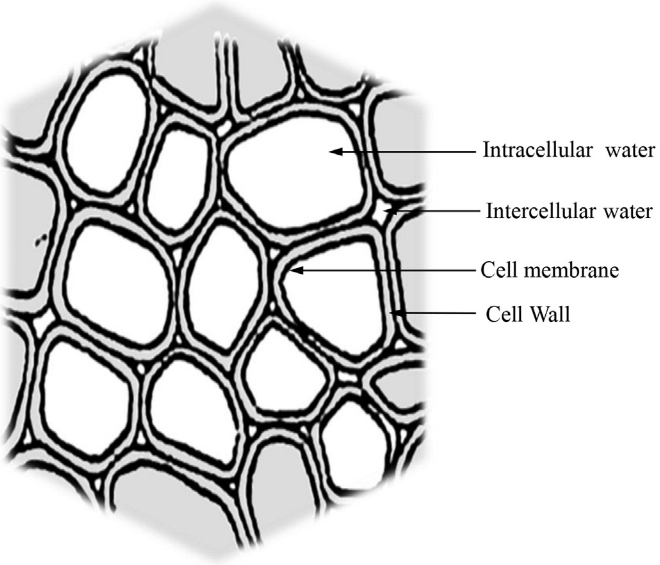

Fig. 1. General water distribution inside Plant-based food materials [5].

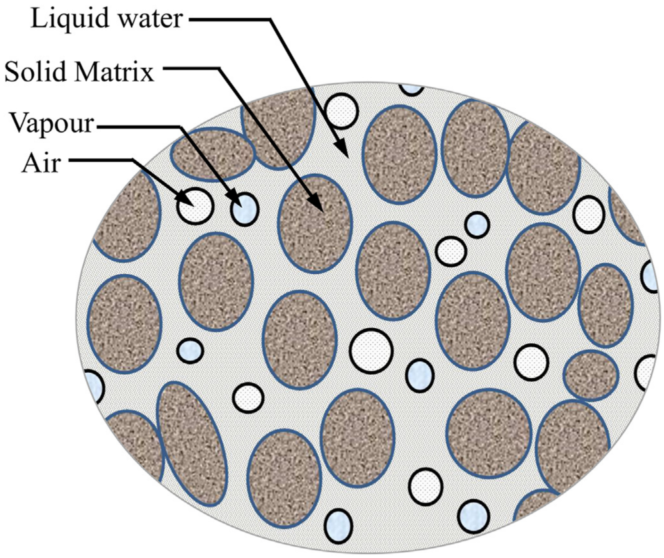

Fig. 2. Domains considered in existing literature [8–12].

Although this assumption leads to the simplified process of multiphase transport, the real transport process remains unclear [7,13]. It is reported that migration of free water has a minimum effect on the food quality. Migration of BW causes cellular shrinkage, pore formation and the collapse of the cells and pore structure and hence has a major effect on food quality [14,15]. Moreover, the energy requirements for drying of a particular food material depend on its cellular structure and cellular level moisture distributions [16]. Transport of bound water requires more energy compared to transport of free water [17]. In most of the cases, energy and time required for first 90% of water is almost equal to the energy and time required for removing last 10% of water present in a food sample [14]. Therefore, in order to accurately predict the heat and mass transport during drying of food material, better understand of the migration mechanisms of BW water is necessary.

There are several techniques available for analysing bound water transport including bioelectric impedance analysis (BIA), differential scanning calorimetry (DSC), differential thermal analysis (DTA), centrifugal settling method (CSM) and nuclear magnetic resonance (NMR) methods. However, not all these methods are suitable for investigating moisture migration mechanisms while drying is in progress. BIA and NMR methods are evaluated as the most appropriate for this type of investigations. BIA is a very simple and established technique for assessing body compositions by measuring the resistance of tissues to the flow of electrical current [6]. The proportion of different contents in a tissue can be calculated as the current flows more easily through the parts of the material that contain more water. This method was used in the study of Halder et al. [4] for calculation of the migration pathways of intracellular water in the plant-based food materials. The temperature influence on the cellular water migration was examined in the same study. It was stated that all of the membranes of the cells would collapse at once after specific temperature is reached. They suggested that below 50 °C the cells remain intact and therefore the conversion of the intracellular water to free water remains unchanged during the drying. As cells remain intact, the intracellular water (BW) moves to intercellular space only through micro-capillaries, denoting this moisture transport as the slow one.

However, their argument is not justified because cell collapse depends on internal thermal stress [15] that first develops near the surface and gradually penetrates to the centre of the sample during convective drying. In other words, entire food sample does not reach 'cell rupture temperature' at a time. Therefore, it is logical that the cells may collapse progressively from the surface to centre [14,15]. Moreover, BIA is mainly used for analysing animal fat composition. It may not be a sufficiently accurate technique for predicting moisture migration pathways in plant tissue as BIA cannot detect the position of different types of water (FW and BW).

Nuclear magnetic resonance (NMR) is a widely used method for investigating the distribution of different types of water in various locations inside plant-based food material [18]. Proton nuclear magnetic resonance (^{1}H-NMR) relaxometry study has been proven to be a viable method in the study of plants and plant-based food materials submitted to stress reflecting anatomical details of the entire tissue and the water status in particular [19,20]. ^{1}H-NMR signals, which are an average over the whole sample, provide information about the water content of the plant tissue since the proton signal is dominated by water protons and the proton NMR signal intensity is directly proportional to the proton density of the tissue [21,22]. The water proton relaxation behaviour strongly depends on the water mobility in the microscopic environment of the tissue, local magnetic field fluctuations (related to the molecular environment) and the strength of the applied magnetic field. The spin-spin (T_2) relaxation is the transverse component of the magnetization vector, which exponentially decays towards its equilibrium value after excitation by radio frequency energy.

Some researchers have tried to investigate the changes in water compartmentation during drying of plant tissue [23,24]. These studies found a strong relationship between different water T_2 relaxation times and the percentage of moisture loss during drying. However, they did not investigate the migration mechanisms of bound water and free water separately. Moreover, it is not clear when the cell exactly collapses and what are the consequence for the migration of bound water.

Therefore, the primary aim of this study is to investigate the free and bound water migration mechanism in plant-based food material during drying.