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Ultrasound in wet materials subjected to drying: A modeling study

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ABSTRACT

The aim of this paper is to present wave phenomena induced by the external action of ultrasound on porous wet materials subjected to drying. The purpose of these studies is to analyze the distribution of ultrasonic waves in such a complex medium and to discover the mechanism of ultrasonic interaction with both the solid skeleton and moisture in pores. The results obtained here should allow to state how ultrasonic waves are distributed in such material depending on ultrasonic frequency and on resistance between relative motion of the constituents. This knowledge may help to explain enhancement of the drying mechanism by ultrasound, and in particular in biological products such as fruits and vegetables where a significant elevation of temperature is not required.

1. Introduction

The problem of ultrasound (US) wave propagation in porous media has been a subject of interest in many sectors of science (e.g. geophysics, environmental science, hydrology) and engineering (e.g. civil engineering, oil industry), and others [1,2]. Recently, an increasing amount of literature has reported the very positive influence of higher-power ultrasound at frequencies 20–100 kHz on the drying efficiency of biological materials such as fruits and vegetables [3–7]. These reports show the ability how ultrasound enhances drying rate and improve quality of food products. However, they did not explain the heart of the US mechanism contributing to process intensification and improvement of product quality by drying with the help of ultrasound, which is the interest of present considerations.

Judging from the published literature [8–11], high-power ultrasound are capable of improving heat- and mass-transfer processes in drying materials, and in particular in the drying of heat-sensitive biological materials such as fruits and vegetables. However, one should state that drying processes enhanced with ultrasounds have still not emerged from the laboratory research phase. The current quest is for the most economical versions of hybrid technological processes combining the ultrasound method with other drying techniques (convective, microwave, infrared) in such a way as to complement one another and to increase the moisture removal rate.

The limited applicability of ultrasound to drying methods is primarily due to ultrasound high-power demand. The existing currently ultrasound radiators operating in gas media (e.g. siren) mostly do not fulfil this requirement. An original construction of a laboratory hybrid dryer based on an ultrasound airborne transducer was constructed in the author's drying laboratory. This dryer enables hybrid drying in combinations of convective, microwave and ultrasound techniques. Fig. 1 presents, as a forerunner, the kinetics of convective drying enhanced with airborne ultrasound, which was applied to drying a layer of 16 apple slices of dimensions 40 × 20 × 5 mm, realized on this new equipment [12].

The moisture ratio (MR) as a function of time (drying curve) presented in Fig. 1 reveals that the drying time amounted to 235 min for pure convective drying (curve 1), while for drying with ultrasonic assistance at ultrasound power of 100 W and frequency 26 kHz it took only 160 min (curve 2). Besides, the ultrasonic assistance elevated the sample temperature only by about 1 °C on average as shown in Fig. 1, which is of significant importance in the drying of temperature sensitive biological materials.

The main aim of this article is, first of all, to recognize the interaction mechanism between the ultrasonic wave and biological material, which could entail the reason for the intensification of moisture removal from dried products. The research hypothesis is a supposition that the periodical waves which are characteristic of ultrasound cause periodical changes of porosity and pore pressure. In this way they may evoke the moisture streaming from inside the material towards the surface, where it evaporates.

Biological materials such as fruits and vegetables need very sublimed drying methods as they are very sensitive to temperatures higher than 60–70 °C and also to long drying time. The common drying methods (e.g. the hot convective air drying), may cause degradation of their valuable features (color, vitamin, minerals).

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For this reason the author of this paper has developed hybrid methods which are a combination of convective, microwave and infrared drying [13–17]. This work proposes an extension of hybrid drying additionally on ultrasound assistance. This needs, however, first a more detailed analysis of ultrasound wave distribution in wet materials subjected to drying. The positive outcome of these studies may contribute to essential changes important in the drying technology of biological material. Modified drying technology carried out in dryers supported with ultrasound equipment could find application in the industry, increase competitiveness by increasing productivity and decreasing energy consumption, and contribute to balanced research and development (R&D).

2. Theory

2.1. Fundamentals

The theory of ultrasound propagation in wet porous materials is constructed on the basis of the mechanics of continua. Natural tools for development of such a theory are the balances of mass, momentum, moment of momentum, energy, entropy and the principles of irreversible thermodynamics. A version of such a drying theory was presented in [18, Chapter 3 and 4]. In this paper the dynamic terms such as inertia forces are introduced to the former theory which allow to extend it to ultrasonic enhancement of drying processes [19–21].

The present model of drying based on the mechanics of continua incorporates the following assumptions:

- The considered material is a saturated porous body consisting of a solid skeleton ($\alpha = s$) and moisture ($\alpha = m$), which is a mixture of liquid ($\alpha = l$) and gas ($\alpha = g$) in pores.
- Individual components are represented by mass concentrations and volume fractions, which are continuous functions of space and time due to an averaging procedure applied to the *representative volume element* (RVE)*.
- The theory includes dynamic terms, such as accelerations, inertia forces, kinetic energy, etc. in the momentum and energy balance equations.
- Stress in moisture is represented by pressure only, as the stress deviator in moisture is considered insignificant with respect to that in the solid skeleton.
- The skeleton is a deformable body and the deformations resulting from the ultrasounds are assumed to be small (strain fluctuations).

The following definitions are used in the further considerations:

Volume fraction ϕ^α – is a fraction of the RVE occupied by the constituent α (s-solid, m-moisture, being a mixture of l-liquid and g-gas).
Porosity ϕ – is a fraction of the RVE occupied by pores. One assumes that the pore space is filled by the moisture (liquid/gas mixture), i.e. $\phi \equiv \phi^m = \phi^l + \phi^g = 1 - \phi^s$.
Body saturation φ – is a fraction of pore space occupied by the liquid phase, $\varphi = \phi^l/\phi$.
Constituent mass concentration $\rho^\alpha = \rho^{\alpha r}\,\phi^\alpha$ [kg/m^3] – is the mass of constituent α in the RVE per volume of this element.
True (intrinsic) constituent mass density $\rho^{\alpha r}$ [kg/m^3] – is the mass of constituent α per volume of this constituent.
Production of constituent mass ${}^*\rho^\alpha$ [kg/m^3 s] – is the rate of mass change between liquid and gas due to phase transitions within the RVE.
Constituent velocity $\boldsymbol{v}^\alpha$ [m/s] – is defined as the volumetric flux of constituent α per unit area of the body (filter velocity).

2.2. Balance equations

The balance equations are developed by applying Euler's description using the spatial coordinates $\boldsymbol{x}\{x,y,z\}$. A control volume $V(t)$ separated within the drying body is attributed to the deformable skeleton and enveloped in a smooth control surface $A(t)$ oriented spatially with the outward-directed unit normal vector $\boldsymbol{n}$, Fig. 2.

The individual constituents (phases) located primarily in volume V at time t are displaced during drying with different velocities $\boldsymbol{v}^\alpha$ and take different configurations V' and V'' after time increment Δt. Consider an arbitrary physical quantity $\Psi^\alpha(t)$ (mass,

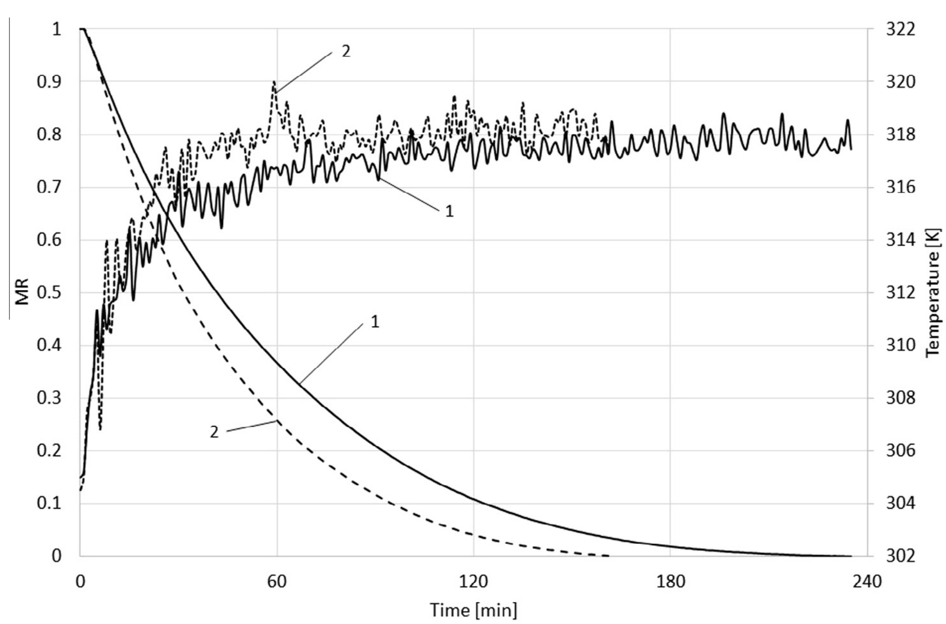

Fig. 1. Drying curves and temperature of apple samples: 1-pure convective drying, 2-drying with ultrasound assistance.