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Quantitative contactless photothermal monitoring of drying in foodstuff materials

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In this work a quantitative method for the study of drying in foodstuff systems is presented. This study relies on the fact that changes in moisture content influence the effective thermal transport properties of porous or fibrous materials. Here, we analyze frequency dependent thermal wave signals recorded on the basis of infrared detection at several drying states by considering that the foodstuff system is not perfectly opaque at the surface. The consideration of transparency allows an asymptotic linear analysis that gives direct information about combinations of optical and thermal parameters. This therefore simplifies a further theoretical numerical approach for the signals within the scope of a two-layer model. Under the condition of constant optical properties at the system surface and neglecting the moisture dependence of thermal diffusivity in comparison with changes induced upon the thermal effusivity, the number of effective parameters necessary to follow the drying progress reduces to two: the thermal diffusion time at the drying surface layer and the thermal effusivity of the bulk. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1523131]

I. INTRODUCTION

Drying processes and the measurement of the moisture content are of basic importance in the production of foodstuff. Ripening processes and roasting that are accompanied by drying are processes that have to be monitored in production processes on an industrial scale. In previous experimental work on foodstuffs,[1] textiles,[2] and construction materials,[3] we already explored the possibility of determining the moisture content and the distribution of its depth in different types of materials by means of thermal wave measurements using noncontact frequency-dependent infrared (IR) detection.

In this work a study is presented which provides additional information for quantitative interpretation of the drying processes in foodstuff materials investigated by conventional frequency dependent IR radiometry. Compared to pulsed optothermal transient emission radiometry (OTTER) that relies in addition on the optical hydration depth profile,[4] the conventional method provides pure thermal information which is most suitable for strongly heterogeneous soft materials. In the porous or fibrous materials investigated here the effective thermal transport properties change if the space between different fibers or the pore space in the dry matrix material either contains air or is partially filled with water and water vapor. In these materials heat diffusion can additionally be supported by the diffusion of water vapor. Our method of analyzing the progress of drying in foodstuff samples that are partially transparent at the surface is illustrated here for the particular case of European sausage.[1]

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II. EXPERIMENT

The foodstuff system under consideration was a German sausage of the type known as ''rotwurst, Pommersche art'' (''black sausage, Pommeranian style'') that consisted of a mixture of ingredients (swine meat, liver, blood, and bacon, several spices, and ascorbic acid as a preservative), all stuffed into the skin of natural swine intestine and smoke dried afterward. It was bought in an ordinary supermarket in the usual plastic wrapped package. The caducity date indicated 15 days after purchase (without opening) under usual refrigeration storage conditions, although this sort of sausage is known for its long preservation under dry storage conditions. The sample was left exposed to the air and kept at room temperature for the whole experiment and during this time bacteriological spoilage due to microorganisms was not visually observed.

A series of photothermal signals were recorded at different times during drying for the sausage whose skin showed a well defined thin transparent homogeneous region.[1] Loss of moisture content was systematically controlled by weighing before and after each photothermal measurement.

Infrared photothermal radiometry in a reflection configuration with a focal lens arrangement was used to investigate the photothermal response of the samples. The experimental equipment consisted of an infrared detector (Judson infrared J15D12-M204-S02M-60) and an argon-ion laser working at an operating power of 500 mW, whose monochromatic light (514 nm) was modulated with the help of an acousto-optical modulator (Laser Components LM080) in the frequency range of 0.4–410 Hz. Details of the measurement system and its performance are published elsewhere.[5]

For calibration and analysis (to be discussed next) the signal of a reference sample of glassy carbon of well-known

thermal and optical properties was recorded under the same measurement conditions as the sample to be investigated. This calibration procedure, consisting of reference-to-sample signal normalization, a procedure known as (sample) inverse normalization, allows one to eliminate the influence of technical parameters and the frequency characteristic of the system.[2]

III. SIGNAL ANALYSIS

For signal analysis we consider a one-dimensional theoretical description of the inverse normalized photothermal amplitude $S_n^{-1}=S_{\mathrm{ref}}(f)/S_{\mathrm{sample}}(f)$ for the solid translucent sample and the reference. It yields the following frequency dependent relation that is governed by the thermal and optical properties of the sample and references:[6]

$$S_n^{-1}(f^{-1/2})=\frac{(e/\eta\epsilon)_{\mathrm{sample}}}{(e/\eta\epsilon)_{\mathrm{ref}}}\times\left[\frac{(1+\sqrt{4\pi f/\alpha\beta^2}+2\pi f/\alpha\beta^2)_{\mathrm{sample}}}{(1+\sqrt{4\pi f/\alpha\beta^2}+2\pi f/\alpha\beta^2)_{\mathrm{ref}}}\right]. \quad (1)$$

Here the parameters α and e denote the thermal diffusivity and effusivity, respectively. Parameter β is the optical-absorption constant, ϵ the emissivity, and the heat-conversion efficiency η gives the fraction of incident radiation transformed into heat in the sample (reference).

For a reference material that is a perfect absorber, at least in comparison with the optical translucent sample under consideration, Eq. (1) yields the following linear expression for the high frequency limit for the function $f^{-1/2}S_n^{-1}(f^{-1/2})$ that is, moreover, only dependent on the thermal and optical parameters of the sample:

$$f^{-1/2}S_n^{-1}(f^{-1/2})\approx[\rho c/(\zeta\beta)]_{\mathrm{sample}}+\frac{1}{2\sqrt{\pi}}(e/\zeta)_{\mathrm{sample}}f^{-1/2}. \quad (2)$$

Here, parameter ζ just summarizes the product $\zeta\equiv\epsilon\eta$ of the emissivity and heat-conversion efficiency.

Figure 1 shows the photothermal signal amplitudes $S_{\mathrm{sample}}(f)$ for the drying sausage measured at the indicated times during drying normalized inversely with respect to the signal amplitude obtained for glassy carbon $S_{\mathrm{ref}}(f)$ and plotted as the quantity $f^{-1/2}S_n^{-1}(f^{-1/2})=f^{-1/2}S_{\mathrm{ref}}(f)/S_{\mathrm{sample}}(f)$ as a function of $f^{-1/2}$ for high frequencies. The linear behavior of Eq. (2) is fulfilled by the experimental data in the frequency range of 12.8–205.0 Hz for all drying states. From the slopes and the intersections with the abscissa of the linear fits (lines in Fig. 1) one obtains the combined quantities $[\rho c/(\zeta\beta)]_{\mathrm{sample}}$ and $(e/\zeta)_{\mathrm{sample}}$ for each drying state. Their ratio yields the optical and thermal combined quantity $(\beta\sqrt{\alpha})_{\mathrm{sample}}$. Because these values are obtained in the high frequency limit, they can be considered to correspond to parameters of the surface layer. In order to reduce the number of independent fitting parameters both surface parameters ζ_S and β_S are kept for our further two-layer numerical approach for the signals during drying. The resulting surface thermal parameters are used as references

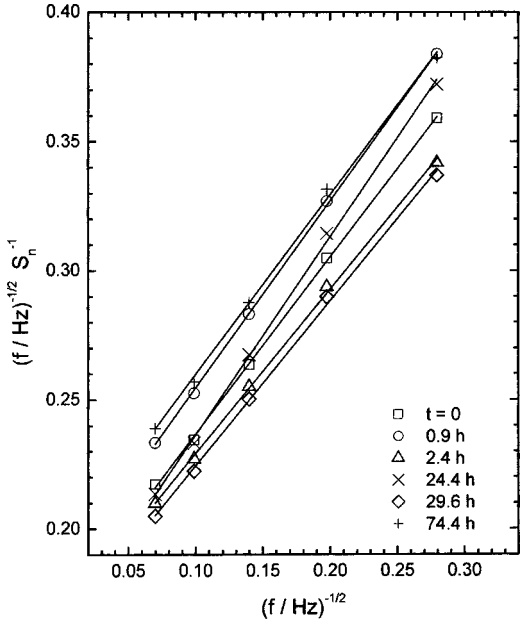

FIG. 1. Inverse normalized amplitudes with glassy carbon as the reference of the thin transparent sausage skin region measured at the drying times indicated and represented by the quantity $f^{-1/2}S_{\mathrm{ref}}(f)/S_{\mathrm{sample}}(f)$ vs $f^{-1/2}$ for high frequencies. The lines represent the best fits to the expression given by Eq. (2).

for the determination of the parameters of the second layer (bulk). As a further simplification, changes induced by variations in moisture content upon thermal diffusivity within the bulk are neglected. This assumption merely expresses the already observed fact[7] that the effects of moisture and porosity on the thermal conductivity k and on the heat capacity per volume ρc manifest themselves more strongly in the effusivity, $e=\sqrt{k\rho c}$, than on the thermal diffusivity, $\alpha=k/\rho c$, where the changes induced may possibly compensate. With the simplifications introduced the only independent parameters to be obtained numerically by means of a two-layer model are the thermal effusivity e_B of the bulk and the thermal diffusion time $\tau_S=(d^2/\alpha)_S$ of the surface drying layer of (in principle, unknown) thickness d_S. Figures 2 and 3 show the amplitudes and phases obtained from inverse normalization with respect to the signal of the fresh sample of the thin transparent sausage skin measured at the drying times indicated (shown by symbols), together with corresponding theoretical curves obtained (showed by lines).

The amplitudes in Fig. 2 are plotted as a function of $1/\sqrt{f}$ which is proportional to the penetration depth. As can be seen, in contrast to in previous results of the progression of drying[1,2] there is no recognizable decrease in the pattern between the inverse normalized signal amplitudes, corresponding to diminishing moisture content at high and medium frequencies (surface region). However, in the right part of the plot (bulk region) all inverse normalized amplitude curves show a tendency to decrease over the drying time. Another manifestation of this signal trend at the bulk region can also be observed in the leftmost part of the plot in Fig. 3 for which the common phase versus $\sqrt{f}$ representation was adopted. Figure 3 yields evidence that, with the exception of the curve corresponding to 1777 min of drying time, the

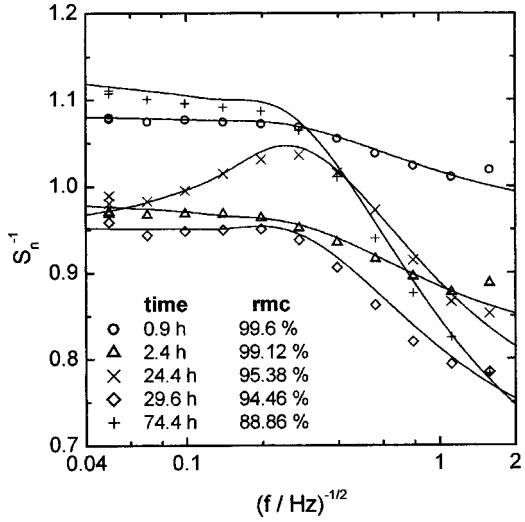

FIG. 2. Experimental (symbols) and theoretical (lines) inverse normalized amplitudes with respect to the signal of the fresh sample of the thin transparent sausage skin region at the drying times indicated and relative moisture content (rmc).

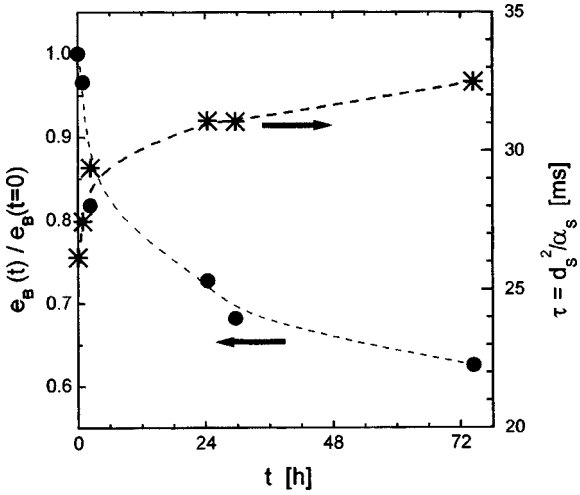

FIG. 4. Ratio of the bulk effusivity during drying to the initial bulk effusivity (closed circles) and thermal diffusion time of drying the surface layer (stars) of the thin transparent sausage skin region as functions of the drying time. The trends are emphasized by the dashed lines.

phase maxima increase during the progression of drying.

The numerical results for the thermal effusivity of the bulk and the thermal diffusion time of the drying surface layer obtained by means of our theoretical approach are graphically summarized in Fig. 4. The ratio to the initial bulk effusivity of the bulk effusivity at different drying times $e_B(t)/e_B(t=0)$ (closed circles), together with the drying time dependent thermal diffusion time of the surface layer $\tau_S=(d^2/\alpha)_S$ (stars) is presented. It is evident that over the time of drying the thermal diffusion time of the surface layer registers a continuous increase, whereas equally continuous diminishing of the bulk effusivity progression $e_B(t)/e_B(t=0)$ takes place. The rising trend of $\tau_S=(d^2/\alpha)_S$ indicates growth of the surface layer. The thermal diffusion time of the surface layer increases approximately 24.1% above its initial value after three days of drying when tendency towards asymptotic behavior seems to begin. An asymptotic trend is also observed for bulk effusivity progression after the same amount of time, around which a reduction of about 37.5% of the initial bulk effusivity is reached. This diminishing tendency agrees with our previous observations of these effects of the moisture content upon thermal effusivity in several materials.[1–3]

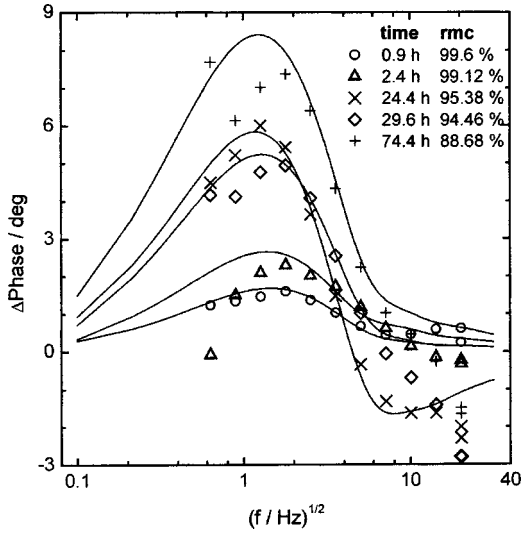

FIG. 3. Expeirmental (symbols) and theoretical (lines) phases of the inverse normalized signals with respect to the signal of the fresh sample of the thin transparent sausage skin region at the drying times indicated and relative moisture content (rmc).

IV. CONCLUSIONS AND OUTLOOK

In this work quantitative characterization of drying in a foodstuff system was achieved by thermal depth profiling analysis for optical translucent systems. To this end the asymptotic behavior of inverse normalized signals at the high frequency limit was used to determine combined quantities of optical and thermal parameters for each drying state. For further numerical approaches for the signals during drying, the optical parameters are kept fixed and the resulting thermal parameters for each drying state are used as the values of the thermal properties of the drying surface layer of a two-layered system. Further simplification consisting of keeping constant the bulk thermal diffusivity during drying finally allows one to reduce to two the number of additional free parameters that need to be obtained: the bulk thermal effusivity and the thermal diffusion time of the surface layer. These parameters, determined by using an approach of both experimental signal amplitudes and phases, give a quantitative impression of the progression of drying in two different surface and bulk system regions.

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