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Drying kinetics study of food pulps by continuous relative humidity measurements: Air flowrate and electric field effects

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ABSTRACT

In this investigation, a method based on continuous measurements of the variation of air relative humidity ($\Delta\Phi$) is used to monitor the drying kinetics of food pulps. For this purpose an experimental set-up devoted to the study of drying of vegetable pulps consisting of a laboratory-scale filter-press type apparatus (capacity of 50 cm^3) is used. The moister content of the pulp could thus be indirectly and un-interruptedly evaluated from the measurements of the humidity of the drying air at the inlet and the outlet of the filter-press, by two thermo-hygrometers. In order to validate the method, the effect of flow rate of air as well as the impact of a pulsed electric field treatment, were investigated.

KEYWORDS

Filter-press;
Pulp;
Humidity;
Non-intrusive and un-interrupted measurements;
Drying kinetics;
Electric fields.

INTRODUCTION

Drying is a major operation in food industry, consuming large quantity of energy. Dried foods which are expanding rapidly, are stable under ambient conditions, easy to handle, and can be easily incorporated during food preparation. The operation of drying is used either as primary process for preservation, or as secondary process in certain product manufacturing operations. Generally, the study of the mechanism of dehydration consists in following the evolution of the mass of the dried food versus time while controlling factors affecting the process such as the mode of drying, temperature, and air flowrate[1-3]. When these parameters are favorable, the evolution of the sample mass can preferably be obtained in a continuous way without interruption of the drying process. Most of the time, to control the extent of drying, it is necessary to stop the procedure periodically or to extract one or more samples in order to separately determine the weight in the course of time[4-9].

In many cases, the experimental device itself is not suited to the discontinuous measurements of sample mass. Indeed, technical solutions required by construction to take advantage of some functionalities, make discontinuous measurements more difficult to realize[10]. Moreover, establishing statistically valid kinetics of drying in a discontinuous way requires a considerable number of test runs in comparison with a method of continuous measurement.

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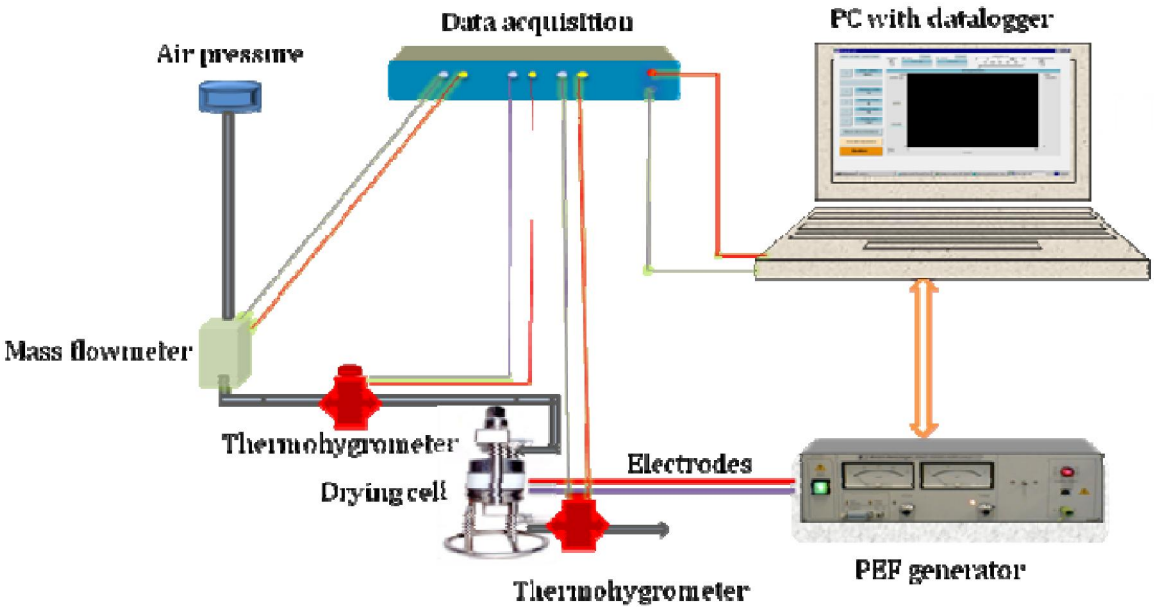

Figure 1 : Schematic of the experimental drying unit

The method developed in this paper consists in controlling the drying rate of vegetable particles continuously without having to stop the test runs. The determination of the drying rate is based on continuous measurements of relative humidity and temperature of drying air at the inlet and the outlet of a filter-press, in which, some vegetables pulp is contained. A series of discontinuous measurements of the mass of sample were also carried out to validate the continuous method. The present work constitutes the first part of a more general study of the effect of pulsed electric field PEF on the kinetics of drying. The device is designed to allow the electrical treatment of the samples in combination with a process of drying, filtration or pressing[10-12].

MATERIALS AND METHODS

Material

The vegetable used in this study was carrot, purchased in a local supermarket. The variety mainly used is sold under French trademark "Primeale legumes du terroir". Before each experiment, the product was subjected to two controls:

- Quantitative control: by which the dry matter was determined by means of an infrared dessiccator (SMO 01, Scalter).
- Qualitative control: by which a visual appreciation of the product state was done (rigid or soft aspect, appearance of moults, etc).

Before proceeding to the filling-up of filter-press, carrot roots were reduced to small particles (gratings). Hence, a small kitchen type grater was used, giving particles with a length varying from 30 to 40mm and with a section of about 2 mm2. The drying tests were carried out by using relatively small quantities of product (30 ± 2g).

Drying apparatus

The tests were carried out with a laboratory experimental unit, which allows to apply the PEF treatment and to dry the product. A detailed scheme of this unit is presented in figure 1. The unit is essentially made-up of a drying cell, a pulsed electric field generator and a microcomputer coupled to a data acquisition system.

The drying cell (Figure 2) is a filter-press type "laboratory model" designed in collaboration with the company Choquenet (Choquenet SA, France). It is made-up of a polypropylene casing comprising a cylindrical cavity, two metal plates, and two grids in stainless steel used as electrodes. The cylindrical cavity has a diameter of about 55mm and a width of about 20mm. The drying surface is about 25cm^2. The operating pressure can reach 35 bars. Two O rings were placed between the plates and the polypropylene casing to ensure the sealing of the whole of the filter-press.

The gratings of carrot are introduced in the interior

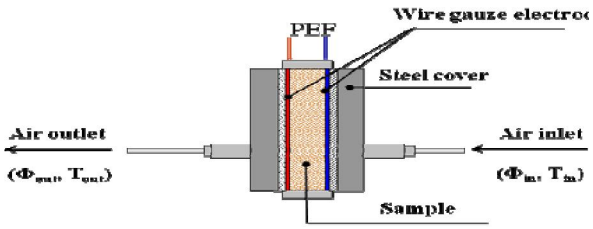

Figure 2 : Schematic of the drying cell

of the filter-press and between the two electrodes connected to the PEF generator. The special grid type electrodes allow both the electric treatment and a good distribution of drying air through the product. The pressure and the flowrate of the drying air circulating in the experimental device are adjustable from 0 to 12 bars and from 0 to 100 l/min, respectively. The adjustment of the pressure is obtained by means of a pressure reducer (Joucomtic). The air flowrate is recorded on a numerical mass flowmeter (AALBORG GEC47).

Relative humidity, Φ as well as temperature are measured by two thermo-hygrometers, Testo 645 (0 to 100% HR /-20 to 240°C, Germany), connected to the input and output of filter-press. The particles surface excess liquid ex-purged through the metal electrode at the beginning of the experiment is recovered in a container and weighed by a balance (Mettler PM6100). The various components of the device, namely, the mass flowmeter, the thermo-hygrometers and the balance are connected to an acquisition board with USB bus. This board is then connected to the microcomputer which allows both the control of the generator of PEF and the continuous acquisition of the different parameters using the same program developed in the visual programming environment HPVEF 3.2.

Method description

As described below, simultaneous measurement of the temperature and the humidity of the drying air, at the inlet (*Tin*, Φ*in*) and at outlet (Tout, Φout) of the filter-press, are used to calculate the saturation vapor pressure *Psat* and the absolute humidity evaluation versus time. The *Psat* values were calculated from the following relationship:

$$\log(P_{sat}) = 7.96681 - \frac{1668.21}{228 + T} \quad (1)$$

Where, T is the temperature of drying air at the experimental conditions in °C and the Psat in mmHg. The relationship between the absolute humidity W and the relative humidity Φ is described by the following equation:

$$W = \frac{\Phi \cdot 0.622 \cdot P_{sat}(T)}{P - P_{sat}(T)} \quad (2)$$

Where P and Psat are the atmospheric pressure and the saturation vapor pressure, respectively, at the temperature of the mixture of air-vapor, in Pa.

The water loss mass of the samples between 0 and *t* is expressed as follow:

$$\frac{dm_w}{dt} = \dot{m}_a (W_s(t) - W_e(t)) = \dot{m}_a \Delta W(t) \quad (3)$$

Where mw and $\dot{m}_a$ are respectively the mass of water loss and the air flowrate (in kg/mn).

$$I_{\Delta W} = \int_0^t \frac{dm_w}{dt} dt = \dot{m}_a \int_0^t \Delta W(t) dt = m_0 - m \quad (4)$$

The total mass of water loss for all the duration of drying between 0 and is described as follow:

$$I_{\Delta W}^{\infty} = \int_0^{\infty} \frac{dm_w}{dt} dt = \dot{m}_a \int_0^{\infty} \Delta W(t) dt = m_0 - m_{\infty} \quad (5)$$

The integral IΔW which is the area under the curve of ΔW, could be calculated numerically by the trapezoidal method. In fact, it is a cumulative function for all the duration of drying and is proportional to the water loss of the sample. The normalization of this integral can, thus, be assimilated to the normalized mass of the sample:

$$m^* = \frac{m - m_{\infty}}{m_0 - m_{\infty}} = \frac{I_{\Delta W} - I_{\Delta W}^{\infty}}{0 - I_{\Delta W}^{\infty}} = 1 - \frac{I_{\Delta W}}{I_{\Delta W}^{\infty}} \quad (6)$$

For ambient temperature and for a lower DT the ratio, $\frac{I_{\Delta W}}{I_{\Delta W}^{\infty}}$ relative to the absolute humidity is assimilated to $\frac{I_{\Delta \Phi}}{I_{\Delta \Phi}^{\infty}}$ of the relative humidity and all results and figures in this paper will be expressed in term of relative humidity. Knowing the initial (m_0) and final ($m_¥$) masses of the particles, the drying kinetics can be deduced from the equation (6) as follows:

$$m(t) = (m_0 - m_{\infty}).m^* + m_{\infty} \quad (7)$$

The deviation of continuous drying kinetic measurements from those of the discontinuous method is estimated in terms of the mean relative percentage deviation modulus, E, as defined by equation (8)[9]:

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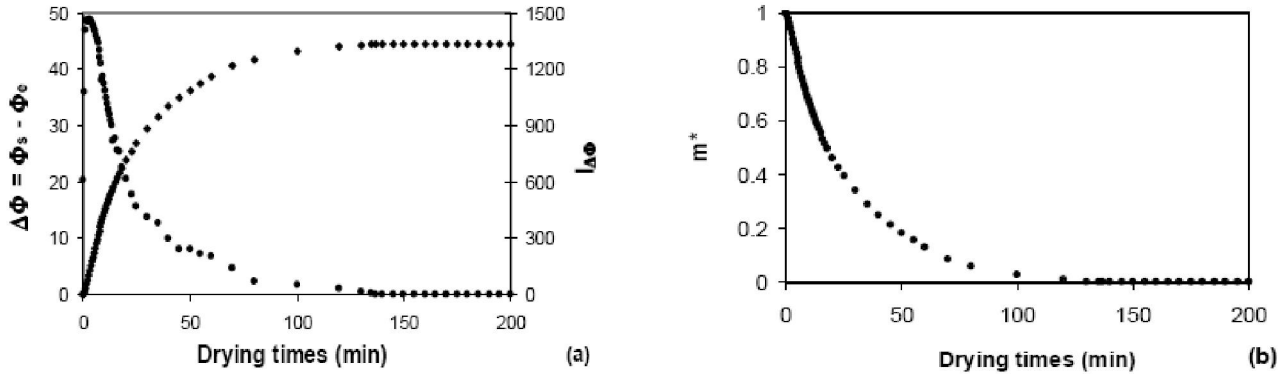

Figure 3 : (a) Integral under the curve of ΔΦ = f(t) and (b) standardized form of the integral, IΔΦ, for a dry air flowrate of about 48 l/mn at ambient temperature

$$E\% = \frac{100}{N} \cdot \sum_{i=1}^{N} \frac{\left| m_{disc,i} - m_{cont,i} \right|}{m_{disc,i}} \qquad (8)$$

Where i, corresponds to the i[th] data value being compared, *mdisc* and *mcont* are the discontinuous and continuous measured masses of the particles, respectively.

RESULTS AND DISCUSSION

Figure 3(a) shows the evolution of the difference, ΔΦ, and the integral, IΔΦ, during drying times. The filter-press is well sealed, so that the measured difference ΔΦ represents the quantity of water given off by the particles to the drying air.

The integral, IΔΦ, in function of time and its standardized form m* are represented in figures 3(a) and 3(b). The curve of drying lets appear a classical exponential decrease. The standardized form is then used to deduce the evolution of the mass of the particles bed during drying, as shown by figure 3.

This evolution compares well to the evolution of the mass observed in the case of discontinuous experiments, i.e. based on the measurement of the mass of the dried sample. The mean relative percentage deviation is about 5.38%.The treatment of the results of drying in terms of absolute humidity instead of the relative humidity, at ambient temperature, does not mark a significant deviation compared to the discontinuous measurements. The continuous line in figure 3 shows the variation of mass calculated from absolute humidity. A good agreement is observed with the corresponding values of relative humidity. In fact, in the case of calculated mass based on absolute humidity, W, this deviation, compared to the experimental discontinuous measurement, is about 5.03%.

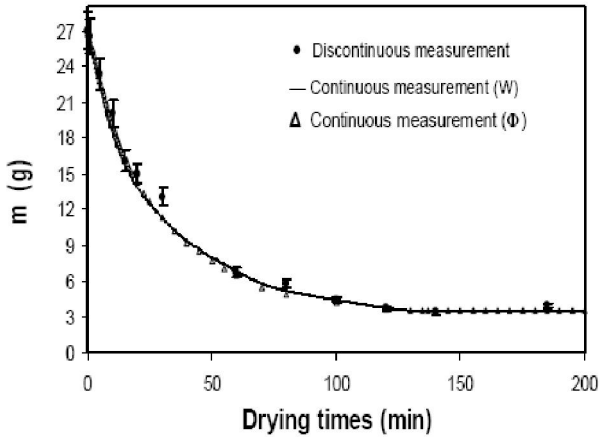

Figure 4 : Evolution of the mass of carrot particles versus time for a dry air flow-rate of about 48 l/min at ambient Temperature

The curve obtained by continuous measurements results from the average of three tests, each one lasting approximately 3 hours (that needs one day of tests). On the other hand, discontinuous measurements correspond to 13 points and at least two repetitions for each point (that needs between two and three days of tests). That illustrates the interest of uninterrupted measurements which require significantly less time to obtain equivalent results.

The experimental device was used to study the effect of the flowrate of air upon the rate of drying of carrot gratings. Drying usually occurs in several stages, each one characterized by a particular regime of drying rate.

Figure 5(a) and 5(b) respectively show the evolution of the standardized mass m* and rate (-d*m**/d*t*) various flowrate of drying air. It is clear that the drying rate increases with the flow rate of air. Furthermore, the curves of drying rate (particularly with the higher air flow rate) let appear an initial phase of constant drying

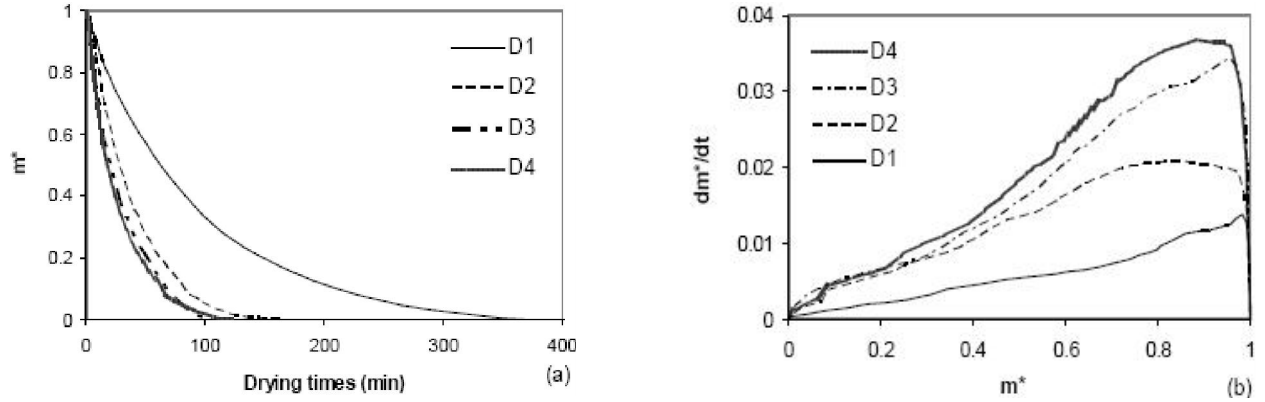

Figure 5 : Drying kinetics and rates of carrot gratings versus time at different dry air flowrate at Tamb; D4 = 48 l/min, D3 = 38 l/min, D2 = 20 l/min and D1 = 10 l/min

rate, for m* comprised between 1 and approximately 0.8. For a values of m* between 0.8 and 0.35 a first period of falling rate appears. During this period, the rate of drying is mainly controlled by diffusion of unbound water throughout the particles. When the standardized mass, m* drops below 0.35, the rate of drying enters a second falling rate period, characterized by a water activity less than 1, due to bound moister. In the second falling rate period, the water vaporization is assumed to take place within the particle rather than at the surface, as it is the case during the first two periods where free water has time to migrate to the surface before vaporization. The representation of the results in terms of (-dm*/d*t*) = f(m*), reveals a behavior characteristic of foodstuff (i.e. structural deformation limiting the drying, hardening of the external layer of particles in contact with drying air, etc.)[4-6].

The curves in figure 6 let see a typical example of the change of the temperature at the output of the drying cell. The difference between the input and output temperatures of the air is due to the increase of the humidity of the air flowing throughout the bed of gratings. However, at the end of the drying process, this difference vanishes when a balance is achieved between the humidity of the drying air and the water content of carrot gratings.

The PFE pre-treatment was applied in a similar manner with respect to an experimental optimization done in a previous study[11-13] and the different parameters are: pulses number = 1000, period = 1ms, duration of pulse = 100µs and the field intensity is of 1000 V/cm. So, the effect of an electric pre-treatment by a PEF (1000 impulsions, impulsion duration =100µs; for

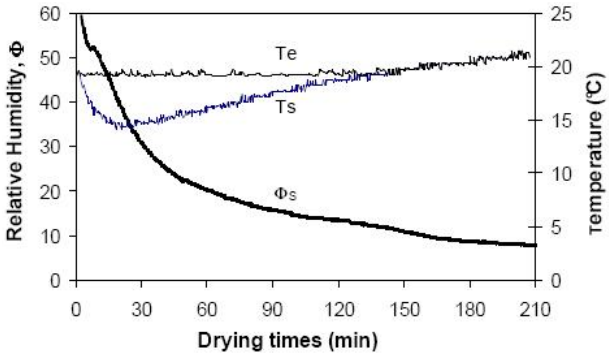

Figure 6 : Humidity and temperature evolution during drying of carrot gratings at air flowrate of 48 l/min

a period of 1 ms period and 1000V) was studied in the same experimental device. The drying process, carried out at ambient temperature under an air flowrate of 10 l/min, showed a beneficial effect of a PEF pre-treatment to enhance water diffusivity. Moreover, the drying kinetics of the carrot pulp was significantly improved (Figure 7(a)) and the drying time was decreased by about 110 minutes (i.e. reduction of about 30% of the total drying time). Furthermore, the stage of constant rate is more pronounced and larger in the case of pre-treated samples. Applying an electric field results in a high degree of permeabilisation of cellular membrane (a phenomenon referred as electroporation) facilitating internal mass transport. After a PEF treatment, a larger amount of water is available near the surface of the gratings. Furthermore, the constant rate period due to mechanism of electroporation results in water availability for a longer time.

CONCLUSION

This paper is the first part of a study concerning the

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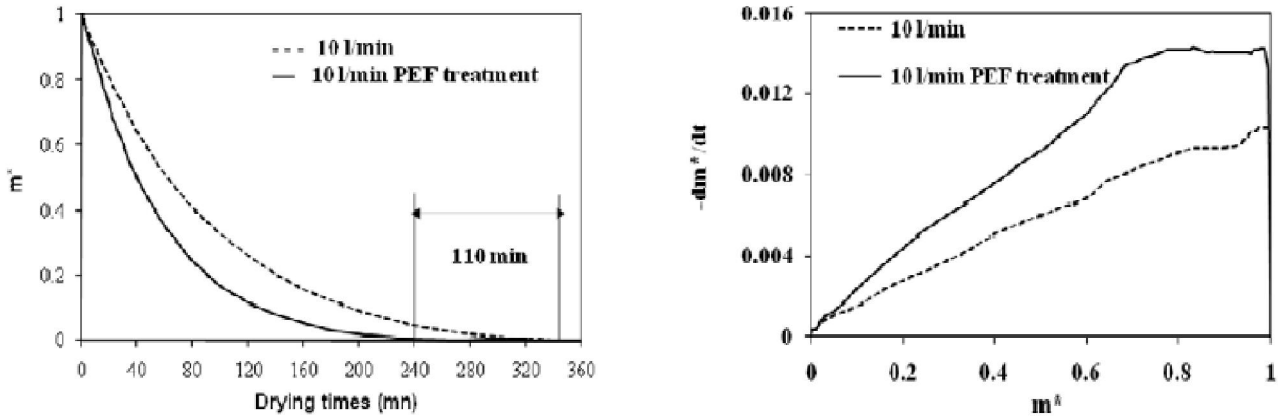

Figure 7 : PEF pre-treatment effect on drying kinetics and rates of carrot gratings at air flowrate of 10 l/min and ambient temperature: (…) untreated samples, (—) treated samples

impact of an electric treatment with a PEF on the drying kinetics of food products. The objective of this study is the validation of the measurements method and experimental device for drying. It showed that using relative humidity measurements at the inlet and at outlet of the filter-press, it was possible to deduce the kinetic of drying in a continuous way. By studying the effects of changing the air flowrate, a complex behavior of the carrot pulp, characteristic of the foodstuffs, was observed. The measurement technique was validated by a series of tests in which drying is stopped in order to be able to dismount the cell and to weigh the samples. For a given air flow rate, one day of tests was sufficient to perform the kinetics of drying (average of three tests) compared to more than three days of tests with the discontinuous method and for the same drying conditions. This illustrates well the time saving obtained without incidence on the precision of measurements. In addition, the use of pulsed electric field pre-treatment in a certain number of runs showed that the drying rate of carrot gratings is significantly improved so that the total drying time is decreased.

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