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Control of citrus surface drying by image analysis of infrared thermography

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Abstract

Citrus surface drying is one of the most important unit operations in a fresh fruit processing plant. A common risk in citrus surface driers (CSD) is using an excessive air temperature or keeping the fruit in the drier too long, since an important loss in sensorial quality may occur as well as a decrease in the fresh fruit shelf life. Nowadays, most of the new CSD use systems to control air temperature, but do not include elements to monitor the process by defining the required drying time. A new system to control the surface drying time by image analysis of the fruit surface temperature distribution, using infrared techniques was tested. The control of fruit surface temperature during drying allowed us to determine the moment when the surface drying finishes and the peel drying begins. Oranges (var. *Valencia Late*) washed with water or covered with a commercial wax were dried at 20, 25 and 35 °C with 1, 1.5 and 2 m/s air velocities. During the first drying step the lowest surface temperature of the fruit was measured from infrared images captured with an AGEMA 470 camera and was assumed to be the wet bulb temperature. Drying time could be well established when temperature at any point on the fruit surface exceeded this value. An empirical model was developed to correlate drying times with air conditions. Parameters of the model may be used in control systems for industrial CSD equipment.

Keywords: Drying; Infrared thermography; Fresh fruit processing

1. Introduction

Quality and shelf life of fresh fruit depends mainly on post-harvest treatment (Shewfelt & Schimnom, 1988). Deficient coating and drying reduce sensorial quality and shelf life of fresh fruit (Ben-Yehoshua, Burg, & Young, 1985). In citrus post-harvesting treatment lines fruit surface drying, after washing and coating, is a critical step. Frequently, citrus surface driers (CSD) use high temperature processes or inadequate holding time in the dried. This causes decay and citrus quality loss such as peel damage, undesirable flavors development, etc. (Fito, Asensio, Fito, & Ortolá, 1999). Despite many works have been published on food drying processes not so many papers have been devoted to analyze the citrus surface drying operation and to determine the guidelines for CSD design and control (Asensio, Fito, Ortolá, & Fito, 2000a, 2000b). Major problems in CSD design and control are:

- the very high output of post-harvesting fruit lines (some 20,000 kg fruit/h);
- the low quantity of water to be removed (some 20–40 kg water/h);
- the sort drying time (some 70–300 s).

These specifications imply extremely low water/product ratios and consequently the use of very high hot air flow rates, usually with low energy efficiency. Under such conditions the usual way to control the final point of drying, through measurement of the air temperature, becomes inadequate because of the low change in this control variable throughout the drying process. This constraint is extremely important in CSD since if a fruit remains inside the drier after its surface water has been removed, the drying phenomenon continues on the fruit peel inducing severe damage to fruit quality (Asensio et al., 2000b).

Image analysis of infrared thermography (IRT) have been used in some studies involving measures of surface temperature in vegetal material (Workmaste, Palta, & Wisniewski, 1999) but is a new optical technology in

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Nomenclature

CSD	citrus surface drying	T_W	wet bulb temperature (°C)
IRT	infrared thermography	S_{wh}	surface water holding (kg W/m^2)
T_D	drying temperature (°C)	t_D	drying time (s)
T_S	adiabatic saturation temperature (°C)	ε	emissivity (dimensionless)

citrus post-harvesting that offers the possibility of determining drying kinetics through the measurement of temperature distribution on the fruit surface. These measures themselves may also be used to determine the fruit final drying point and also to develop an on-line control system.

The objective in this work is to analyze the suitability of image analysis use and IRT to determine the final drying point in citrus surface drying in order to develop a system to control industrial CSD.

2. Materials and methods

Fresh, unwashed and uncoated oranges, var. *Valencia Late* (*Citrus sinensis*) were obtained directly from a local groves. Water–wax emulsion (Waterwax), containing waxes at 18% (180 g/l) (Carnauba and Shellac), was supplied by FOMESA S.A. (Spain). A pilot drying plant (Fito, Chiralt, & Asensio, 1997) was used to perform the surface drying experiments. An "AGEMA thermovision 470" infrared camera was installed on the dryer to observe and record the IR emission from the surface of the oranges. The fruit diameter was measured with a caliper (AISI caliper 304), the fruit volume was obtained by the Mohsenin method (Mohsenin, 1981) and the fruit surface was calculated using the sphere volume equation.

The fruits were washed, dried with blotting paper, and wax coated (water–wax emulsion) in a previously designed pilot plant (Fito, Ortolá, Chiralt, & Fito, 2001; Ortolá, Fito, Fito, & Asensio, 1999, 2001) where the fruits were coated with different film thicknesses (1.6 ± 0.1, 4.8 ± 0.4 and 10 ± 1 μm). The three different coating thicknesses correspond to 7.04×10^{-3}, 2.43×10^{-2} and 4.58×10^{-2} kg/m^2 surface water (S_{wh}). After coating, the fruit surface was dried in the UPV post-harvesting hot air dryer (Fito et al., 1997) at 20, 25 or 30 °C and 1, 1.5 or 2 m/s air velocity. The procedure, shown in Fig. 1, consists of a typical fruit surface drying process, where the fruit surface is recorded with an infrared camera. The value of fruit surface emissivity was previously measured ($\varepsilon = 0.95$) by tempering the fruit surface at 20 °C. In this way it was possible to know the temperature of the fruit surface throughout the drying period. The spin velocity of fruit throughout drying period (21 rpm) was coupled with the frequency of camera pictures in order to observe always the same area on the fruit surface.

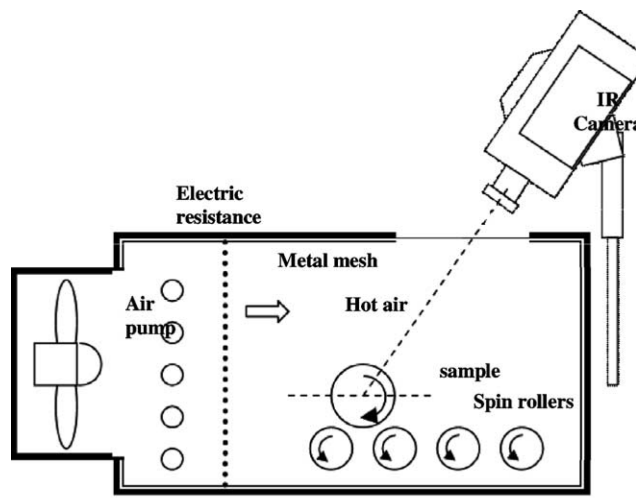

Fig. 1. Diagram of experimental equipment.

3. Results and discussion

About 7500 IR thermographies were obtained and recorded for each of the 81 performed experiments. As an example, in Fig. 2 some selected IR thermographs from a typical drying experiment are shown. The sequence of temperature distributions throughout the orange wax coating drying experiment (performed at 25 °C, 1 m/s air velocity and surface water of 2.43×10^{-2} kg/m^2) may be observed. In this experiment the adiabatic saturation temperature (T_S) was 15.1 °C but the wet bulb temperature (T_W) was 19.2 °C (defined as the lower value recorded at the beginning of experiment). The difference $T_W - T_S$ is the consequence of the low value of the air velocity in the drier, lower than 5.8 m/s (Perry, Green, & Maloney, 1992).

In Fig. 3, the effect of the air velocity on the wet bulb temperature may be observed. The two thermographs correspond to oranges coated with 2.43×10^{-2} kg/m^2 (S_{wh}), dried for 20 s at 25 °C air temperature (adiabatic saturation temperature equal to 14.5 °C). The thermograph on the right side corresponds to an experiment carried out at 1 m/s air velocity (wet bulb temperature, 19.2 °C) and that on the left side to a 2 m/s air velocity

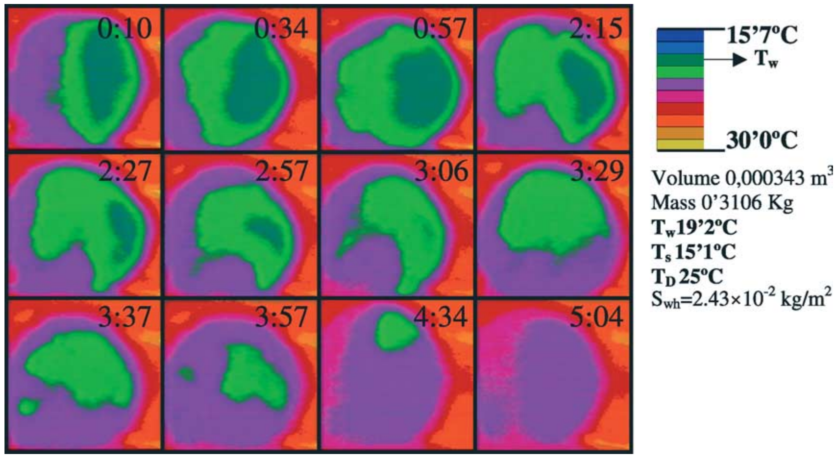

Fig. 2. The citrus surface temperature development throughout surface drying. Drying time was 3.2 min. This experiment corresponded to drying of orange wax coating with 2.43×10^{-2} kg/m^2 (S_{wh}), drying at 25 °C air temperature and 1 m/s air velocity where the adiabatic saturation temperature was 15.1 °C and wet bulb temperature was 19.2.

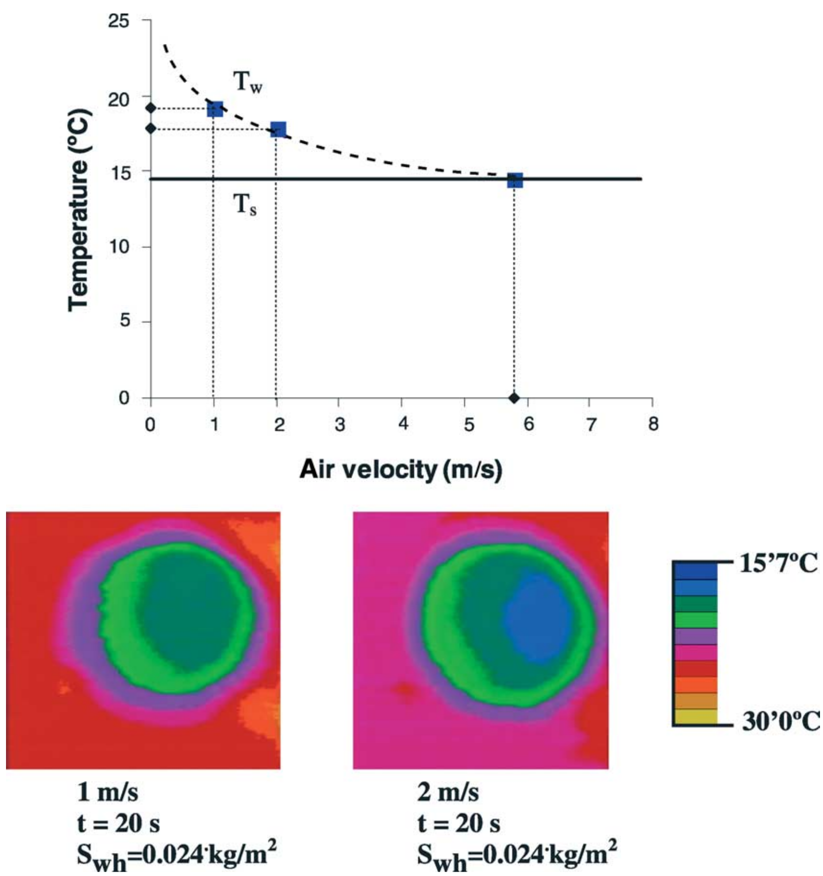

Fig. 3. Effect of the air velocity on the wet bulb temperature. The two thermographs correspond to oranges coated with 0.024 kg/m^2 (S_{wh}), dried at 25 °C air temperature (adiabatic saturation temperature of 14.5 °C). The thermograph on the right was treated at 1 m/s air velocity where wet bulb temperature was 19.2 °C. The thermograph on the left was treated at 2 m/s air velocity where wet bulb temperature was 17.8 °C.

(wet bulb temperature, 17.8 °C). The value of T_W and T_S must become equal when the air velocity exceeds 5.8 m/s (Perry et al., 1992). In the same figure, the lines representing T_W and T_S values as a function of air velocity are plotted.

Preliminary experiments with pure water showed the occurrence of the two drying steps (Asensio et al., 2000a, 2000b):

1. *The film water evaporation on the fruit surface*. In this case the water temperature on the surface (T_W) will

be depend on the water activity of the coating liquid and on the air temperature and velocity. The temperature distribution on the orange surface (Fig. 2) may be explained in terms of the heterogeneous distribution of effective air velocities over this surface. The lowest temperature value at the very beginning of drying process must be considered as the true wet bulb temperature and therefore the end of first drying step (t_D) will occur when the entire orange surface is at a higher temperature than T_W. In Fig. 2, the drying time was calculated as 3.02 min ant the wet bulb temperature as 19.2 °C.

2. *Orange peel drying*. This step occurs when no water is present on the orange surface and it must be avoided because it contributes to fruit surface damage.

With the criteria explained above, drying times (t_D) were calculated for each experiment. The dependence of t_D on the S_{wh} and the air temperature and velocity is evident as may be observed in Figs. 4–6; the higher the air velocity the lower the t_D dependence on air temperature. For the maximum values of S_{wh}, the air temperature influence on t_D is negligible in the experiments carried out at 2 m/s air velocity. It seems that in these experimental conditions some water was blown off the orange surface, thus decreasing the drying time. The experimental points included in Figs. 4–6 have been correlated to obtain predictive equations useful in CSD design and control.

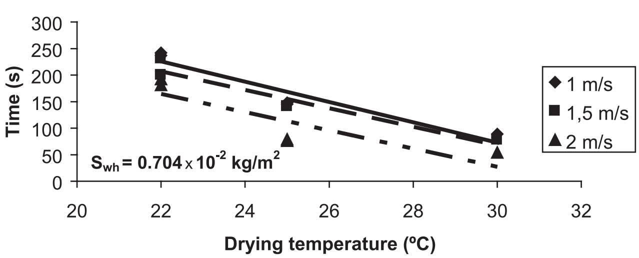

Fig. 4. Effect of drying temperature on the surface drying time at different air velocities (1, 1.5 and 2 m/s), calculated with 0.704×10^{-2} kg/m^2 surface water holding.

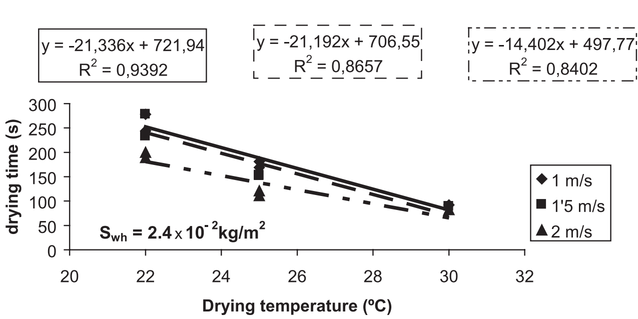

Fig. 5. Effect of drying temperature on the surface drying time at different air velocities (1, 1.5 and 2 m/s), calculated with 2.4×10^{-2} kg/m^2 surface water holding.

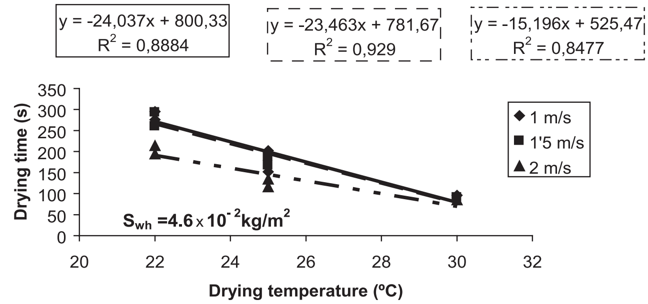

Fig. 6. Effect of drying temperature on the surface drying time at different air velocities (1, 1.5 and 2 m/s), calculated with 4.6×10^{-2} kg/m^2 surface water holding.

4. Conclusions

Image analysis of IRT observations of fruit surface during drying may be used as a non-destructive measure to determine the final drying time. This possibility is relevant for improving both, heat consumption and fruit quality and may be used in the control operation.

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