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HEAT PUMP DRYING OF BANANA SLICES: INFLUENCE OF CYCLIC VARIATION OF AIR TEMPERATURE ON PRODUCT QUALITY

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ABSTRACT

Drying is an energy intensive process and considerable wastage of energy occurs in the traditional method of drying. The quality, in terms of appearance and nutrients, of the product is also affected by drying conditions. In a traditional dryer, it is difficult to maintain temperature and relative humidity of the drying medium independently. Heat pump enables to conserve energy, and control temperature, humidity and flow rate independently and accurately. A two-stage heat pump dryer has been developed and extensive studies, both analytical and experimental, have been conducted to determine the performance under different operating conditions with various food materials.

Pieces of banana were dried in a two-stage heat pump dryer capable of precise control of air humidity with predetermined cyclic variations of air temperature entering the drying chamber. The air temperature variations tested were : a cosine, a reversed cosine and three different square wave profiles with peak-to-valley variations from 20 °C to 40 °C. The cycle time was about 60 minutes with drying time of approximately 300 minutes. The drying samples were placed on trays in a thin layer. With appropriate choice of temperature-time variation, it is possible to reduce the overall color change while maintaining high drying rates.

INTRODUCTION

The North Central Region Committee on Food Losses and Conservation (NCR-122) of USA has established the definitions of "yield", "loss" and "waste", in food processing. The term "loss" was classified into two categories, namely, avoidable losses and waste, that is loss which is avoidable by use of the best practical technology and unavoidable losses (Mark, 1983). Now the challenge that faces researchers in drying and food science is to find new solutions to convert the unavoidable quality losses to avoidable quality losses as much as possible to set new standards in food quality requirements.

In convective drying, air temperature, humidity and velocity have significant effects on the drying kinetics and quality of food products. It is then possible to control the quality of the dried products through direct control of these parameters. Devahastin and Mujumdar (1999) have demonstrated, via a mathematical model, the feasibility and advantages of operating a dryer by varying the temperature of the inlet drying air in terms of reducing drying time by up to 30%.

Colour is a very important attribute of food products and is subject to appreciable changes during processing (Cohen and Saguy, 1983). It gives the consumers the direct visual correlation to freshness and taste. As technology advances, more options are available to improve quality. One potential avenue in improving quality degradation in food products during drying is to employ time-varying temperature profiles that minimise quality degradation and dry the products to the desired moisture content within an allowable production time.

Several researchers have studied the degradation of quality of dried products under sine or square wave temperature fluctuations (Powers et al., 1965, Wu et al., 1974 and Kamman et al., 1981) during storage. However, little work has been reported to study the effect of temperature profiles on quality during convective drying process.

The present work has several objectives. Firstly, we have examined through experiments, the possibility of minimizing colour degradation of the dried products, through judicious selection of inlet air temperature profiles. Secondly, we examined if the control strategy implemented in a two-stage heat pump dryer is able to regulate the temperature of the drying air to produce prescribed temperature profiles. Thirdly, we studied the drying kinetics of banana samples by varying the inlet air temperature with a prescribed pattern.

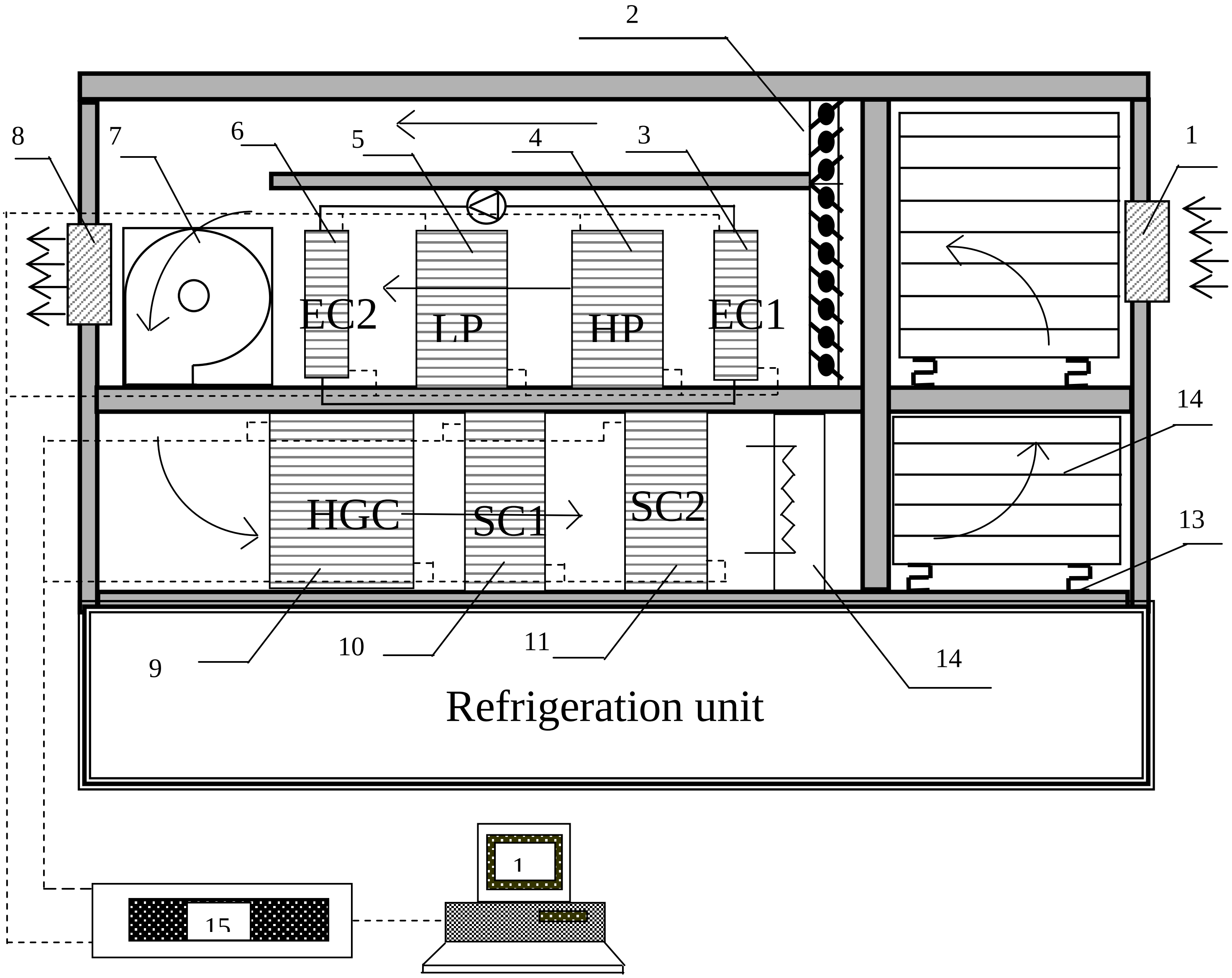
Due to the complex chemical reactions which can occur during the drying of foods and agro-products, it is necessary to measure experimentally the appropriate quality parameters. To quantify the global colour change of each product during drying, we studied four color parameters. The four Hunter parameters were redness (a), yellowness (b), lightness (L) and the total color change (E).

MATERIALS AND METHODS

Preparation of banana samples

Fresh ¾ ripe Del Monte banana samples were peeled and sliced with an adjustable food-slicer to a thickness of 3 mm and cut to a size of 30 mm x 30 mm with a twin-knife fixture. Twelve identical pieces of banana, in single layer, were placed on netted trays positioned in the drying chamber of a heat pump dryer (Chou et al., 1998). The required air temperature and humidity, representing each cyclic temperature-time profile, were programmed into the respective PID controllers to regulate the refrigerant flow for temperature control and the by-pass air damper position through the evaporators for humidity control. Air humidity was held constant in this study at 0.0089 kg/kg of dry air while only the temperature was varied with time.

Drying in a two-stage heat pump dryer, as shown in Figure 1, was carried out using 8 different time-temperature varying profiles shown in Table 1. Three constant temperature drying air runs (a, b and c) were made to serve as base cases. Taking a typical ambient temperature of 30 °C, square-wave and cosine-wave temperature variations were programmed into the PID controller to study the effect of drying temperature variation on the product colour. As drying progressed, one sample was removed at a time for weight and colour measurements.



Item #	Parts	Description	Item #	Parts	Description
1	-	Fresh air intake air louver	**9**	HGC	Hot gas condenser
2	-	Air damper	**10**	SC1	Subcooler 1
3	EC1	Economiser 1	**11**	SC2	Subcooler 2
4	HP	High pressure evaporator	**12**	-	Heating bank
5	LP	Low pressure evaporator	**13**	-	Load-cell
6	EC2	Economiser 2	**14**	-	Product tray
7	-	Centrifugal fan	**15**	-	Micromac data-logger
8	-	Exhaust air louver	**16**	-	Personal computer

Figure 1. Schematic diagram of a 2-stage heat pump dryer.

Table 1. Drying air conditions for the various temperature profiles.

Temperature profile	Drying conditions	
a constant temperature	T_a=25 ± 0.4 °C, Relative Humidity = 43.2 ± 1.5% ω = 0.0085 kg/kg dry air V_a = 2.4 ± 0.3 m/s	
b constant temperature	T_a=30 ± 0.5 °C, Relative Humidity = 32.5 ± 1.2% ω = 0.0086 kg/kg dry air V_a = 2.5 ± 0.2 m/s	
c constant temperature	T_a=40 ± 0. 7°C, Relative Humidity = 19.8 ± 1.8% ω = 0.0092 kg/kg dry air V_a = 2.5 ± 0.2 m/s	
d cosine wave-form about 35 °C amplitude = 5 °C peak to valley=10 °C cycle time=60 minutes	$T_{a,h}$=40 ± 0. 5°C Relative Humidity = 20.0 ± 1.4% ω = 0.0093 kg/kg dry air V_a = 2.4 ± 0.3 m/s	$T_{a,l}$=30 ± 0. 5°C Relative Humidity = 28.1 ± 1.4% ω = 0.0074 kg/kg dry air V_a = 2.4 ± 0.2 m/s
e reversed cosine-wave-form about 35 °C amplitude = 5 °C peak to valley=10 °C cycle time=60 minutes	$T_{a,h}$=40 ± 0. 6°C Relative Humidity = 22.3 ± 1.7% ω = 0.0103 kg/kg dry air V_a = 2.4 ± 0.2 m/s	$T_{a,l}$=30 ± 0. 6°C Relative Humidity = 33.0 ± 1.7% ω = 0.0087 kg/kg dry air V_a = 2.4 ± 0.2 m/s
f square wave-form about 25 °C amplitude = 5 °C peak to valley=10 °C cycle time=60 minutes	$T_{a,h}$=30 ± 0. 8°C Relative Humidity = 31.8 ± 1.4% ω = 0.0084 kg/kg dry air V_a = 2.5 ± 0.3 m/s	$T_{a,l}$=20 ± 0. 8°C Relative Humidity = 65.1 ± 1.4% ω = 0.095 kg/kg dry air V_a = 2.5 ± 0.3 m/s
g square wave-form about 30 °C amplitude = 5 °C peak to valley=10 °C cycle time=60 minutes	$T_{a,h}$=35± 0. 8°C Relative Humidity = 24.8 ± 1.4% ω = 0.0087 kg/kg dry air V_a = 2.5 ± 0.2 m/s	$T_{a,l}$=25 ± 0. 8°C Relative Humidity = 49.7 ± 1.4% ω = 0.098 kg/kg dry air V_a = 2.4 ± 0.2 m/s
h square wave-form about 35 °C amplitude = 5 °C peak to valley=10 °C cycle time=60 minutes	$T_{a,h}$=40 ± 0. 8°C Relative Humidity = 18.9 ± 1.4% ω = 0.0087 kg/kg dry air V_a = 2.4 ± 0.3 m/s	$T_{a,l}$=30 ± 0. 8°C Relative Humidity = 33.5 ± 1.4% ω = 0.0088 kg/kg dry air V_a = 2.4 ± 0.3 m/s

Measurement of colour

To measure the colour of the banana replicates, all samples were soaked in 2% $NaHSO_3$ solution for 5 to 6 minutes (Singh et al., 1983) to suppress enzymatic reactions, since the focus of the present work is to study the effect of drying conditions on product color due to non-enzymatic browning. Samples of each product were scanned at five different locations to obtain the averages of L, a and b values. The changes in each colour parameter were then calculated with respect to the target values. The colour values of each sample were measured using the latest Minolta CM-3500d Spectrophotometer to obtain the Tristimulus colour values (Hunter L, a and b values). Hunter L represents lightness, a represents redness or greenness while b represents blueness or yellowness values. The changes in each individual colour parameters were calculated as follows:

$$\Delta L = L - L_o; \qquad \Delta a = a - a_o; \qquad \Delta b = b - b_o \qquad (1)$$

The subscript 'o' refers to the target value or the initial colour parameters of each product at the beginning of the drying experiments. The total color difference (ΔE) was then determined using the following equation:

$$\Delta E = \left[\Delta L^2 + \Delta a^2 + \Delta b^2\right]^{1/2} \qquad (2)$$

RESULTS AND DISCUSSION

Drying kinetics

According to Karel (1988), the dynamic method for determining degradation kinetics, under conditions representative of drying, requires the acquisition of moisture, temperature, concentration and quality data during drying. The drying rate curves for each one of the temperature profiles are shown in Figure 2. It can be observed from these figures that varying temperature drying produced intermediate drying rates between constant inlet air temperatures. Devahastin and Mujumdar (1999) have shown through the simulation of their validated model for grain drying that the drying rate is higher for step-wise temperature above those for constant temperature drying. It was, therefore, not surprising that our present temperature profiles produced intermediate drying rates compared to the drying rates produced by constant temperature drying.

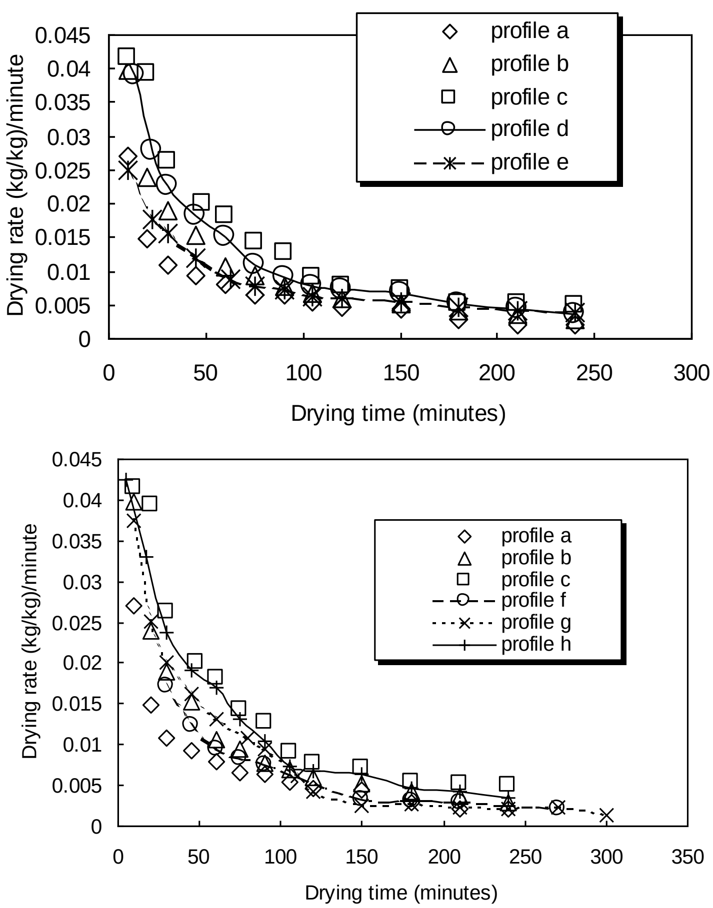


Figure 2. Drying rate comparing varying temperature profiles d, e, f, g and h to constant temperature profiles a, b and c.

Change in lightness (Δ L), redness (Δ a) and yellowness (Δ b)

From Figure 3 we observe that time-temperature profiles e and f were able to maintain the lightness of the banana samples close to the original value. Both profiles produced lightness results between profiles a (improved lightness) and c (increased darkness) with reduced drying rate when compared to profile a (See Figure 2).

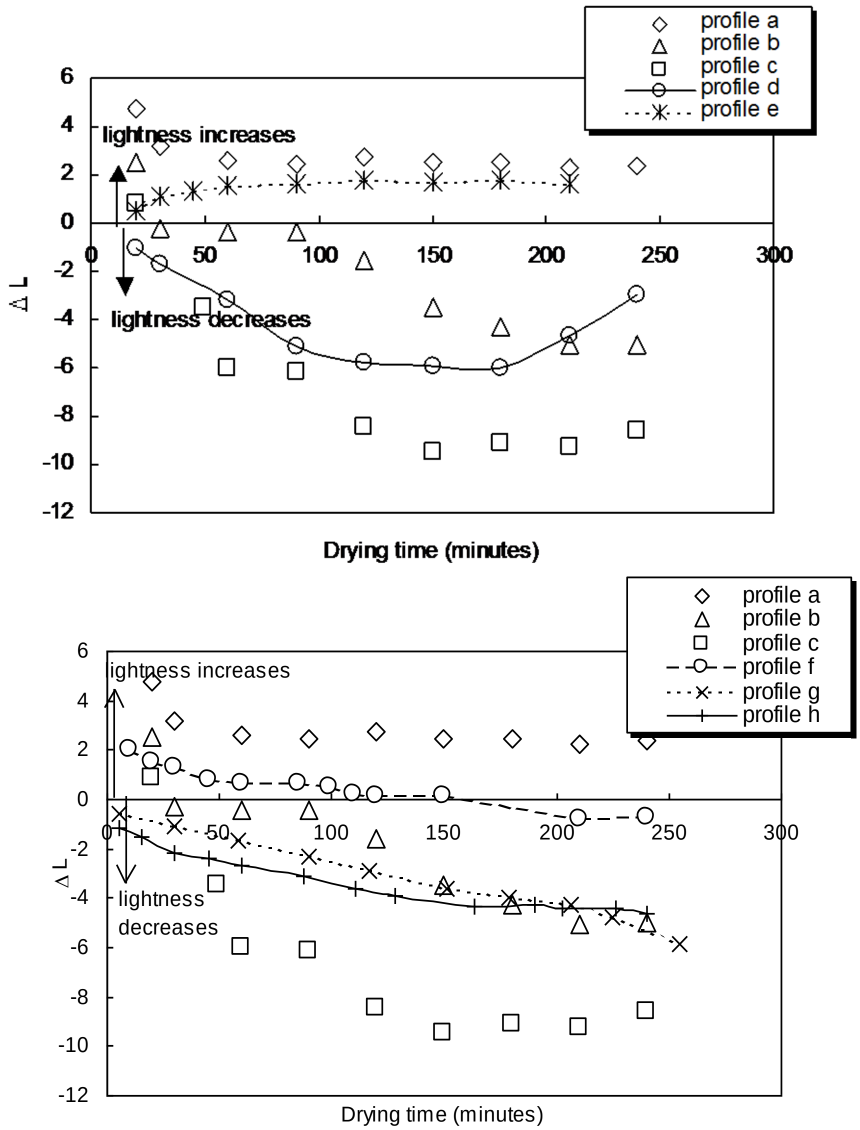


Figure 3. Changes in Lightness ΔL versus time for temperature profiles d, e, f, g and h compared to constant temperature profiles a, b and c.

Temperature profiles d and e were observed to maintain the original level of redness of the banana samples, as seen in Figure 4. Profiles d and e resulted in redness levels above and below the original level. On the other hand, temperature profiles f, g and h had no significant influence on redness reduction,as indicated in Figure 4.

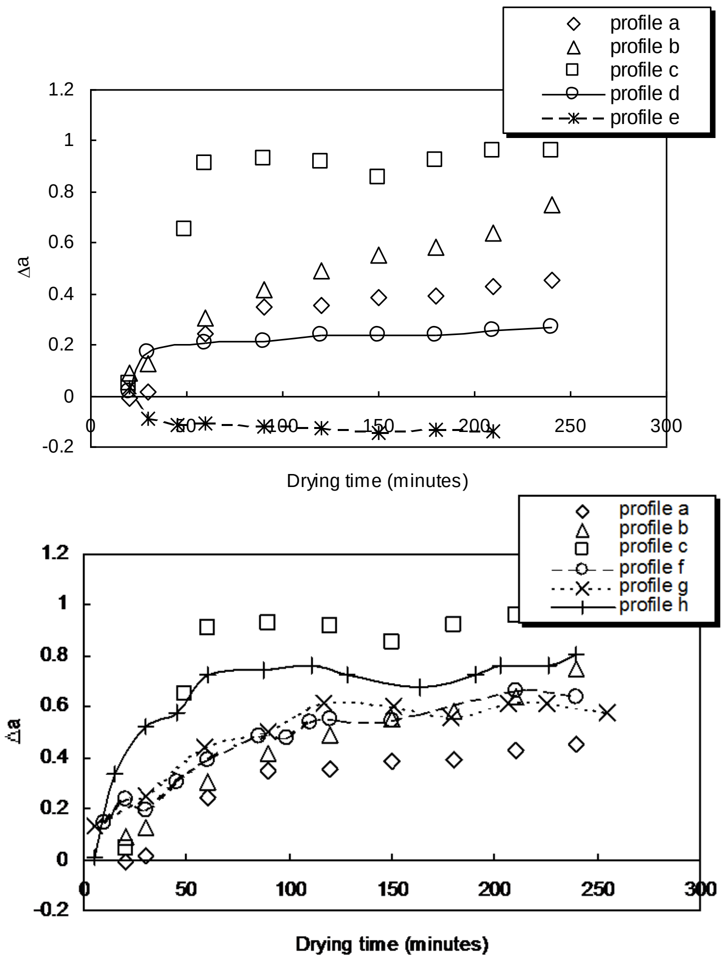
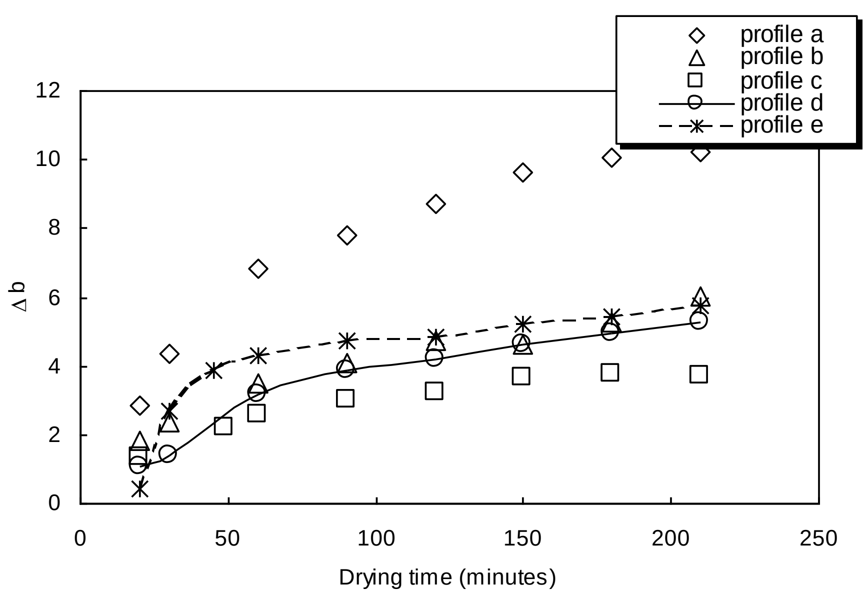


Figure 4. Changes in Redness Δa versus time temperature profiles d, e, f, g and h compared to constant temperature profiles a, b and c.

During the drying of the banana samples, constant temperature drying profile c, with temperature of 40 °C, was observed to minimize the change in yellowness (Figure 5). Varying the temperature of the inlet air to the drying chamber did not reduce the change in yellowness.



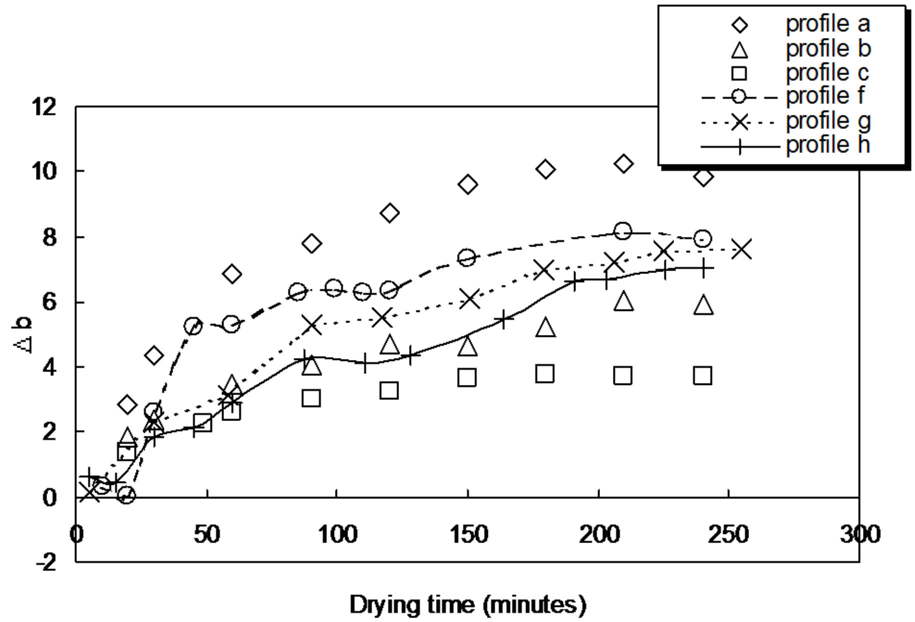


Figure 5. Changes in Yellowness Δb versus time temperature profiles d, e, f, g and h compared to constant temperature profiles a, b and c.

Overall colour change (Δ E)

A sinusoidal inlet air temperature with cold starting point, profile e, was found to be able to minimize the overall color change in banana drying, as portrayed in Figure 6. For this profile, the temperature amplitude was 5 °C (about 35 °C). Comparing the values of Δ E from profiles e and c, a 67 % reduction in total color change was obtained through the use of the time-varying temperature profile e.

The starting temperature of profile e and its oscillatory pattern resulted in a low initial drying rate. This allowed sufficient time for the internal moisture to diffuse to the surface ensuring a constant film of moisture at the surface. Thus, banana, a product with high sugar content, would be continuously coated with a layer of moisture during the initial stage of drying. This layer reduces the effect of surface heat-up, resulting in a lower surface reaction. When food preparations are heat-processed, a number of chemical reactions occur, one of which is the well-known Millard reaction (Milton, 1985), known to be responsible for non-enzymatic browning. The Maillard reaction involves the reaction of an aldehyde (usually a reducing sugar) and an amine (usually a protein or amino acid) and is highly temperature-dependent. The degradation of the Amadori compound (a product of the Millard reaction) involves dehydration of the sugar molecules to ultraviolet (UV) absorber compounds during the browning process (Milton, 1985). The layer of surface moisture, during the initial drying stage, probably prevents dehydration of the surface sugar molecules and hence reduces the rate of the Maillard reaction, thus lowering the overall colour change.

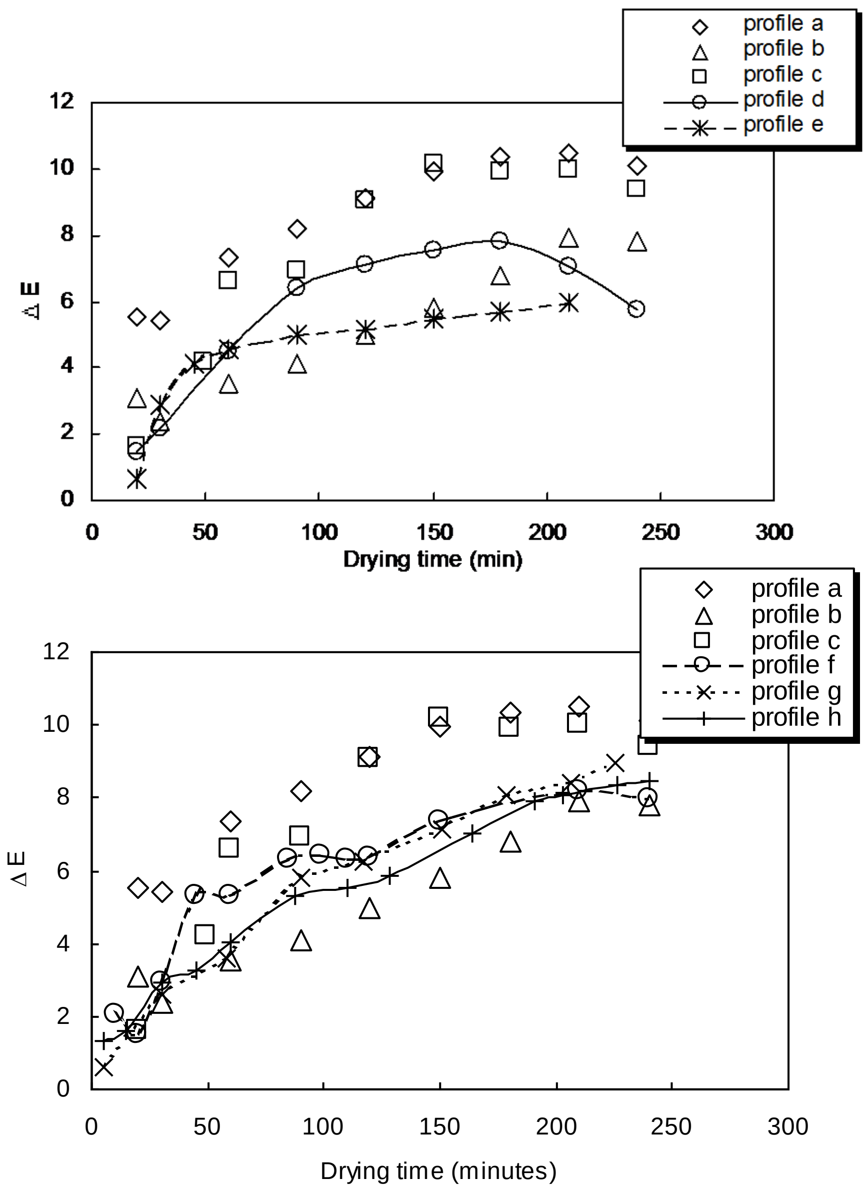


Figure 6. Total changes in colour ΔE versus time for temperature profiles d, e, f, g and h comparing to constant temperature profiles a, b and c.

CONCLUSIONS

We have demonstrated that a two-stage heat pump dryer can be controlled to produce prescribed time-varying air temperature profiles to study the effect of non-uniform temperature drying on the colour change of banana samples. We have also shown that by subjecting the banana samples to different temperature profiles in a heat pump dryer, it is possible to reduce the change in individual color parameters as well as in the overall colour change in the food products. High-sugar content products, such as the banana, favour a sinusoidal temperature wave profile with a cold starting temperature of 30 °C. The percentage reductions in overall colour change for banana was 67%.

NOMENCLATURE

A	cross-sectional area or surface area	m^2
T_{amb}	temperature of ambient	°C
a	Hunter redness value	-
b	Hunter yellowness value	-
E	Hunter colour difference	-
L	Hunter lightness value	-
V	air velocity	m/s
X	moisture content	kg/kg dry basis

Greek symbols

Δ	change in colour parameters	-
ω	absolute humidity	kg/kg of dry air

Subscripts

a	air	-
avg	average	
h	high	-
l	low	-
o	initial	-

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