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An intelligent integrated control of hybrid hot air-infrared dryer based on fuzzy logic and computer vision system

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ABSTRACT

In this study, an intelligent fuzzy-machine vision control system (FMCS) was developed to control the operating variables throughout a hybrid hot air-infrared drying process. The total discoloration and the shrinkage of thin layer kiwifruit slices were monitored in real time using a computer vision system (CVS). These values along with calculated energy consumption obtained from preliminary experiments, were fed into a genetic algorithm (GA) framework to optimize a fuzzy logic control system. The performance of the fuzzy controller was evaluated for kiwifruit drying using a laboratory-scale hot air-infrared dryer. The results indicated that the hybrid drying could significantly reduce the drying load/time compared with the hot air drying. The FMCS application showed a good balance between energy consumption (0.158 kW h) and product quality ($\Delta E = 2.32$).

1. Introduction

Preventing unfavorable changes of product quality is a crucial task in food industry. Shrinkage and color are considered the most important organoleptic properties, determining marketability of the product after drying. To avoid unfavorable changes of organoleptic properties, the quality of food must be accurately and rapidly detected using real time computer vision system (CVS). An online CVS can continuously collect information about the shape, size (Campos-Mendiola et al., 2007; Hosseinpour et al., 2011; Yadollahinia and Jahangiri, 2009) and color (Chen and Martynenko, 2013; Hosseinpour et al., 2013; Nadian et al., 2015) of the food product in the process of drying.

Another crucial task in food industry and particularly in drying is to maximize the profitability due to reducing the associated costs. In this regard, reducing energy consumption is the main concern because industrial dryers consume a significant part of the total energy, i.e. 12% on average (Mujumdar, 2014). Generally, the reduction of drying time is a possible avenue to increase the efficiency of operation. Hence, hybrid technologies such as microwave- and infrared-assisted convective drying becoming more popular (Hebbar et al., 2004; Zhang et al., 2006). Although such combined technologies are more efficient than hot-air drying (HAD), the deterioration of organoleptic properties of the end product is of significant concern. The problem is that without careful monitoring the sample temperature may still continue to rise, resulting in overheating or burning (Zhang et al., 2010). Since most foods are heat-sensitive in nature, it is desirable to implement intelligent control system, such as neural networks or fuzzy logic, to preserve product quality.

Fuzzy control systems are applied in nonlinear and probabilistic processes, or for the situations where processes could not be modeled mathematically (Herrera et al., 1998). In addition, the organoleptic characteristics of foods are imprecise attributes with no defined boundaries. However, using linguistic attributes they could be characterized as high, low and medium quality, etc. Considering these inherent characteristics, fuzzy logic control seems to be appropriate approach for foodstuff applications in such as drying (Li et al., 2010). Hence, a fuzzy-machine vision control system (FMCS) application, which combines a CVS to continuously extract visual information of agro-food product under drying and sends this information to a fuzzy control system, can be a suitable alternative to traditional control strategy. Although most of research with CVS has been done in image-based quality monitoring of drying process, to the best of authors' knowledge, no development is

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Nomenclature

HAD	hot air drying
HID	hybrid hot air- infrared drying
FMCS	fuzzy-machine vision control System
A	area of slice (number of on pixels binary image)
Sh	shrinkage (%)
L^*	lightness value
a^*	redness value
b^*	yellowness value
ΔE	total color difference
T	air temperature (°K)
V	air velocity (m/s)
Q, W	energy (kW h)
E	total energy consumption (kW h)
X	length of control volume
Y	width of control volume
Z	height of control volume
I	radiation (W/cm^2)
MR	moisture ratio (dimensionless)
RH	relative humidity (dimensionless)
P	pressure (Pa)
C	specific heat (kJ/kg °C)
J	desirability value (dimensionless)
h	enthalpy (kJ/kg)
t	duration of drying (h)
ρ	density (kg/m^3)
ω	humidity ratio (kg/kg)

Subscripts

0	initial value
1	ambient conditions (outside dryer)
2	hot air conditions (inside dryer)
HA	hot air
Fan	fan
IR	infrared
a	air
da	dry air
ws	saturated vapor
wv	water vapor
at	atmospheric
we	vaporization

available in regard to using CVS for feedback control of drying process.

Therefore, the research objective was to develop general structure of intelligent control system for hybrid hot air-infrared dryer, using CVS for observation and fuzzy logic for decision making process. It was anticipated that FMCS permits real-time manipulation of process variables within optimal ranges, thereby minimizing the quality loss and energy consumption. To test this hypothesis, a laboratory-scale hybrid hot air- infrared dryer (HID) was constructed and used for kiwifruit drying. Multiple variables, such as moisture ratio (MR), energy (E), shrinkage (Sh) and total color change (ΔE) of kiwifruit slices dried at different temperatures and air velocities were monitored and analyzed in real time. Based on these preliminary experiments, a genetic algorithm was implemented in a Genetic Fuzzy System (GFS) framework with an adaptation and learning capability according to Herrera (2008). The GFS was employed to generate an optimized set of rules to be fed into the following fuzzy control system that was developed to optimize the drying effects. The performance of the control system was tested for kiwifruit drying, reflecting optimum levels of MR, E, SH and ΔE.

2. Materials and methods

2.1. Dryer

The constructed laboratory-scale hybrid hot air-infrared dryer was equipped with a CVS and a control system (Fig. 1). This dryer was used for both HAD and HID drying. The main parts of the hybrid dryer are: four IR lamps (250 W, SICCATHERM-RED, OSRAM, China), some electrical heating elements (total wattage of 7000 W), a fan (2000 m^3/h, equipped with a 0.75 kW three-phase electromotor, MOTOGEN, Iran), a digital weighing scale (±0.01 g, A&D Co., Japan) connected to a PC (for continuously measuring the sample's weight), an air duct, a wire meshed tray and three integrated temperature and relative humidity sensors, model AM2303, installed before and after the tray and the third one outside the dryer for measuring ambient air temperature and humidity. The distance between the IR lamps and the tray, determined from preliminary trials, was 20 cm. Also, the uniformity of IR radiation and temperature on the tray were confirmed by a thermal camera (NEC G120, Nippon Avionics Japan). Kiwifruit slices were placed on the tray over which the IR lamps were located. The whole body of the dryer was thermally insulated with fiberglass.

2.2. Computer Vision System (CVS)

The CVS consisted of a digital camera (COOLPIX P510, Nikon Co., Japan) and illumination chamber. The illumination chamber was composed of eight power LED lamps (5 W) placed 20 cm above the sample tray at the angle of 45° with respect to the sample plane (see #9 in Fig. 1) to provide uniform illumination. Computer hardware and software were developed to capture and process the 4608 × 3456 pixel images of the kiwifruit slices during drying. To capture the high quality images of the samples being dried without any influence from the ambient light exposure, the camera was placed outside of the drying chamber, but with its lens placed over an orifice facing directly downwards on the drying tray. A small, 12 V fan was installed adjacent to the camera for cooling. The captured images were transferred to a computer through a Wi-Fi memory card (model Eyefi Mobi, Eyefi Co., US). The captured images were, then, read and analyzed by MATLAB software (Mathworks Inc, US).

2.3. Image features extraction

Image processing was performed through an algorithm written in MATLAB. Image segmentation was among the pre-processing steps applied on the images. In these images, as the objects of interest, i.e. slices of kiwifruit, had a bright green color and the background (the tray) was black, a quality segmentation was obtained by Otsu's method based thresholding of the high contrast image of green and blue difference (2G-2B) (Otsu, 1975). After binarizing images, a morphological flood-fill operation was performed to fill the holes inside the regions of kiwi slices particularly due to the small black seeds. Several features including the area of slices and their color values were extracted from the pre and