Development of smart sensors for the supervision of a solar dryer: agro-products dehydration application

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Abstract
Solar dryers are increasingly used in developing countries as an alternative to drying in open air, however the inherent variability of the drying conditions during day and along year drive the need for achieving low cost sensors that would enable to characterize the drying process and to react accordingly. This paper provides an approach for smart sensors that make use of the psychrometric properties of the air inside the drying chamber along day. The proposed model shows a high agreement with bibliographic data.
Key words: multi-distributed supervision, automated control, smart sensor

1. Introduction

Drying agricultural products enhances their storage life, minimises losses during storage, and saves shipping and transportation costs (Leon et al., 2002). Conventional drying processes range from natural sun drying to industrial drying but since the 1960s, several types of solar kiln for food drying have been studied and improved on, due to some advantages of the solar kilns, as lower or no operating cost since no fuel is needed for air heating. On the other hand the main disadvantage is its dependence on weather conditions resulting in less controllability by the operator, and less predictable outcomes (Haque and Langrish, 2005). Commercial kilns (i.e. Solar Dryers Australia Pty. Ltd. or CONA SOLAR AUSTRIA) are available, ranging from very simple systems with only a solar kiln with an integrated collector and small capacity, to automated dryers with an integrated energy storage system. Sharma et al., (Sharma et al., 2009) present an extensive review about the different types of solar dryers and their applications in the agri-food products since most of the solar dryers developed are designed for specific products or class of products.

In some solar dryers, the product to be dried receives energy not only from the hot air supplied by a solar collector but by direct exposure to solar radiation, being the product protected from rain, insects and dust (Fargali et al., 2008). One of the functions of the closed-type solar dryers is to avoid and isolate the humid environment from the drying process, including sometimes a dehydrator unit to enhance the drying process and to reuse the hot air. Other types of solar dryers make use of a solar collector that utilizes directly the energy from the sun to heat water that passes through it (Fargali et al., 2008). The output water from the collector is stored in a water tank. Such dryers attenuate the effect of solar radiation variability along the day, due to cloudy conditions, as well as due to the absence of radiation during night.

According to Kumar in 2005 (Kumar and Kandpal, 2005), the potential of using solar dryers requires detailed relevant data on the crops and solar radiation availability. The energy requirement strongly depends upon the initial and final moisture content of the crop. Thus, the useful energy requirement for drying ranges from 0.43 MJ/kg to 20.35 MJ/kg. Many materials can be used for making a closed solar dryer (copper, aluminium, toughened glass, absorber paint,…) which greatly affect the embodied energy in a solar dryer. Some average estimation proposes 2968 MJ/m^2 of aperture area. Solar drying can plan an important role in saving bio fuels and fossil fuels in developing countries such as India, where presently used in the drying of many crops.

According to Chen in 2005 (Chen et al., 2005), in traditional open-sun drying methods the drying rate is controlled by a number of external factors (solar radiation, ambient temperature, wind velocity and relative humidity) and internal factors (initial moisture content, type of product, and the mass of product per unit exposed area). Such procedure, does not allow for obtaining a suitably high and reproducible product quality, especially for food, mainly because of the inherent limitations in controlling the drying process.

Chillies in Bangladesh are traditionally sun dried in open sun on a mat, with very slow drying rate (7-15 days). Hossain and Bala in 2007 (Hossain and Bala, 2007), proposed the use of a solar dryer that consists of a transparent plastic covered flat plate collector and a drying tunnel connected in series to supply hot air directly into the drying tunnel decreasing the drying period to 32 hours. For such dryer, the air temperature at the outlet of the solar collector rises to 40 to 66ºC compared to 20 to 35ºC at the inlet of the collector. That is to say an average rise in temperature inside the collector is 21.6ºC and stays in the basis of the high decrease in drying duration.

Fargali in 2008 (Fargali et al., 2008), states that conventional drying methods such as open sun drying are time-consuming and may not be suitable for medicinal herbs since they yield a less quality product due to contaminations, and attacks of rodents, insect and fungi; neither conventional-fuel dryers, are suitable due to the increase in the drying cost.

Low cost sensors are most suitable for the supervision and control of solar dryers, and can be easily upgraded by including smart capabilities. According to Corsi, the term smart sensor refers to those elements containing sensing and signal processing capabilities and understanding, with objectives ranging from simple viewing to sophisticated remote sensing, surveillance, search/track, robotics, perceptronics and intelligence applications (Corsi, 2007). The smart sensor is expected to have the capability that functionality and architecture, as well as raw data acquisition are based the existence of microprocessing unit (Son et al., 2009).

Rapid advances in sensors, wireless communications, Micro Electro Mechanical Systems (MEMS) have the potential to assist in dealing with a large amount of data that is generated by a monitoring system. On board processing at the sensor allows a portion of the computation to be done locally on the sensors' embedded microprocessor, with self diagnosis and self-calibration capabilities, thus reducing that data amount of information that needs to be transmitted over the network. It is important to state that the basic difference between a smart sensor and a standard integrated sensor is its intelligence capabilities (Spencer et al., 2004). Son in 2009 (Son et al., 2009) proposes the use of intelligent classification systems as to assist the condition monitoring tasks by correctly interpreting the fault data in machine fault diagnosis. Result by these authors demonstrated the advantage of smart sensor systems compared to conventional ones.

Another term relevant to our work refers to smart environment, defined by Cook (Cook and Das, 2007) as one that is able to acquire and apply knowledge about the environment and its inhabitants in order to improve the experience in that environment. Automation in a smart environment can be viewed as a cycle of perceiving the state of the environment, reasoning about the state together with task goals and outcome of possible actions, and acting upon the environment to change the state. Among the desired features in a smart environment, sensor/actuator networks need to be fast, easy to install and maintained, robust and self organizing to create a ubiquitous/pervasive computing platform. Smart sensors move some the reasoning work down to the physical level without the intention of solving the entire intelligent environment design problem, but to provide intelligent functionalities within the confines of a single object and task.

Recently, Luna (Luna et al., 2009) in a review on the trends in solar kilns for drying timber uses an analytical method for product design based on TRIZ theory, and proposes the use of eight laws to evaluate developments in solar dryers. Two of such laws, *Coordination of Rhythms* and *Increase in Level of Improvement*, are specially defined to solve problems caused by the alternating day/night, seasonal rhythms or weather variations. The guidelines of this article can help addressing the quality of any dryer design. The definition, implementation and integration of intelligent sensors in solar dryers, which is faced in current research work actively enhances the quality of the dryer design.

2. Materials and Methods

Solar dryer. An experimental solar dryer was used during the experiment. This dryer has a capacity of 0.3 m^3, is equipped with a solar collector of 2 m^2, a 12 V DC fan, a chamber for drying, various metallic trays for samples positioning, a gate that controls the recirculation of air and a plenum chamber. The air comes into the dryer by one side, then heated in the roof, sucked into the plenum chamber and is ducted to the fan which blows it into the drying chamber where the wood is placed on trays. Figure 1 shows the air movement into the dryer.

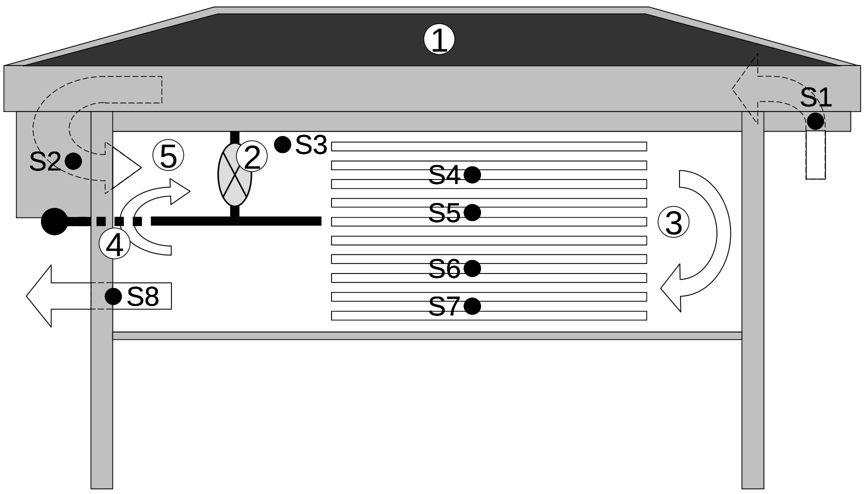

Figure 1. Scheme of the solar dryer, solar collector (1), fan (2), chamber for drying (3), gate for recirculation of air (4), and plenum chamber (5). The arrows indicate the airflow. Also, the location of the eight Sensirion S1-S8 (●)

Temperature and relative humidity sensors. In this paper Sensirion SHT sensors were used to characterize the drying air. The SHT is a single chip relative humidity and temperature multisensor module that delivers a calibrated digital output. The device includes a capacitive polymer sensing element for relative humidity (RH) and a band gap temperature sensor. Both are seamlessly coupled to a 14 bit analog to digital converter and a serial interface circuit on the same chip. Eight Sensirion sensors (see Figure 1) were located at different positions: at solar collector inlet and outlet, and several locations inside the drying chamber. The sensors were connected by wire to a board with a PIC (Peripheral Interface Controller) microcontroller. In the PIC the signals are multiplexed and then sent to a computer.

3. Proposed mathematical models

3.1. Psychrometric model

The ASAE D271.2, defined in April 1979 and reviewed in 2005 (ASABE_Standards, 2006), was used for computing the psychrometric properties of the air in the dryer. This standard enables the calculation of all psychrometric data of air whenever two independent psychrometric properties of an air-water vapor mixture are known in addition to the atmospheric pressure. A network with eight sensors provides air temperature (τ) and relative humidity in eight critical points in the dryer. Absolute humidity H (water mass over dry air mass), wet bulb humidity H_w (water mass over dry air mass), wet bulb temperature (the temperature of a volume of air cooled adiabatically to saturation by evaporation of water into it) τ_w, specific volume V_s (air volume over dry air mass) and specific enthalpy h (enthalpy over dry air mass), characterized the air at each point. The implementation of the psychrometric model in a *ad hoc* Matlab routine, allows supervising in real time the drying air conditions in different points.

3.2. Smart sensor model

It is possible to define a smart sensor based on the temperature and relative humidity of the air inside the kiln, measured for the network of eight Sensirion™ sensors. This smart sensor will allow determining the drying rate and the food moisture distribution into the dryer.

The drying rate expressed as $-dM/dt$, where M is the oven dry food moisture (water mass over oven dry food mass), allows identifying two different kinetics: one with a constant drying rate, for very damp products that present free water at surface, and a second one reached when water activity at product surface is below the unit, characterized for a decreasing drying rate (Barbosa-Cánovas and Vega-Mercado, 2000). Anyway, the transport of water during the food dehydration process takes place predominately in the falling rate period (Babalis et al., 2006), at this stage, diffusion is the mechanism that governs the drying process. There are many methods used to calculate drying diffusion, the most common being the solution of Fick's law described in the literature by (Crank, 1979) and (Luikov, 1968). For fruit and vegetables prepared as slices, the thin layer drying model for an infinite plate (one-dimensional problem)

$$\frac{M(t)-M_s}{M_0-M_s}=\frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}\times\exp\left(-\left(\frac{(2n-1)^2\pi}{2L}\right)^2 D\,t\right) \quad \text{Eq. 1}$$

assumes that the moisture transport is primarily by diffusion with no external mass transfer limitation and that shrinkage is negligible. Eq. 1 expresses the dimensionless food moisture, where $M(t)$ and M_0 are the averaged product moisture content at any time t and t = 0 respectively. M_s is the moisture content at food surface that can be taken to be negligible because it assumed a dry hot air surrounding that avoids staying water at timber surface. L is the half thickness of food, and D represents the temperature dependent diffusion coefficient defined by the Arrhenius equation

$$D=D_0\exp\left(-\frac{E_a}{RT}\right) \quad \text{Eq. 2}$$

where D_0 is the reference diffusion coefficient, E_a is the activation energy, R is the universal gas constant and T is the absolute temperature of food taking into account that it has been consider negligible the difference between T and τ .

In a solar dryer, continuous changing surrounding conditions (H and τ of the drying air) in the drying chamber during drying process are observed due to transient variation of weather parameters, since drying temperature varies with the time then if on one hand is possible to consider that the diffusivity does not change with space, on the other hand the diffusivity will depend on time. The Fick´s law solution described in the literature (Crank, 1979; Luikov, 1968) establishes that for a Fourier number Dt/L^2 >0.2, the infinite series solution in Eq. 1 can be approximated by the first term n = 1 of the series (Tripathy and Kumar, 2009). Applying these considerations the equation that enable the drying rate calculation is given by the following expression obtained as the derivative with respect to time of Eq. 1:

$$-\frac{dM}{dt} = \frac{2M_0}{L^2}\left(t\frac{dD}{dt} + D\right)\exp\left(-\left(\frac{\pi}{2L}\right)^2 Dt\right). \qquad \text{Eq. 3}$$

The Smart model is defined for the combined resolution of Eq. 2 and Eq. 3, and its implementation as a Matlab routine time depending, allows recalculating in real time a changeable drying rate according with the temperature and absolute humidity of the air measured with the Sensirion in different positions inside the kiln. The integrated form of Eq. 3 provides the evolution of food moisture content during drying period.

3.3. Simulation

The Smart sensor is based on a hardware element: Sensirion sensor for temperature and relative humidity of the air, plus the model previously described as the software engine of the system. Previous knowledge of drying parameters (E_a and D_0) as a function of material characteristics, and process input arguments (M_0, L), are necessary to optimize the design of the drying process. The availability of published data on drying parameters for a wide range of fruits and vegetables together with the possibility of acquiring temporal profiles of temperature and relative humidity of the air inside the kiln with our instrumented solar dryer, is the basis for simulation.

Product	Model parameters		Input argument	Output	
	E_a (kJ/mol)	D_0 (m^2/s)	*Initial moisture*	D (m^2/s)	*Final moisture*
Carrots slices (Berruti et al., 2009)	31.76	$3·10^{-9}$	88% (w/w).	$0.6·10^{-9}$-$2.312·10^{-9}$	8% (w/w).
Green mango slices (Corzo et al., 2008)	22.3-11.4	$1·10^{-7}$-$1.7·10^{-8}$	6.973 kg $_{water}$/kg $_{dry\ basis}$	$1.7\ 10^{-10}$ - $3.1\ 10^{-10}$	0.105 kg $_{water}$/kg $_{dry\ basis}$
Half-ripe mango slices (Corzo et al., 2008)	9.3-8.7	$7·10^{-9}$-$6·10^{-9}$	6.015 kg $_{water}$/kg $_{dry\ basis}$	$2.3\ 10^{-10}$ - $3.3\ ·10^{-10}$	0.325 kg $_{water}$/kg $_{dry\ basis}$

Table 1: Example of parameters and input arguments available from the bibliography.

Product	Product load inside the kiln	Input arguments	
	Dry matter (kg)	*L (m)*	M_0 (kg $_{water}$/kg $_{dry\ basis}$)
Carrot slices	3.8 4.6 5.0	0.010 0.012 0.013	10

Table 2: Input arguments for carrot slices drying simulation.

A simulation for drying carrot slices was carried out taking into account three different product loads inside the kiln (see Table 3) and using parameters from Table 1 at the smart model compilation. The simulation corresponds to a drying cycle of 66 hours that begins at 12 a.m. of day 1 and finishes at 6 a.m. of day 4.

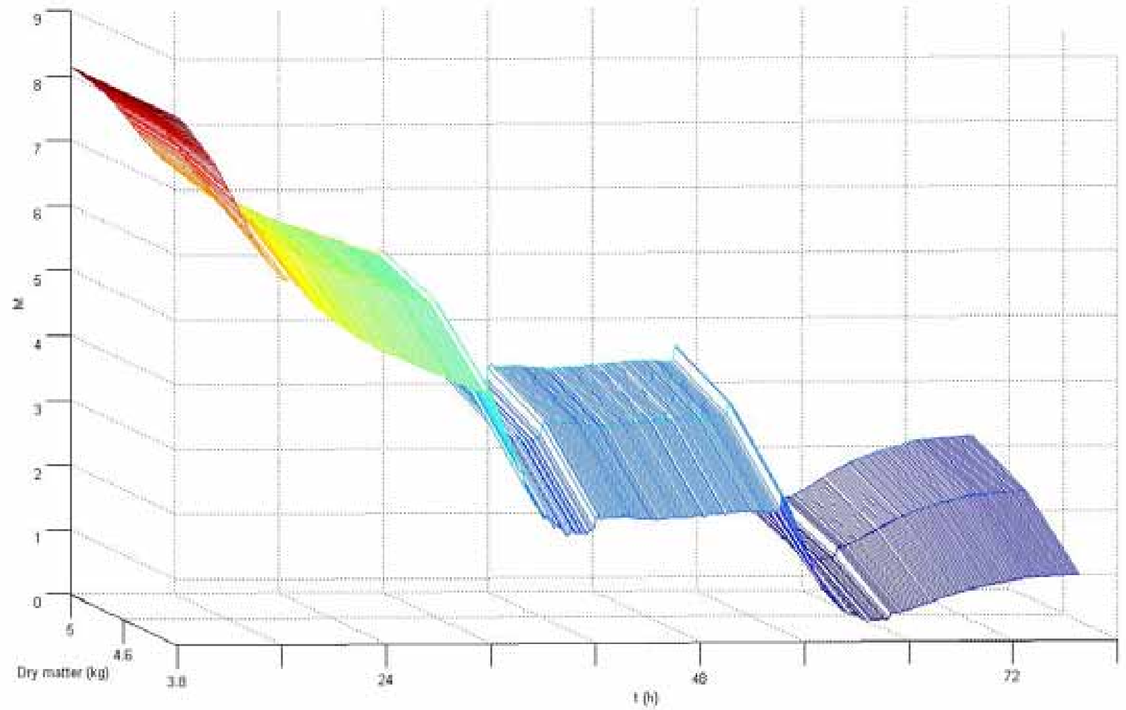

Figure 2. Evolution of oven dry carrot moisture M along one drying cycle. Data corresponding to Sensirion S3 located inside the kiln.

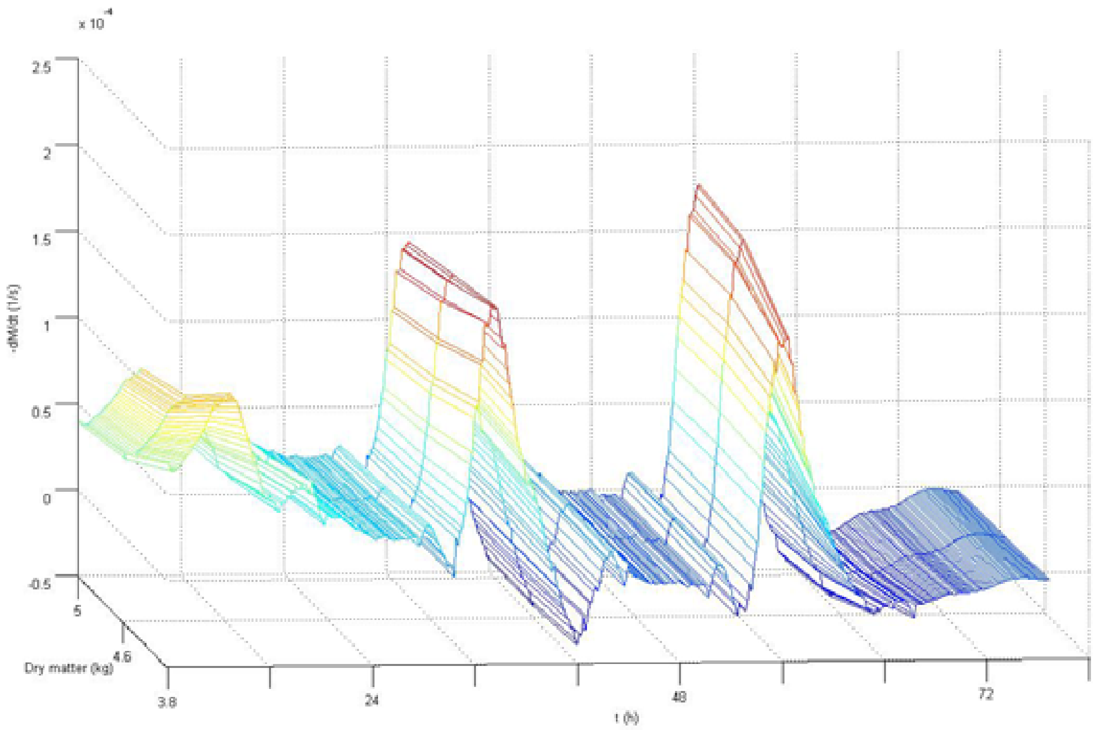

Figure 3. Evolution of drying rate along one drying cycle. Data corresponding to Sensirion S3 located inside the kiln.

Figure 3 shows the evolution of drying rate of carrots along the drying period. Although the general behavior of drying kinetic shows a decreasing trend, it is obvious that day/night alternation has a strong effect on drying rate. In Figure 3 positive peaks occur at 8 a.m. approximately, that is the end of night conditions and the beginning sunlight and thus of a quick decrease of carrots´ moisture (Figure 2). The negative peaks in Figure 3 at the end of evening (around 4 p.m.), marks the beginning of drying periods with little effect on moisture reduction of carrots (see Figure 2).

As Figure 2 shows, when carrots present high moisture values, even during night, is possible to observe a decrease in moisture content, while at the end of drying period, during the last night, the vapour pressure is greater than that at the product surface and thus product reabsorbs moisture from the air: carrots at 6 a.m. of day 4 show higher moisture values than those simulated along previous 12 hours.

The effect of product load inside the kiln, obtained as a function of the thickness of carrot slices simulated, is also clear. For increasing L values, higher M values are estimated for each time. Considering that the final optimum moisture content of $1 kg_{water}/kg_{dry\ basis}$ for carrots is achieved at 10 a. m. of day 3 for L=0.010 m (see Figure 2), carrots with L=0.013 m will need at least one other complete drying day to reach such moisture value.

4. Conclusions and further work

The operation and decision making in most dryers systems is guided by highly empiric recipes and rules which are usually too rigid to adapt the operation to sudden changes in the process conditions, especially important in solar dryers. The implementation of this model on MEMS become smart sensor where data corresponding to the temperature and relative humidity of the air inside the kiln collected by Sensirion^{TM} sensors, allows to estimate the most important and complex parameters in thermal drying: drying rate and actual product moisture for real time applications. Simulation tool allows, optimizing dryer design and dryer regulations and control.

The next step of this research will be an external validation of the proposed model with an experimental work based on a complete drying cycle for food.

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