Computers and Electronics in Agriculture 78 (2011) 167–175

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Development of model based sensors for the supervision of a solar dryer

E. Correa-Hernando [a,*], F.J. Arranz [b], B. Diezma [b], E. Juliá [c], J.I. Robla [d], L. Ruiz-Garcia [b], J. García-Hierro [d], P. Barreiro [b]

[a] Departamento de Ciencia y Tecnología Aplicadas a la Ingeniería Técnica Agrícola, Escuela Universitaria de Ingeniería Técnica Agrícola, Universidad Politécnica de Madrid, Av. Complutense s/n, 28040 Madrid, Spain
[b] Departamento de Ingeniería Rural, Escuela Técnica Superior de Ingenieros Agrónomos, Universidad Politécnica de Madrid, Av. Complutense s/n, 28040 Madrid, Spain
[c] Grupo de Energías Renovables, Facultad de Mecánica, Universidad de Oriente, Avenida Las Américas, Santiago de Cuba, Cuba
[d] Laboratorio de Tecnología de Sensores, Centro Nacional de Investigaciones Metalúrgicas, Consejo Superior de Investigaciones Científicas, Av. Gregorio del Amo 8, 28040 Madrid, Spain

ARTICLE INFO

Article history:
Received 21 January 2011
Received in revised form 24 May 2011
Accepted 13 July 2011

Keywords:
Ubiquitous monitoring
Psychrometric model
Automated control
Energy efficiency
Wood
Smart sensor

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 three different and complementary approaches for model based sensors that make use of the psychrometric properties of the air inside the drying chamber and the temperature oscillations of the wood along day. The simplest smart sensor, SMART-1, using only two Sensirion sensors, allows to estimate the accumulated water extracted from wood along a complete drying cycle with a correlation coefficient of 0.97. SMART-2 is a model based sensor that relays on the diffusion kinetics by means of assesing temperature and relative humidity of the air inside the kiln. SMART-2 model allows to determine the diffusivity, being the average value of D for the drying cycle studied equal to $5.14 \times 10^{-10}\ \mathrm{m^2\ s^{-1}}$ and equal to $5.12 \times 10^{-10}\ \mathrm{m^2\ s^{-1}}$ for two experiments respectively. The multidistributed supervision of the dryer shows up the lack of uniformity in drying conditions supported by the wood planks located in the inner or center of the drying chamber where constant drying rate kinetics predominate. Finally, SMART-3 indicates a decreasing efficiency along the drying process from 0.9 to 0.2

1. Introduction

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 (2007), 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. The smart sensor is expected to have the capability that functionality and architecture, as well as raw data acquisition are based on the existence of a microprocessing unit (Son et al., 2009).

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).

More and more, intensive and real-time data acquisition networks point that it is feasible to reconstruct spatial information in large areas from relatively scarce local data, though there is a need for simultaneously engineer the application and the technology knowledge (Camilli et al., 2007), as well as bringing together engineering and agronomics (Kitchen, 2008).

Integrating environmental data into model based concepts allow estimating risk of epidemic development in the fields even on a daily basis that can be web-based consulted (Wharton et al., 2008; Matese et al., 2009; Zhu et al., 2010), and can be used for more efficient closer-to-crop practices (Cunha et al., 2010) with closed loop on-site control of agricultural practices such as irrigation (Vellidis et al., 2008). Special requirements are found when wireless nodes are mounted on moving targets such as animal (Nadimi et al., 2008; Umstätter et al., 2008; Tøgersen et al., 2010).

Information models can be centered on the decision maker for the generation of management systems, which will lead to new working habits and to gaining increased insight into their production processes, as well as to access and utilize better available scientific research and technological developments (Sorensen et al., 2010).

Wood drying is an important step in wood manufacturing and the highest energy consumer with about 70% of the total energy

* Corresponding author.
E-mail address: evacristina.correa@upm.es (E. Correa-Hernando).

0168-1699/$ - see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.compag.2011.07.004

used in the manufacturing of most wood products (Khater et al., 2004). Since the 1960s, several types of solar kiln for timber 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; Reuss et al., 1997). 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.

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). In such case, 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 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 suitable and reproducible product quality, especially for food, mainly because of the inherent limitations in controlling the drying process.

Recently, Luna et al. in a review on the trends in solar kilns for drying timber uses an analytical method for product design based on TRIZ theory (Luna et al., 2009), 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, stacional rythms or weather variations. The guidelines of this article can help addressing the quality of any dryer design. The definition, implementation and integration of intelligent model based sensors in solar dryers, which is faced in current research work actively enhances the quality of the dryer design.

2. Materials and methods

2.1. Solar dryer

An experimental solar dryer, constructed by CONA SOLAR (Austria) and sited in Cuba (20°1′N, 75°50′W), was used during the experiments carried out in July and October (2009). 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 where samples of pine (*Pinus sp.*) wood were placed, a gate that controls the recirculation of air and a plenum chamber. The air comes into the dryer by one side, being heated in the roof, sucked into the plenum chamber and ducted to the fan which blows it into the drying chamber where the wood is placed on trays. Fig. 1 shows the air path inside the dryer and accross the stocked timber, highlighting the possibility of air recirculation. After passing through the trays, a percentage of the air exits from the underneath, the other fraction is recirculated towards the fan. The position of the hand regulated recirculation gate, was the same for both experiments (50% open).

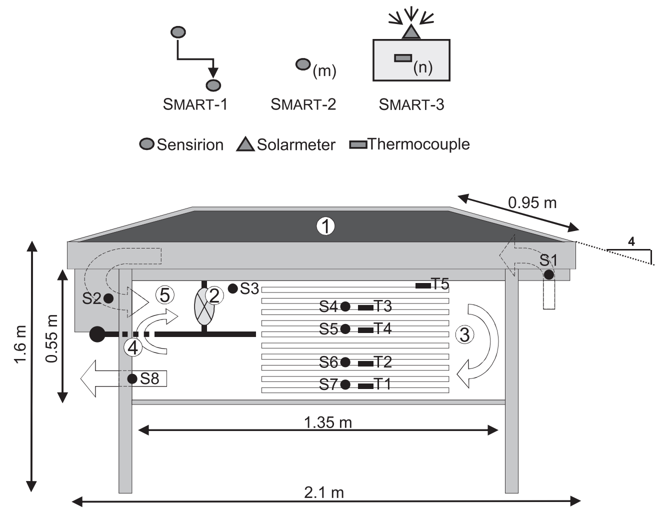

Fig. 1. (Up) Schematic representation of the proposed Smart sensors. Type and (number) of sensors required is presented. (down) Scheme of the solar dryer: solar collector (1), fan (2), chamber for drying (3), gate for recirculation of air (4), and plenum chamber (5). The arrows indicate the airflow. Also, the location of the eight Sensirion S1–S8 (•) and the five thermocouples T1–T5 (■) is indicated.

2.2. Experiments

Two experiments are presented in this paper: one for the dynamic characterization of the air inside the dryer, while the second assesses the energy balance related to solar irradiation and daily timber temperature oscillation.

For the first experiment eight Sensirion sensors (see Fig. 1) were used to characterize the drying air at different positions in the dryer: at solar collector inlet and outlet (S1 and S2), at drying chamber inlet and outlet (S3 and S8) and four locations between the wood planks (from S4 to S7). The sensors were connected by wire to a board with a Peripheral Interface Controller (PIC) as showing Fig. 2. In the PIC the signals were multiplexed and then sent to a computer via RS232. The Sensirion (SHT) is a single chip relative humidity and temperature multi-sensor 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. Each SHT is individually calibrated in a precision humidity chamber. The calibration coefficients are programmed into the OTP (One Time Programmable) memory. These coefficients are used internally during measurements to calibrate the signals from the sensors. For temperatures significantly different from 25 °C, it is necessary to perform humidity compensation; the temperature coefficient of the RH sensor should be considered according to manufactured expressions. The dryer was full filled with wet wood and data were collected at day time (from 8 to 16 h approximately) along 5 days (480 data per sensor). No data collection was carried out during nights because instrumentation was dismantled every day due to the tropical storm risk in this season. The sample weight loss was measured at the end of each drying working day, using a precision electronic balance ADG10 (Adam Equipment Co. Ltd., Heraeus, Madrid, precision ±0.1 g).

For the second experiment carried out in July, one sensirion sensor (S3 in Fig. 1) was available as to characterize the drying air, together with a solarimeter (RD009 G.I.S. Iberica, resolution 1 W/m^2 and precision ±10 W/m^2) for measuring the flux of solar radiation on solar panel and five thermocouples type T