ANALYSIS OF CONVECTIVE DEHYDRATION OF APPLES

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Dehydration is an energy intensive process, a very large portion of the energy used in all industrial processes being used by this process. Between 15 to 20% of the total industrial energy consumption worldwide is used for dehydration, therefore optimization of the design and selection of equipment, process control and rational logistics are important factors for improving this process, thus reducing pollution and increasing the economic throughput. In this we paper analyze a portion of the convective dehydration of apples in order to identify opportunities for process optimization through monitoring and control of essential parameters (temperature, relative humidity and air velocity), as well as providing some automatic control algorithms for the dehydration process.

Keywords: fruits and vegetables, conservation, dehydration.

1. Introduction

Fruits and vegetables are important for their contribution in vitamins, minerals, fiber, enzymes, volatile aromatics, etc. Those elements contribute to the development of metabolic processes in the human body. Eating fruits and vegetables plays an important role in preventing chronic diseases, cardiovascular problems, diabetes type II, dementia, and some cancers. As a result of the role they have in human nutrition, fruits and vegetables must have at least 20-25% contribution in our diet [4]. The large volume of fruits and vegetables needed to meet the consumption needs and because they are highly perishable is an issue of great importance for ensuring the quality of the diet throughout the year. Preservation using high temperatures or exposure to oxygen lead to the loss of a significant portion of nutrients, especially vitamins, some of which are destroyed at temperatures above 40 degrees Celsius [8]. Dehydration is one of the oldest forms of conservation of fruits and vegetables and is used in order to reduce both the water content of the products, consequently reducing the activity of microorganisms and their multiplication, and mass and volume products, reducing in this way the costs of packaging, storage and transport [9]. After dehydration,

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the products must retain as many of their original characteristics (flavor, color, nutritional value, vitamins, etc.) as possible.

Horticultural products contain large amounts of water, in most cases a percentage between 70% and 96%. By dehydration the content of water is reduced to percentages usually between 6% and 25%, depending on their final destination. Table 1 presents data on fruit dehydration process [2], [3], [4], [7]. In case of fruits and vegetables, the dehydration can be done immediately after harvest to reduce their weight and size. Thus, dehydration applied early in the process chain can reduce the weight and volume of products thereby reducing transportation and storage costs. Some dehydration parameters are presented in Table 1 for a some fruits species [2], [3], [5], [10].

Table 1

Fruit dehydration process parameters

Nr.	Fruit	Duration [h]	Temperature [°C]	Final Humidity content [%]	Density [kg/m^2]
1	Apricots	18…24	45…50 / 55…65	15	4…5 (halves)
2	Cherries and sour cherries	6…10	45…55 / 65…72	6…12	6…8 and 8…10
3	Peaches	6…12	55…60	16	5…6
4	Plums	24…30	50…55 / 70…75	22…24	10
5	Grapes	12…20	50…55 / max. 70	13…20	8…10
6	Apples (slices)	6…10	50…60 / 70…72	5…12	6
7	Pears (slices)	5…9	45…50 / 65…70	10…12	13
8	Quince (slices)	6…8	65…70	22	10

2. Material and Method

Dehydrating fruits and vegetables consists in removing water vapors from the surface of the body subjected to dehydration using a heat source and a humidity transport agent (hot air). To get a better rate of dehydration, the products must have an exposed surface as large as possible, this being the case to achieve that the products (apples) in this experiment have been sliced [6].

Dehydration process (Fig. 2) is usually divided into several main phases. Depending on the product subject to this process the number of phases may vary but the main stages are: heating, drying and cooling.

Heating (AB) was done in a saturated atmosphere to heat the products in a controlled manner. The heating gradient was set to 20 ºC/h. *Drying itself* (BE) was realized by rising the temperature from 50 to 68ºC in a 12 hour interval, at the same time venting out the moisture. For moisture exhaust, the flaps C1 and C2 were commanded in phase, while C3 was in antiphase to reduce air recirculation. The dehydration was stopped after 12 hours because we gathered all the necessary data for our analysis, dehydrating further being unnecessary for our purpose. *Cooling* (EF) was done for 1 hour by venting in fresh air with 0% recirculation.

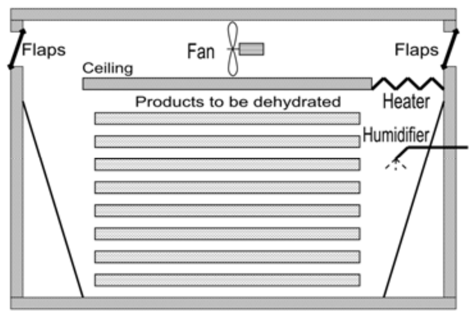

Fig. 1. Chamber for convection dehydration - schematic drawing

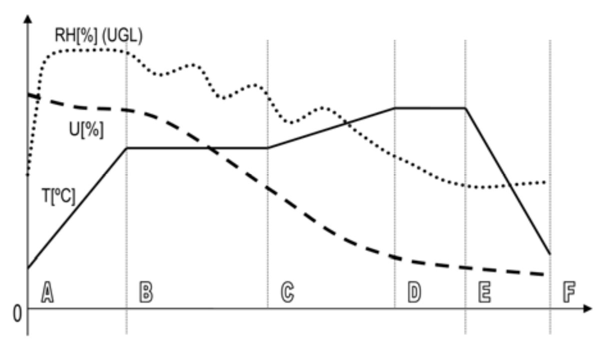

Fig. 2. Dehydration stages

In order to study the convective drying process of apples, we used a dehydration plant equipped with an automation system and a system for recording air parameters and mass of the products placed on one of its trays (Fig. 3). The dehydrator consists in an enclosure made out of polystyrene insulated panels and stainless steel sheet walls, 24 perforated stainless steel trays of 0.62 by 0.62m and a total drying area of 9.2 m^2. As main actuators, the installation consists in: a 0.75 kW (3 phase) / 1450 rpm fan (*V*) for hot air recirculation through the enclosure powered trough a frequency inverter, a water-air heat exchanger for air heating with a 3 way control valve (*V3C*), this being supplied with hot water with a temperature of 70-90 °C provided by a burner (*CT*) that runs on wood chips or sawdust, that has a maximum power of 75 kW, three flaps: one for venting out the moisture (*C2*), one for fresh air intake (*C1*) and one flap for air recirculation obstruction (*C3*). The installation's schematic is shown in the Figure 4. The system is powered from a 3x400V power line, the total power requirements being

1kW. All the actuators are controlled by the automation system (*SA*). The automation system reads the temperature and relative humidity from the *S0* sensor positioned in the middle of the dehydrator between the product's trays. The monitoring system has four temperature and relative humidity combined sensors (*S1 – S4*) and four separated air speed sensors (placed in the same places as the others). The system also has a weight (*m*) sensor placed under one of the middle trays to read the product's weight. The sensors feed information (4-20mA) to two ADC to Ethernet TCP/IP converters (*ADC/NET*), connected to an Ethernet network switch. The monitoring software that runs on the computer collects data from the *ADC/NET* converters that reads the analog values of the sensors and stores it in an Access 2003 database.

Fig. 3. Dehydrator (left) equipped with an automation and monitoring system (right) and the sensors used (center)

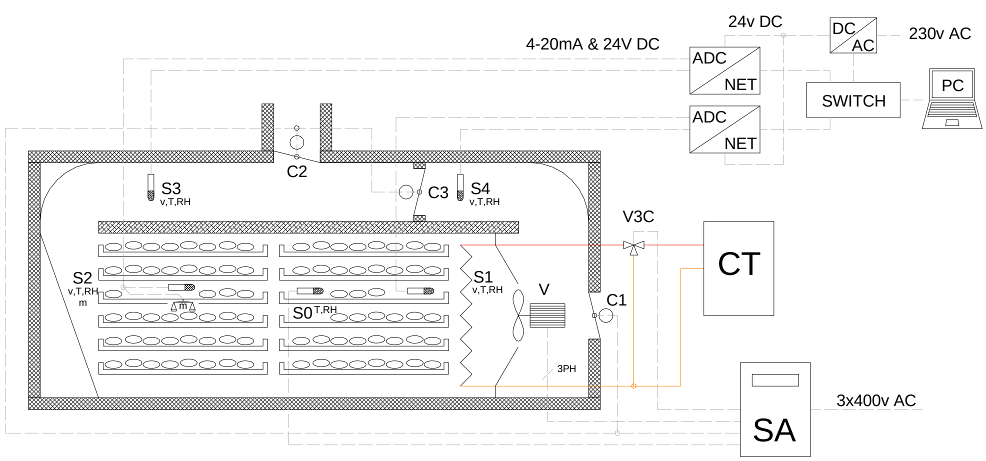

Fig. 4. Dehydration plant layout

The sensors are placed as follows (Figure 4): *S1* is placed immediately after the heat exchanger, before the first tray of products, *S2* is placed between the product's trays at three quarters of the length of the trays, *S3* is places after the products, in the air recirculation tunnel, before the air exhaust flap, *S4* is placed after the air exhaust flap and before the fresh air intake flap and m is placed under the tray where the *S2* probe is placed. The values are recorded in the database at a configurable interval, in this case being set at 10 seconds. The Access 2003 database can be exported in various formats used for further processing. The experiment consisted in the dehydration of 15 kg of apples. The apples were washed, sliced in 6-8mm thick pieces and placed evenly on the trays.

3. Results

The weight of the fresh products at the beginning of the process was 15kg. For apples that have 85% water content, the total weight of water m_{wi} in the products subjected to dehydration is:

$$m_{wi} = \frac{m_f \cdot w_{fresh}}{100} = \frac{15kg \cdot 85\%}{100} = 12.75kg \quad (1)$$

where m_f is the fresh fruit total weight and w_{fresh} is the water content.

The weight of the dry substance m_d in the products is:

$$m_d = m_i - m_{wi} = 15kg - 12.75kg = 2.25kg \quad (2)$$

Fig. 5. Products before (left), during (center) and after (right) dehydration

At the end of the dehydration process, the weight of the products was 4kg. The water content of dryed fruits is:

$$w_{dry} = \frac{mw_{dry} \cdot 100}{m_f} = \frac{1.75kg \cdot 100}{4} = 43.7\% \quad (3)$$

Air parameters variation during the dehydration process of apples for a period of 810 seconds is shown in Figure 7. We analyzed various parameters over several successive periods of air exhaust, a period being the time elapsed between the closing of the flaps, e.g. sample 1 and the next time the flaps are closing, sample 12 in this case. The trial was set for total recirculation and air inside exhausted upon reaching a relative humidity threshold high enough to provide meaningful data for the analysis. Samples were extracted during the slow dehydration period because it has the longest time of all phases and improving its effectiveness, the efficiency of the entire process will be influenced.

The whole dehydration process lasted for 5h and 30m. In Figure 5 are pictures with the products before, during and after dehydration. In Figure 6 is presented the dehydration chart for sensor S2 and the weight of the products (for the tray under that the sensor was placed).

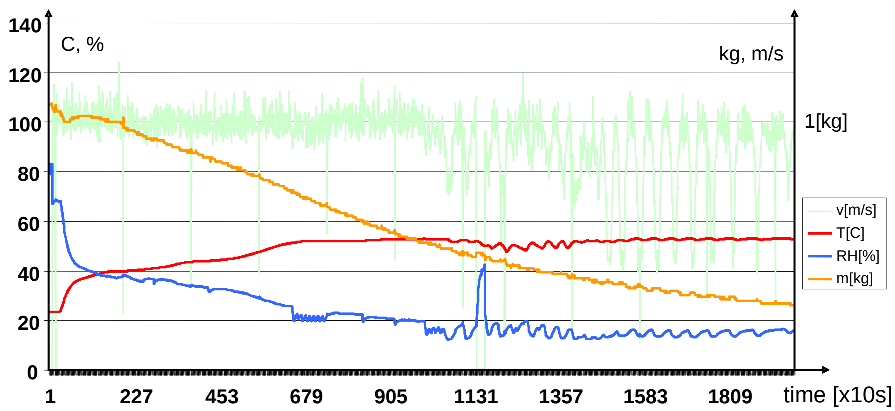

Fig. 6. Dehydration chart

To ensure that the results will not be affected due to the measuring errors of the sensors, the data from the beginning of the process, before the heating phase, was processed in order to determine the measuring error. To calculate the measuring error we looked at the measuring difference between the values of sensor S1 and sensor S3, because these sensors in this phase had to indicate the same value. Because the measuring error of the temperature was very small and because usually the temperature probes can be very well calibrated, we attributed the error to the relative humidity sensor. In this experiment we only care about the water vapor content in the air, and its error was calculated as being equal to: $\dot{\varepsilon}_{dx_{3-1}} = 1.38 g / kg$. This value is the average of the difference between the value indicated by the S1 sensor and the value indicated by the S3 sensor. This calibration can also be done by starting the process without any products inside the dehydrator; both sensors must indicate the same values, the difference between them representing the error.

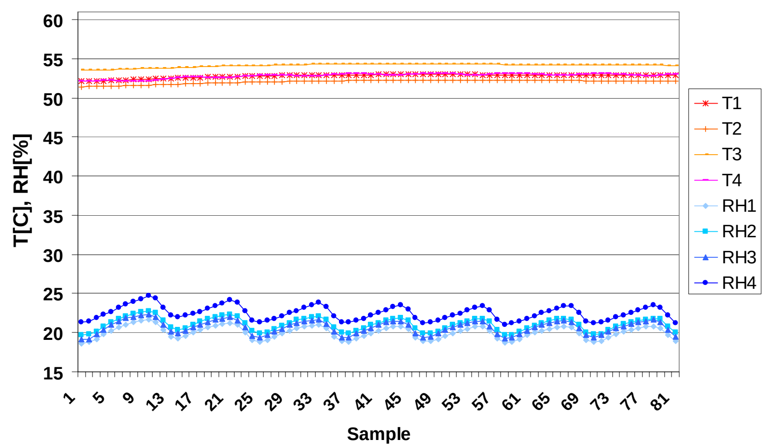

Fig. 7. Air's parameter values in an interval of 810 seconds during the dehydration process studied (10 second samples)

To analyze the process, the closing moments (samples 1 and 16) and opening moments (samples 12 and 23) of the flaps were chosen. After closing the flaps, the relative humidity increases between samples 1 and 12, and falls between samples 12-16 after the flaps closed. The process is repeated in the subsequent intervals. For a quantitative analysis of the process we analyzed the amount of moisture in the air, because relative humidity can not provide relevant information. Thus, the amounts of moisture values were calculated and the graph is presented in Figure 8. To get the moisture content we used the following formula:

$$x_n = 0.622 \cdot \frac{\varphi_n \cdot p_{As}}{p_B - \varphi_n \cdot p_{As}}, \text{ [kg/kg]} \tag{4}$$

where: x_n is the water vapor content [kg/kg]; φ – is the relative humidity [RH % / 100]; p_{As} - Water vapor saturation pressure at the temperature at which the calculation is made [bar]; p_B – Atmospheric pressure [bar].

With these values we can analyze various parameters such as the amount of moisture vaporized from the surface of the products, the amount of moisture discharged from the system and the rate of vaporization.

The amount of moisture vaporized from the product's surface reported per kg of air is represented by the difference between the amount of moisture measured by the sensor S1 placed before the products and its value measured by the sensor S3 placed after the products. The variation of this parameter is shown in Figure 9.

$$dx_{3-1t}(n) = x_3(n) - x_1(n)\,, \tag{5}$$

where n is the sample number.

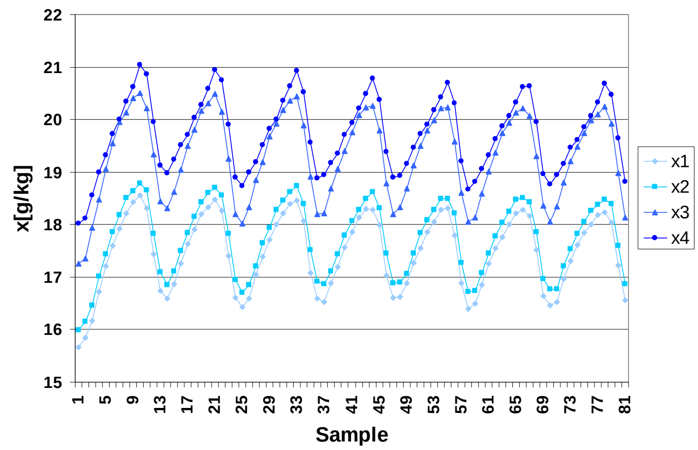

Fig. 8. The values of the amount of moisture in the air

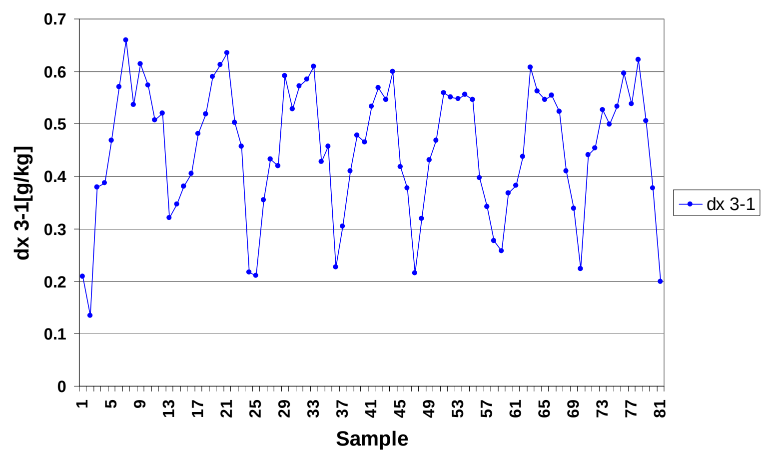

Fig. 9. The amount of moisture vaporized from the surface of the products dx_{3-1} [g/kg]

Since sensor calibration showed a measuring error, the corrected real value becomes:

$$dx_{3-1r}(n) = x_3(n) - x_1(n) - \dot{\varepsilon}_{dx_{3-1}}\,, \tag{6}$$

where n is the sample number, and the real value corrected with the measuring error is:

$$dx_{3'-1r}(n) = x_3(n-1) - x_1(n) - \dot{\varepsilon}_{dx_{3-1}} \quad (7)$$

If a process that takes place in optimal conditions, the integrals of these curves will be equal to the amount of moisture vaporized or amount of moisture discharged from the system. Figure 10 shows the trend of this parameter.

$$m_{vap} = \int dx_{3-1}\delta t \text{ and } m_{ev} = \int dx_{3'-1}\delta t \quad (8)$$

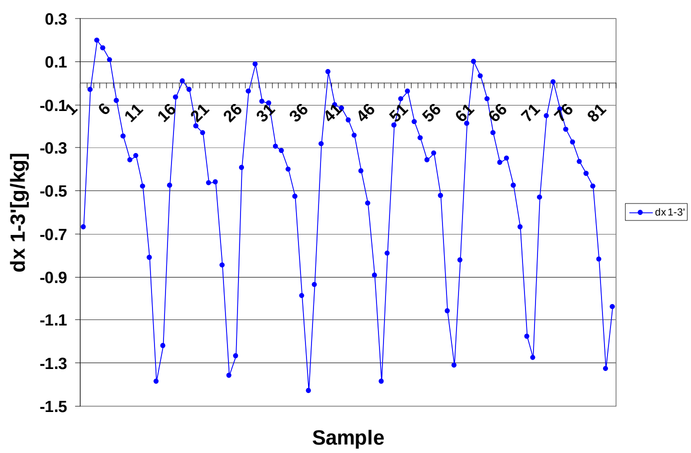

Fig. 10. The amount of moisture discharged from the system $dx_{1-3'}$ [g/kg]

Because we have discrete values we summarize these values and we get the amount of moisture vaporized per unit of mass of fluid that is circulated:

$$m_{vap} = \sum_{1}^{40} dx_{3-1}(n) = 36.851 \text{ g/kg} \quad (9)$$

and the amount of moisture discharged from the system compared to the same unit mass is:

$$m_{ev} = \sum_{1}^{40} dx_{3'-1}(n) = 36.433 \text{ g/kg} \quad (10)$$

One can see that this two values are very close, indicating that not all of the moisture has been evacuated from the system.

The difference between the two values is the amount of moisture exhausted out of the enclosure:

$$\Delta x = m_{vap} - m_{ev} = 0.418 \text{ g/kg} \quad (11)$$

To quantify the real value of the amount of moisture in the air the values must be reported for the mass of the air being circulated. Because in the experiment we used sensors to measure air velocity, we can calculate the mass flow rate of air circulated so the mean air velocity in the examined time being:

$$\bar{v}_3 = \frac{\sum_{1}^{40} v_3(n)}{81} = 4.94 \text{ m/s} \tag{12}$$

for the sensor S3, in a flow section of $0.69\,m \times 0.4\,m$, meaning a flow surface S of $0.276\,m^2$. This being said, the air mass flow is:

$$\dot{m}_3 = \rho_{aer} \cdot \bar{v}_3 \cdot S = 1.085\frac{kg}{m^3} \cdot 4.94\frac{m}{s} \cdot 0.276m^2 = 1.478 \text{ kg/s} \tag{13}$$

where ρ_{aer} is the air density at an average temperature of 54 ºC. The same mass air flow is at sensor S1 and also on the product's surface, but with a lower velocity because the flow section is larger. The average flow velocity in this area is:

$$\bar{v}_1 = \frac{\sum_{1}^{40} v_1(n)}{40} = 0.976 \text{ m/s} \tag{14}$$

If we multiply the value of $dx_{3-1}(n)$ with the air flow mass $\dot{m}_3$, we will get the speed of moisture vaporization from the product's surface in respect to the unit of time $\dot{m}_{3-1}$:

$$\dot{m}_{3-1} = dx_{3-1} \cdot \dot{m}_3 \text{, [g/s]} \tag{15}$$

where $\Delta t = 10s$ is the time interval between two consecutive samples.

In the period considered, the mass of vaporized moisture from the surface of products is:

$$m_{total} = \sum_{1}^{40} (\dot{m}_{3-1}) \cdot \Delta t = 544.6 \text{ g} \tag{16}$$

For the period considered, the average surface speed of vaporization is:

$$\overline{\dot{m}}_{1-40} = \frac{\dot{m}_{total}}{t_{total}} = \frac{544.6g}{810s} = 0.672 \text{ g/s} \tag{17}$$

To plot the moisture content versus time, the Henderson-Pabis model [*1*] can be used:

$$m_c = \frac{m_a}{m_s} = a \cdot e^{-k \cdot t}, \text{ [kg/kg]} \tag{18}$$

where: m_a is the moisture content; m_s = is the mass of the solid content; $a = 5.2606$ and $k = 0.000783$ are calculated coefficients.

So, for the studied process, the equation is:

$$m_c = 5.2606 \cdot e^{-0.000783 \cdot t}, \; R^2 = 0.994 \tag{19}$$

where *t* is the time, measured in tens of seconds.

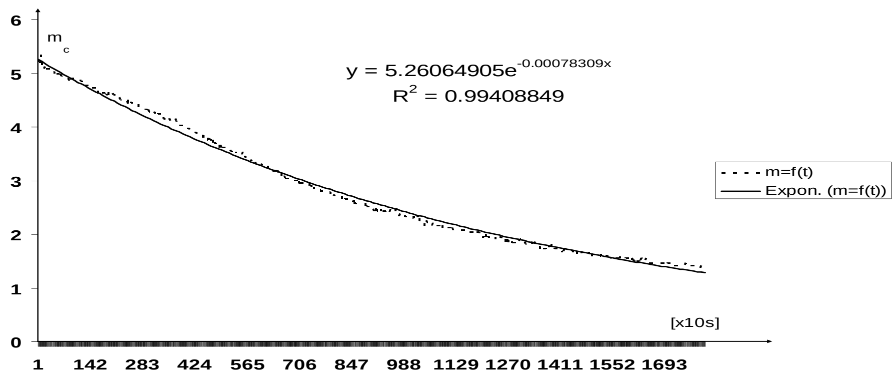

Fig. 11. The amount of moisture depending on time

For an accurate calculation of coefficients the time period between the beginning and the end of the dehydration was examined, ignoring irrelevant information during heating.

4. Conclusions

For effective control of dehydration equipment we need at least two sets of sensors placed before and after the products subjected to the process. Through this site we obtain vital information for increasing the process efficiency.

Using the calculated values we can get some important information regarding the development of the process even during dehydration, such as: the time until the end of the process, energy consumption, internal and external temperature of the products etc. The process time is a useful parameter that can be estimated after a certain process time has passed, because some data on the dehydration speed is needed in order to establish the mathematical model to be used, such as Newton, Page, logarithm, etc. The temperature of the inner and outer surfaces of the products can be calculated using the wet bulb temperature, since we know that the products have this surface temperature, so their inside must be at a lower or equal temperature of the wet bulb.

Due to the large measurement error of the sensors for this analysis, a calibration is required before starting the process. This eliminates the need for absolute calibration of each sensor which leads to savings in time and money. It is well known that a relative humidity sensor regardless of the method of transforming the physical size to electrical quantities can provide at best modest measurement accuracy. Because of the environment in which they are used, these sensors would require a calibration pretty often. By implementing a relative calibration we can increase the calibration interval. Also this will provide accurate absolute values and more relevant information than obtained by a precision close to that provided by the manufacturer. After the relative calibration of the sensors, an offset value can be assigned to one of the RH sensors so it's value can be used in calculations and process control.

The Henderson-Pabis model, offers a good precision for the plum's dehydration process analysis with a square root error of: $R^2 = 0.9985$.

REFERENCES

[1]. *Ali Mohammadi*, *Shahin Rafiee*, *Alireza Keyhani* and *Zahra Emam*, Moisture Content Modeling of Sliced Kiwifruit (cv. Hayward) During Drying, 2009; Pakistan Journal of Nutrition 8 (1): 78-82, 2009; ISSN 1680-5194

[2]. *R. Boyer*, *K. Huff*, Using Dehydration to Preserve Fruits, Vegetables, and Meats, Virginia Tech publication, 2008, pp. 348-597;

[3]. *J.E. Brekke*, *L. Allen*, Banana Dehydration, Technical Progress Report No.153 1966;

[4]. *A. Gherghi*, Tehnologia valorificării produselor horticole. Păstrarea produselor horticole în stare proaspătă (Technology for the capitalization of horticultural products. Keeping fresh the horticultural products), vol. I-II, U.I. "Titu Maiorescu" F.I.H.A., Bucharest, 1994;

[5]. *V.R.R. Jalali*, *N. Narain*, *G.F. Da Silva*, Ciência e Tecnologia de Alimentos ISSN 0101-2061, 2008;

[6]. *Mohammad Sirousazar*, *Akbar Mohammadi-Doust* and *Bahram Fathi Achachlouei*, Mathematical Investigation of the Effects of Slicing on the Osmotic Dehydration of Sphere and Cylinder Shaped Fruits; Czech J. Food Sci., Vol. 27, 2009, No. 2: 95–101

[7]. *Nikolay Valov*, *Irena Valova*, International Conference on e-Learning'14 - System for monitoring and control of the drying process; 2014

[8]. *P.C. Njoku*, *A.A. Ayuk*, *C.V. Okoye*, Temperature Effects on Vitamin C Content in Citrus Fruits, Pakistan Journal of Nutrition 10 (12): 1168-1169, ISSN 1680-5194, 2011; pag. 1168

[9]. *** Dehydrated Fruits and Vegetables, Food And Agricultural Industry For U. S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Emission Factor and Inventory Group, 1995;

[10]. *** Quality Changes In Food Materials As Influenced By Drying Processes. Modern Drying Technology Volume 3: 2011 Wiley-VCH Verlag GmbH & Co. KGaA.