ANALYSIS OF A CONVECTIVE DRYING PROCESS OF PLUMS

Phd. Stud. Eng. Marius INGEAUA, Prof. Phd. Eng. Tudor PRISECARU

UNIVERSITY POLITEHNICA OF BUCHAREST

Abstract: Fruits and vegetables play an important role in human nutrition providing vitamins, minerals, fibers and essential nutrients. In order to prolong the marketing of these products and ensure nutrients throughout the year, preservation by different methods of fruit and vegetables is necessary. 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 product and thus the activity of microorganisms and their multiplication, and the mass and volume of products, the costs of packaging, storage and transport. This paper aims analyze a convective drying process of plums, in order to identify opportunities for process optimization through monitoring and controlling essential parameters like: temperature, relative humidity and air velocity, as well as automatic control algorithms of the dehydration process.
Keywords: fruits and vegetables, conservation, dehydration, plums.

1. INTRODUCTION

Fruits and vegetables play an important role in human nutrition. Besides vitamins and minerals fruits and vegetables are good sources of fibber and essential nutrients that have a number of beneficial effects on health such as antioxidants, anti-inflammatory, decreasing fats and have beneficial effects on blood pressure and endocrine functions (Boyer R., Huff K., 2008). To provide these elements thought the entire year, it is necessary to preserve of fruit and vegetables by different methods. Preservation using high temperatures or exposure to oxygen leads to the loss of a significant portion of nutrients, especially vitamins, some of which are destroyed at temperatures above 40 degrees Celsius (Njoku P.C. et al. 2011). Dehydration is one of the oldest forms of conservation of fruits and vegetables. The dehydration process reduces both water content of products in order to preserve them, as well as mass and volume reducing the cost of packaging, storage and transport. It also reduces the activity of micro organisms and prevents their growth, which leads to the preservation of fresh edible products for a long time. After dehydration products must retain as many of their baseline characteristics such as flavour, colour, nutritional value, vitamins etc.

2. MATERIAL AND METHOD

The most common method of dehydration of fruits and vegetables is convective dehydration (Fig. 1), which uses a heat source and an agent for removing water vapour from the surface of the body subject to dehydration. To achieve a higher drying speed, the fruits must be sliced or in this case cut in halves. (Mohammad SIROUSAZAR, 2009)

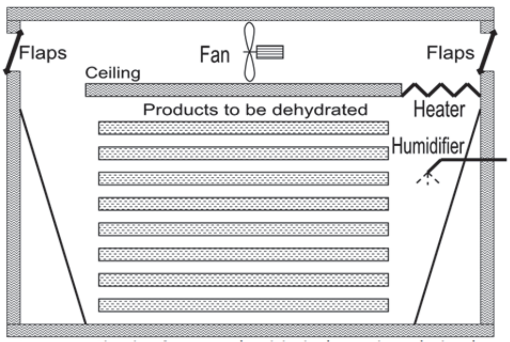

Fig. 1. Chamber for convection dehydration - schematic drawing.

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.

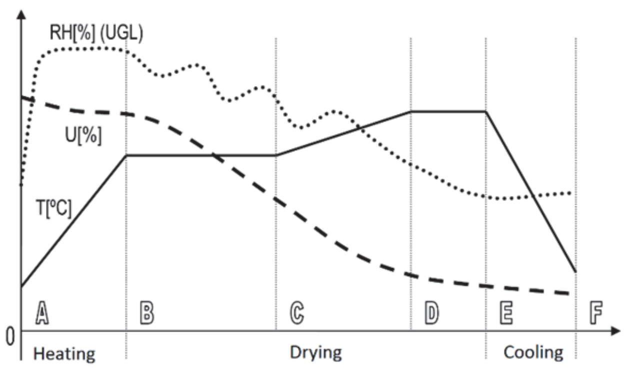

Fig. 2. Dehydration stages.

Heating (AB) is usually done in a saturated atmosphere to heat the products in a controlled manner. In a saturated atmosphere, the heat input is transferred to the products because the evaporation is stopped. The heating gradient is specific to each product and may vary between 1-10 ºC / min for fruits. From the moisture chart we can see that drying curve falls very little in this phase, only as necessary to carry out air saturation. In most cases, heating is done in an atmosphere in which the partial pressure of the vapour on the surface of the products and the pressure of the air are equal (RH < 100%).

Drying (BE) can be divided into several phases depending on the product. For fruits and vegetables this phase is of the order of hours (2-18 hours) and sometimes it is necessary to overheat for some time products to modify some physicochemical properties.

Cooling (EF) is usually achieved controlled to avoid temperature gradients. In the case of fruits and vegetables this may be waived, according to the process following the cooling in the technological chain.

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. In Table 1 presents data on fruit dehydration process (Boyer R., Huff K., 2008), (Brekke J.E., Allen L. 1966), (Jalali V.R.R et al., 2008).

In case of fruits and vegetables, the dehydration can be done immediately after harvest to reduce their weight and size. Thus by applying dehydration early in the process chain can reduce the weight and volume of products thereby reducing transportation and storage costs.

Before dehydrating, fruits and vegetables are prepared by blanching or steaming to increase cell membrane permeability. Products prepared this way can be dehydrated more easily than uncooked products. Products may be sulphured or dipped in lemon juice to prevent colour change during dehydration.

Depending on the subsequent use of products and their characteristics, fruits and vegetables can be dehydrated to a water content percentage that will not harm their characteristics. To keep the vegetables in optimal conditions, dehydration should be stopped at percentages ranging between 6 and 10%. In the case of fruit this percentage may be higher than in vegetables and can be between 12 and 25%.

Dehydration process leads to some changes in the products:

- decrease the volume;
- migration of soluble constituents;
- thermal browning;
- warp;
- reversibility of tissue;
- loss of volatile substances;

In order to study the convective drying process of plums, 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).

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
9	Bananas (slices)	6…8	70	5-15	4…6
10	Strawberries (slices)	5…8	50…60	9-12	7…8

Fig. 3. Dehydration plant equipped with automation and monitoring system.

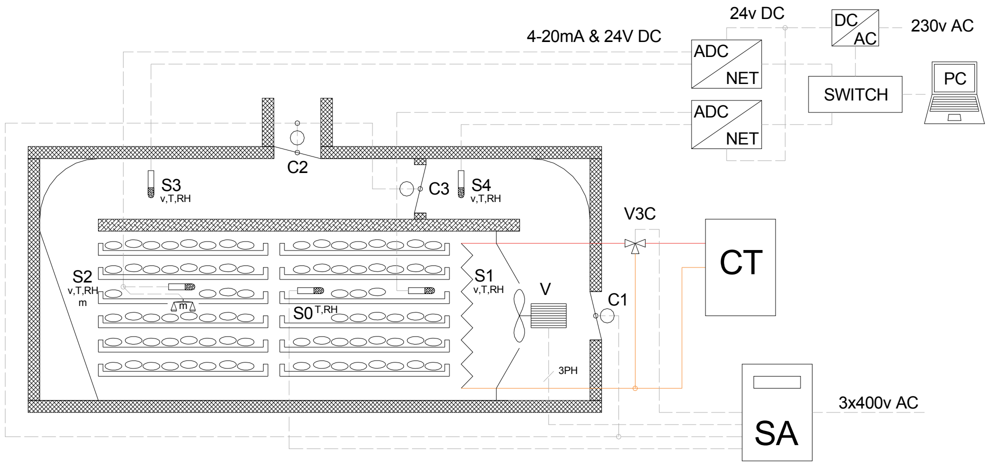

Fig. 4. Dehydration plant layout.

The plant has an enclosure made of polystyrene insulated panels and walls of stainless steel sheet, 24 perforated trays with dimensions of 0.62 × 0.62 m and a total drying area of 9.2 m².

As actuators, the installation presents: a fan of 0.75 kW / 1450 rpm for circulating hot air through the enclosure; a hot water heater for heating the air with the water inlet temperature of 70-90 °C provided by a boiler that runs on wood chips or sawdust, with a maximum power of 75 kW; two flaps for venting out moisture and a flap for air recirculation obstruction. The dehydration plant's layout is shown in the following figure:

The significance of the elements in Figure 4 is as follows: S0 - T + RH probe for the automation system; S1 – v + T + RH probe placed immediately after the radiator; S2 – v + T + RH probe located between product trays; m – the load cell located under the middle tray; S3 – v + T + RH probe located prior to air discharge; S4 – v + T + RH probe placed after air discharge; C1 – fresh air intake flap; C2 – moist air exhaust flap; C3 – recirculation obstruction flap.

Measuring accuracy in the working ranges are as follows: for temperature the accuracy is ± 0.4 °C, for relative humidity the accuracy is ± 2.5% RH, for specific humidity the accuracy is ± 2 g/kg, and for air velocity the accuracy is ± (0.10 m/s + 1% of reading). The values are written in the database at a configurable interval, in this case being set at 10 seconds. The program generates an Access 2003 database, and the data can be exported in various formats used for further processing. The experiment consisted in 60 kg of plum dehydration. Plums were washed, sectioned in half and pits removed. Following these operations the remaining mass was 50 kg of products.

3. RESULTS

Pitted fruit's initial mass was 50 kg and the final mass after completion of the drying process was 15.2 kg, resulting for a product with 85% water content such as plums, i.e. 42.5 kg of water in fruits submitted dehydration, remained 7.7 kg water after dehydration, i.e. 18.1% moisture in the product dehydrated. The drying lasted about 12 hours. Products and dehydration chart are shown in Figures 5 and 6.

Air parameters variation during the drying process of plums for a period of 400 seconds is shown in Figure 7. We analyzed various parameters over several successive periods inside the 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 14 in this case.

Fig. 5. Aspect products before, during and after dehydration.

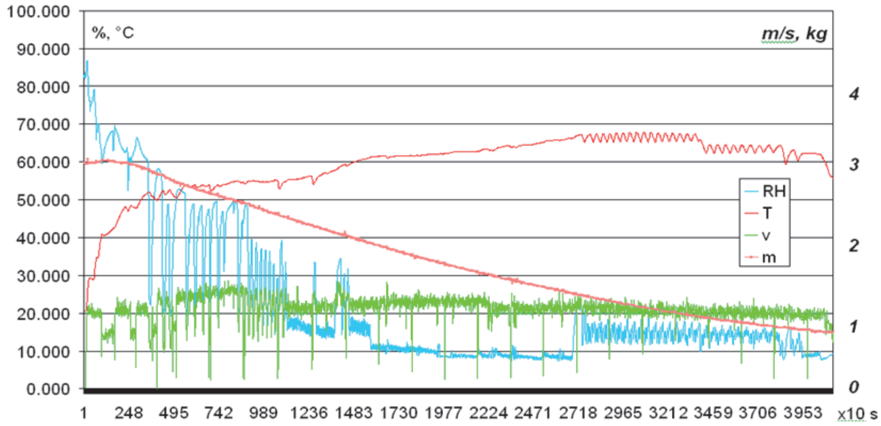

Fig. 6. Plum drying chart.

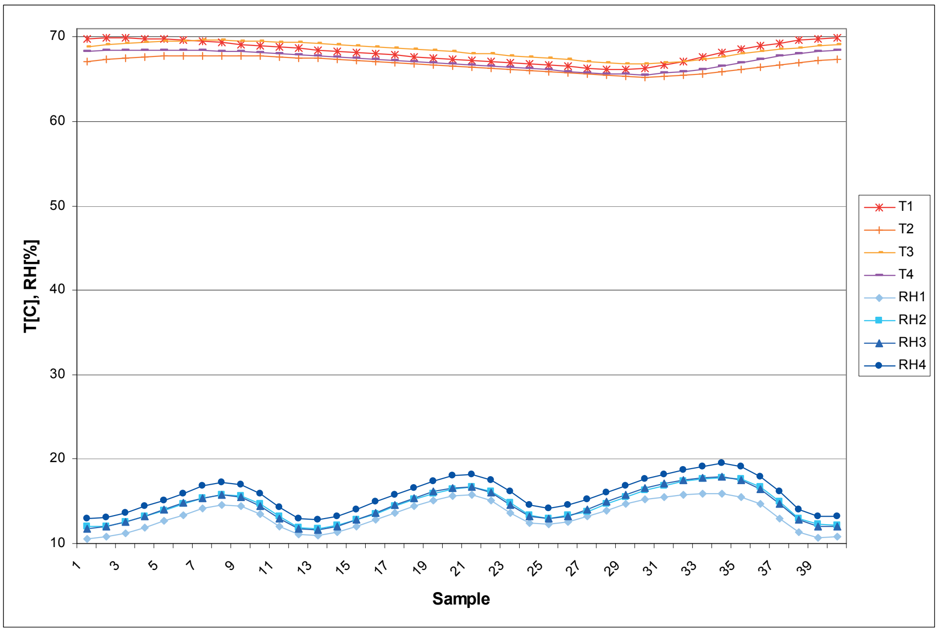

Fig. 7. Air's parameter values in an interval of 400 seconds during the drying process studied (10 second samples).

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. To analyze the process the flaps closing moments were chosen (samples 1 and 14) and flaps opening moments (samples 9 and 22). After closing the flaps, inside relative humidity increases between samples 1 and 9, and falls between samples 10-13 after flaps closing. 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 plotted in Figure 8.

$$x_n = 0.622 \cdot \frac{\varphi_n \cdot p_{As}}{p_B - \varphi_n \cdot p_{As}}, \text{ [kg/kg]} \qquad (1)$$

where: x_n is the water vapour content [kg/kg]; φ – is the relative humidity [RH % / 100]; p_{As} – Water vapour 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.

$$dx_{3-1_t}(n) = x_3(n) - x_1(n) \tag{2}$$

where n is the sample number.

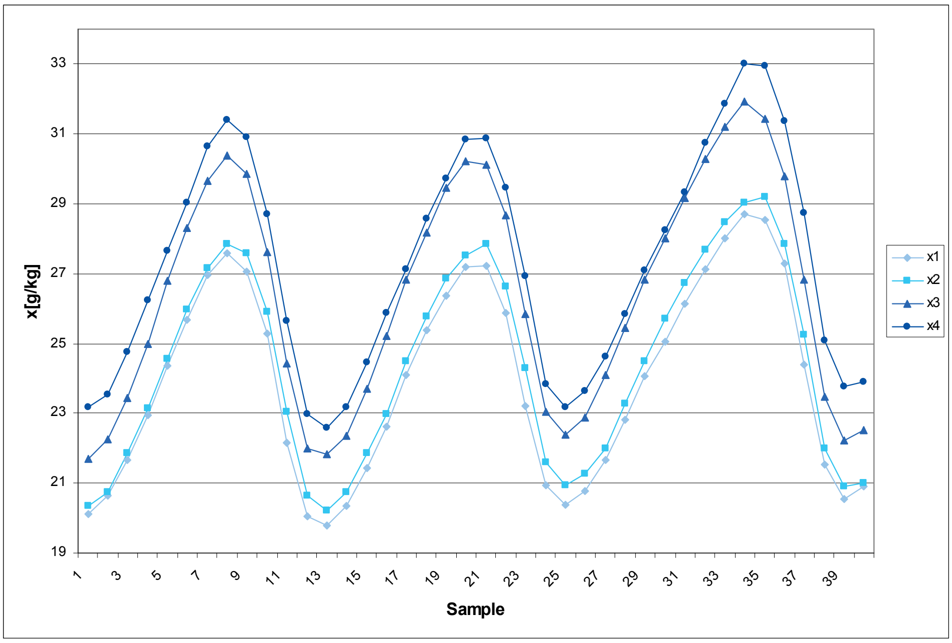

Fig. 8. The values of the amount of moisture in the air.

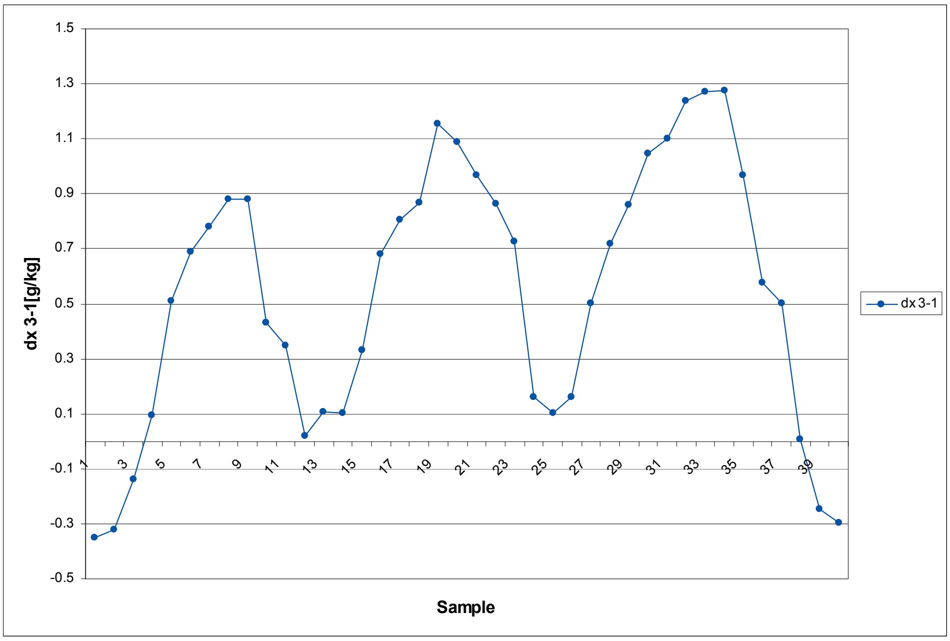

Fig. 9. The amount of moisture vaporized from the surface of the products dx_{3-1} [g/kg].

Since sensor calibration showed a measuring error for dx_{3-1}, the corrected real value becomes:

$$dx_{3-1_r}(n) = x_3(n) - x_1(n) - \dot{\varepsilon}_{dx_{3-1}}$$
$$\dot{\varepsilon}_{dx_{3-1}} = 1.923 \text{ g/kg} \tag{3}$$

By integrating the curve we can calculate the total amount of vaporized moisture that can provide important data on process speed, remaining time, etc.

For the analyzed system, the difference between the previous values indicated by the S3 sensor and the current values of the S1 sensor will indicate the amount of moisture discharged from the system.

$$dx_{3'-1_t}(n) = x_3(n-1) - x_1(n) \tag{4}$$

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

$$dx_{3'-1r}(n) = x_3(n-1) - x_1(n) - \dot{\varepsilon}_{dx_{3-1}} \qquad (5)$$

Figure 10 shows the trend of this parameter.

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.

$$m_{vap} = \int dx_{3-1}\delta t \;; m_{ev} = \int dx_{3'-1}\delta t \qquad (6)$$

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

$$m_{vap} = \sum_1^{40} dx_{3-1}(n) = 21.463 \text{ g/kg} \qquad (7)$$

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

$$m_{ev} = \sum_1^{40} dx_{3'-1}(n) = 21.398 \text{ g/kg} \qquad (8)$$

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

$$\Delta x = m_{vap} - m_{ev} = 0.0648 \text{ g/kg} \qquad (9)$$

Note that the two values are very close indicating that not all of the moisture has been evacuated from the system.

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:

$$\overline{v}_3 = \frac{\sum_1^{40} v_3(n)}{40} = 4.93 \text{ m/s} \qquad (10)$$

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:

$$\dot{m}_3 = \rho_{aer} \cdot \overline{v}_3 \cdot S = \\ = 1.03\frac{\text{kg}}{\text{m}^3} \cdot 4.93\frac{\text{m}}{\text{s}} \cdot 0.276 \text{ m}^2 = 1.401 \text{ kg/s} \qquad (11)$$

where ρ_{aer} is the air density at an average temperature of 68 ºC. The same mass air flow is at sensor S1 and also on the product's surface, but the velocity is less because the flow section is larger. The average flow velocity in this area is:

$$\overline{v}_1 = \frac{\sum_1^{40} v_1(n)}{40} = 1.0549 \text{ m/s} \qquad (12)$$

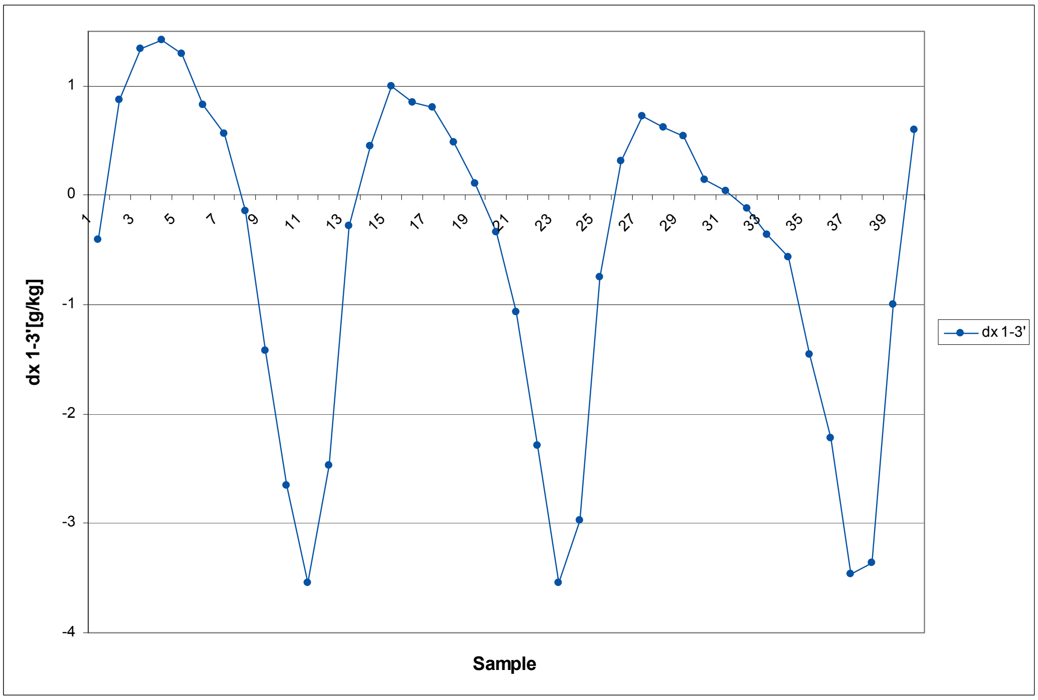

Fig. 10. The amount of moisture discharged from the system dx_{3-1} [g/kg].

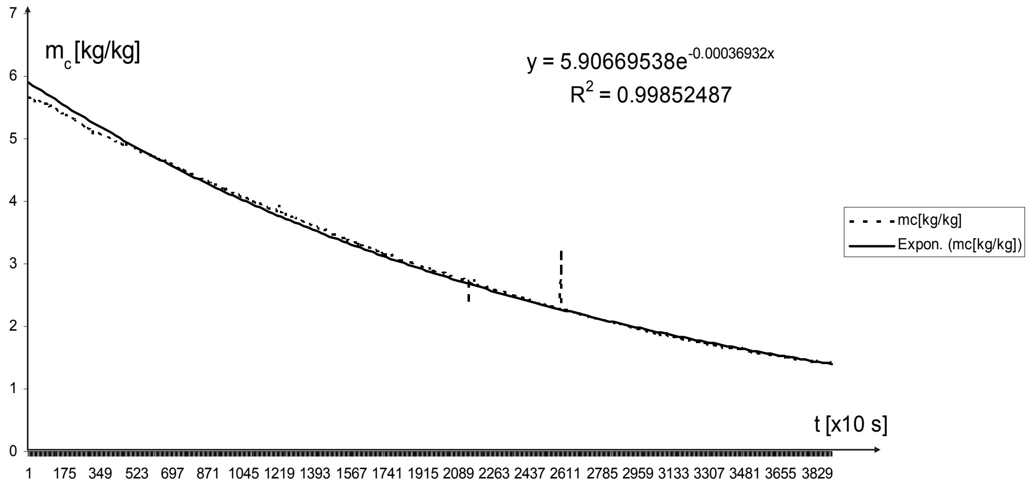

Fig. 11. The amount of moisture depending on time.

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 $\dot{m}_{3-1}$: 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 $\dot{m}_{3-1}$:

$$\dot{m}_{3-1} = dx_{3-1} \cdot \dot{m}_3 \text{, [g/s]} \tag{13}$$

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

$$m_{total} = \sum_{1}^{40} (\dot{m}_{3-1}) \cdot \Delta t = 300.7 \text{ g} \tag{14}$$

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

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

$$\overline{\dot{m}}_{1-40} = \frac{\dot{m}_{total}}{t_{total}} = \frac{300.7g}{400s} = 0.752 \text{ g/s} \tag{15}$$

To plot the moisture content versus time, the Henderson-Pabis model can be used (Ali Mohammadi et al., 2009):

$$m_c = \frac{m_a}{m_s} = a \cdot e^{-k \cdot t} \text{, [kg/kg]} \tag{16}$$

where: m_a is the moisture content; m_s = is the mass of the solid content; $a = 5.906$ and $k = 0.000369$ are calculated coefficients.

So, for the studied process, the equation is:

$$m_c = 5.906 \cdot e^{-0.000369 \cdot t} \text{, } R^2 = 0.9985 \tag{17}$$

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

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 equipments 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 the passing of a certain time from the process because we need some data on the speed of dehydration to use a mathematical model 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 the environment in which they are used, these sensors would require a calibration pretty quick, but by implementing a relative calibration we can increase this interval as accurate absolute values we would provide more relevant information than obtained by a precision close to that provided by the manufacturer. After the relative calibration of the sensors can we choose to assign an offset value to one of the RH sensors so its 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: $R^2 = 0.9985$.

The data obtained from experimentation will allow optimisation of automatic control algorithms and the entire dehydration process in order to improve its overall efficiency. (Nikolay Valov, Irena Valova, 2009)

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