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THEORETICAL RESEARCH ON THE THERMAL CALCULATION OF THE CONVECTIVE DRYING INSTALLATIONS FOR VEGETABLES AND FRUITS

Gheorghe BRĂTUCU[1] Andreea MARIN[1]
Marian M. BONDOC[1]

Abstract: *The paper presents an algorithm for the thermal calculation of a convective-drying installation for vegetables and fruits. Starting from the functional scheme of the drying installation, at first, the chosen or imposed input or output data are specified, thereupon the mathematical modelling of the moisture balance, of the theoretical thermal balance for the drying chamber, and of the specific heat consumption is made. Next, the calculation mode of the real thermal balance, of the incoming and outgoing energies of the system is specified; and the equation of the general thermal balance of the convective drying process of vegetables and fruits in the aforementioned installation is established. At the end, an efficiency calculation of the energy use in the drying installation is made.*
These instructions are formulated for presenting the template used for editing the articles for the scientific journal Bulletin of the Transilvania University of Braşov. The material presents the camera ready form of the articles. The abstract should synthetically outline all the pertinent results, in a short but intelligible form. The abstract should begin through clearly stating the purpose of the paper and should end by formulating the most important conclusions. There will be used short, direct and complete sentences, written in a single paragraph, without "tab"-s. The abstract will have 7...10 lines.

Key words: *vegetables and fruits, convective drying installations, thermal calculation.*

1. Introduction

Convective drying is the most widespread procedure of moisture removal from vegetables and fruits, both due to its simplicity, and especially to the multiple possibilities of obtaining, at low costs, a good quality, in a short amount of time [2].

Wet vegetables or fruits come into contact with the drying agent (hot air or combustion gases), from which they receive, by convection, between 80...90% of the total amount of heat required for the drying process. The parameters of the drying agent (speed, temperature, relative humidity etc.), as well as the connection

[1] Department for Engineering and Management in Food and Tourisme, *Transilvania* University of Brașov, Castelului Street no. 148, Brașov 500014, Romania;
Correspondence: Gh. Brătucu; e-mail: gh.bratucu@unitbv.ro

between humidity and products, condition the heat and mass transfer in the drying process [4]. Usually, during the process, the drying agent changes its temperature, relative humidity and even circulation over time, and the wet material changes its specific heat, density, thermal conductivity and even dimensions. Moreover, during the process, the heat- and mass-transfer coefficients, as well as the viscosity, the superficial tension, and others vary; therefore, in order to accurately know how the process unfolds, it is necessary to correlate the known theoretical results, and the direct experimental research conducted for each product [5].

The particularities of the drying process of vegetables and fruits are emphasized by the *drying curves* (variation of humidity over time), the *curves of the drying speed* (variation of the drying speed with the humidity or over time), the *variation in the temperature of the drying agent and in the temperature of the material over time* etc. The drying curves offer the possibility of examining the influence of the various parameters on the technological process, with a view to establishing some economical drying systems. They are experimentally plotted.

2. Material and Method

The thermal calculation of the dryers for vegetables and fruits aims at establishing the thermal agent and heat consumptions, in close dependence with the drying technology, operating parameters and installation type [3].

The operating principle of the drying installations for vegetables and fruits, with air or air-combustion gas mixture supposes the thermal agent to take an amount of moisture from the product to be dried, followed by the total or partial removal from the dryer of the drying agent.

The schematic diagram of the hot-air drying installation is shown in Fig. 1.

Wet vegetables or fruits enter through the charging funnel *PI* and, by means of a transport device, they move along the drying chamber Cu up to the output connector *RI*. The cold air, aspirated by the ventilator *V*, is heated with the batteries *BI*, then it circulates counter-currently with the material to be dried, absorbing some of its moisture, whereupon it is eliminated from the dryer. Sometimes, the air is further heated in the drying chamber with the additional heating batteries *BSI*.

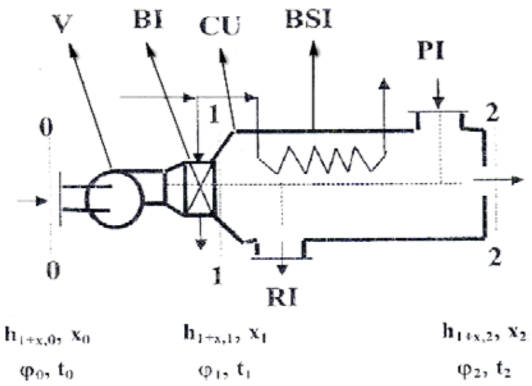

Fig. 1. *Schematic diagram of the hot-air drying installation*

The ventilator sucks the outside air in the condition *0* (t_0, x_0, $h_{1+x,0}$, φ_0) and releases it in the heating battery, where it is heated to the condition *1* (t_1, $x_1=x_0$, $h_{1+x,1}$, φ_1), wherewith it enters the drying chamber of the installation. Upon leaving the drying chamber, the air is in the condition *2* (t_2, x_2, $h_{1+x,2}$, φ_2). In the case of the theoretical dryer, the heat losses to the outside environment are neglected, the equality of the inlet and outlet temperature of the material to be dried, and the lack of additional heating in the drying chamber are accepted; aspects to be considered in the case of the actual dryer.

A flow of wet vegetables or fruits D_1.is introduced in the dryer. If the flow of dry vegetables and fruits is marked with D_{usc} and the humidity content of the material in the state *1*, with W_1, it can be written:

$$D_1 = D_{usc} + W_1 \left[kg/h \right] \qquad (1)$$

After the drying process, the humidity of vegetables or fruits diminishes from W_1 to W_2 so that the flow of material at the outlet of the dryer can be expressed as follows:

$$D_2 = D_{usc} + W_2 \left[kg/h \right] \qquad (2)$$

The humidity eliminated by drying is:

$$\Delta W = D_1 - D_2 = W_1 - W_2 \left[kg/h \right] \qquad (3)$$

Humidity can be also expressed with the notion *specific moisture content*:

$$\Delta W = \frac{D_1 w_{um,1} - D_2 w_{um,2}}{100} = \frac{D_{usc}\left(w_{usc,1} - w_{usc,2} \right)}{100} \qquad (4)$$

Currently, the specific moisture contents of vegetables and fruits are determined by accurately weighing a large number of initial and final samples, and by mediating the obtained results.

The ***moisture balance*** of the drying process allows the determination of the drying-agent flow. By neglecting the drying-agent losses by leakages, the moisture balance consists in the moisture of the material and of the drying agent:

$$m_a x_0 \cdot 10^{-3} + W_1 = m_a x_2 \cdot 10^{-3} + W_2 \left[kg/h \right] \qquad (5)$$

where:

- m_a is the necessary flow of drying agent, in *kg/h*;
- x_0 and x_2 – moisture contents of the drying agent at the inlet and outlet of the drying chamber, in *g vap/kg dry agent*.

From the relation (5), the *drying-agent flow* is obtained:

$$m_a = \frac{W_1 - W_2}{\left(x_2 - x_0 \right) 10^{-3}} = \frac{\Delta W}{\left(x_2 - x_0 \right) 10^{-3}} \left[kg/h \right] \qquad (6)$$

The ***thermal flow*** *necessary for heating the air* has the expression:

$$Q = m_a \left(h_{1+x,1} - h_{1+x,0} \right) \left[kJ/h \right] \qquad (7)$$

The ***theoretical thermal balance*** of the drying chamber is given by the relation:

$$m_{a1} h_{1+x,1} = m_{a2} h_{1+x,2} \qquad (8)$$

The ***specific heat consumption*** is given by the expression:

$$q = \frac{Q}{\Delta W} = \frac{m_a \left(h_{1+x,1} - h_{1+x,0} \right)}{m_a \left(x_2 - x_0 \right) 10^{-3}} = \frac{h_{1+x,1} - h_{1+x,0}}{\left(x_2 - x_0 \right) 10^{-3}} \left[kJ / kg\, umiditate \right] \qquad (9)$$

The ***temperature*** of the ***mixture*** at the inlet of the drying chamber t_1 is limited by the technological conditions for the drying process. Based on the value of the temperature t_1 the value of the excess-air coefficient and the moisture content at the inlet of the drying chamber are established. Given the high value of the air excess (λ_a=20...30), the properties of the air-combustion gas mixture are very close to those of the wet air, therefore the thermal calculation can be made by means of the diagram h_{1+x}-x (Fig. 2). Figure 3 shows the mixing process 0-2 between air and combustion gases, followed by the theoretical drying process 1-2.

The ***real thermal balance*** of the drying installation is made on account of all system losses and considering the reference condition to be characterized by the temperature 0^0C.

The *thermal balance equation* is***:***

$$Q_i = Q_c, \tag{10}$$

where:

Q_i is the energy flow entered into the system, in *kJ/h*;

Q_c – the energy flow come out of the system, in *kJ/h*.

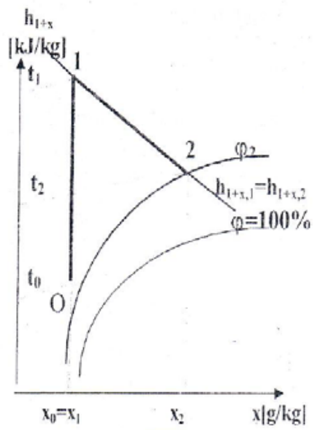

Fig. 2. *Diagram* h_{1+x}*-x*

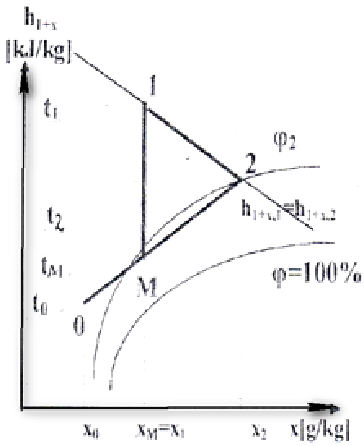

Fig. 3. *Air-combustion gas mixing process, followed by the theoretical drying process* [3]

The energy Q_i ***entered*** into the system consists of:

- *sensitive energy of the sucked air:*

$$Q_{sai} = m_a h_{1+x,0} \tag{11}$$

- *thermal energy for heating the air in the heating battery BI*:

$$Q_{BI} = m_a \left(h_{1+x,1} - h_{1+x,0}\right) \tag{12}$$

- *sensitive energy of the material to be dried, at the inlet*:

$$Q_{m,1} = D_2 c_m t_{m,1} \tag{13}$$

where:

D_2 is considered the flow of vegetables or fruits at the outlet of the dryer, as the sensitive heat of moisture is separately evaluated;

c_m –specific heat of the material, in *kJ/kgK*;

$t_{m,1}$ – temperature of the material at the inlet of the dryer, in ^0C;

- *sensitive energy of the moisture which is removed*:

$$Q_w = W \cdot c_w \cdot t_{m,1} \tag{14}$$

where: c_w is the specific heat of the humidity, in *kJ/kgK.*

- *sensitive energy of the fruit or vegetable transport devices through the drying chamber:*

$$Q_{tr,1} = D_{tr} c_{tr} t_{tr,1} \tag{15}$$

where:

D_{tr} is the weight, in the time unit, of the transporter, in *kg/h*;

c_{tr} – specific weight of the material of the transporter, in *kJ/kgK*;

$t_{tr,1}$ – temperature of the transport, at the inlet, in ^0C.

▪ *thermal energy introduced through the additional heating battery BSI, Q_s.*

The energy Q_c come out of the system consists of:

▪ *sensitive energy of the air at the outlet*:

$$Q_{sae} = m_a h_{1+x,2} \quad (16)$$

The sensitive energy of the air at the outlet consists of balance terms, which can be highlighted by replacing the enthalpy specific to the air:

$$\begin{aligned} h_{1+x,2} &= c_{pa} t_2 + x_2 h_{v2} = \\ &= c_{pa} t_2 + \left(x_0 + \frac{\Delta W}{m_a} \right) h_{v2} \end{aligned} \quad (17)$$

There is thus obtained, for the sensitive energy of the air at the outlet, the expression:

$$Q_{sae} = m_a c_{pa} t_2 + m_a x_0 h_{v2} + \Delta W h_{v2} \quad (18)$$

The three component terms of the sensitive heat of the air at the outlet are:

1. sensitive energy of the dry air at the outlet of the drying chamber:

$$Q_{se,usc} = m_a c_{pa} t_2 \quad (19)$$

2. sensitive energy of the moisture of the aspirated air, at the exhaust state, for which the vapour enthalpy is h_{v2}:

$$Q_{sae,um} = m_a x_0 h_{v2} \quad (20)$$

3. thermal flow necessary for evaporating the moisture:

$$Q_{evap} = \Delta W h_{v2} \quad (21)$$

▪ *sensitive energy of the material at the outlet*:

$$Q_{m,2} = D_2 c_m t_{m,2} \quad (22),$$

where $t_{m,2}$ is the temperature of the material at the outlet of the dryer, in $^\circ C$;

▪ *energy of the transport devices at the outlet:*

$$Q_{tr,2} = D_{tr} c_{tr} t_{tr,2} \quad (23),$$

where: $t_{tr,2}$ is the temperature of the transporters at the outlet of the dryer, in ^0C;

▪ *heat losses through the dryer:*

$$Q_p = k\, S\, \Delta t_{med} \quad (24),$$

where:

k is the global coefficient of heat exchange, in W/m^2K;

S – heat-exchange surface, in m^2;

Δt_{med} – difference of logarithmic average temperature, in ^0C;

▪ *incalculable heat losses of the system, Q_{rest}.*

The thermal balance equation turns into [1], [3]:

$$\begin{aligned} & Q_{sai} + Q_{BI} + Q_{m,1} + Q_w + Q_{tr,1} + Q_s = \\ & = Q_{sae} + Q_{m,2} + Q_{tr,2} + Q_p + Q_{rest} \end{aligned} \quad (25)$$

The relation (25) can be rewritten as:

$$\begin{aligned} & m_a \left(h_{1+x,2} - h_{1+x,1} \right) = \left(Q_w + Q_s \right) - \\ & - \left[\left(Q_{m,2} - Q_{m,1} \right) + \left(Q_{tr,2} - Q_{tr,1} \right) + Q_p + Q_{rest} \right] \end{aligned} \quad (26)$$

If we introduce the notations:

$$\begin{aligned} & Q_m = Q_{m,2} - Q_{m,1}, \\ & Q_{tr} = Q_{tr,2} - Q_{tr,1} si \\ & \Delta Q = \left(Q_w + Q_s \right) - \left(Q_m + Q_{tr} + Q_p + Q_{rest} \right) \end{aligned} \quad (27)$$

the relation (26) can be expressed as:

$$m_a \left(h_{1+x,2} - h_{1+x,1} \right) = \Delta Q \quad (28)$$

From the relation (28), the variation of enthalpy in the process 1-2 can be explained:

$$h_{1+x,2} - h_{1+x,1} = \frac{\Delta Q}{m_a} \quad (29)$$

In general $\Delta Q < 0$, as the heat losses of the drying chamber exceed the heat $Q_{\Delta W} + Q_s$ and hence

$$h_{1+x} = h_{1+x,2} - h_{1+x,1} \langle 0,$$

hence $h_{1+x,2} < h_{1+x,1}$. two other cases can, however, be encountered: if the additional heat input and with the material exceed the amount of losses ($\Delta Q > 0$), $h_{1+x,2} > h_{1+x,1}$; if the heat input totally compensates for the heat losses, $h_{1+x,2} = h_{1+x,1}$, then the real dryer operates just like the theoretical dryer.

Note that h_{1+x} is a function of m_a, which in its turn depends on the moisture content x_2 of vegetables or fruits, at the outlet of the drying chamber. Therefore, in order to represent the real drying process, the procedure is the following:

- the point 2° of intersection of the straight lines t_2 and $h_{1+x,1}$ is determined, which corresponds to x_2^0 and respectively:

$$m_0 = \Delta W / \left(x_2^0 - x_0\right)$$

and

$$h_{1+x,0} = h_{1+x,2} - h_{1+x,1} = \Delta Q / m_0\,;$$

- in the point 2^0 the value $h_{1+x,0}$ is algebraically added on the line x_2^0= *const.*, as in the exhaust air the moisture content does not vary (the condensation of the water vapour does not occur), and thus the point $2'$ results.
- the unification of the points *1* and $2'$ gives the direction of the real process $1 - 2'$, which intersects the straight line t_2 in the point *2*, of sought moisture content x_2 and of enthalpy variation Δh_{1+x}, which is obtained from the similarity of the triangles $1\ 2^0\ 2'$ and $1\ 2''2$:

$$\frac{2^0 2'}{2'' 2} = \frac{\Delta h_{1+x,0}}{\Delta h_{1+x}} \frac{12'}{12} = \frac{x_2^0 - x_0}{x_2 - x_0} \quad (30)$$

From the equation (30), it follows that $2''2$ is really the difference Δh_{1+x} given by the relation (29):

$$\Delta h_{1+x} = \Delta h_{1+x,0} \frac{x_2 - x_0}{x_2^0 - x_0} = \frac{\Delta Q}{m_0} \frac{x_2 - x_0}{x_2^0 - x_0} + \frac{\Delta Q}{\frac{\Delta W}{x_2^0 - x_0}} \cdot \frac{x_2 - x_0}{x_2^0 - x_0} = \frac{\Delta Q}{\frac{\Delta W}{x_2 - x_0}} = \frac{\Delta Q}{m_a} \quad (31)$$

The efficiency or degree of use of the energy afferent to the drying chamber is determined by means of the efficiency indicators.

The ***useful energy*** in the convective drying process of vegetables and fruits consists of the heat necessary for the moisture evaporation (Q_{evap}), the sensitive heat of the material at the outlet ($Q_{m,2}$) and of the transport devices at the outlet ($Q_{tr,2}$):

$$Q_u = Q_{evap} + Q_{m,2} + Q_{tr,2} \quad (32)$$

The main ***efficiency indicators*** of the convective drying installation for vegetables and fruits are:

- *thermal efficiency of the drying process*:

$$\eta_t = \frac{Q_{evap}}{Q_{BI}} 100 [\%] \quad (33)$$

- *thermal efficiency of the technological process*:

$$\eta_{tt} = \frac{Q_u}{Q_i} 100[\%] \qquad (34)$$

▪ *specific heat consumption per product unit*:

$$c_q = \frac{Q_{BI}}{D_2}[kJ/kg] \qquad (35)$$

▪ *total specific heat consumption per product unit:*

$$c_{qt} = \frac{Q_i}{D_2}[kJ/kg] \qquad (36)$$

3. Results and Discussions

The thermal calculation is based on the simplified functional scheme of an installation which may be used for the drying by convection of vegetables and fruit. Knowing the flow of vegetables or fruits introduced in the drying installation, and their humidity, as well as the flow of dry matter and the moisture it still contains at the outlet of the dryer, a theoretical thermal calculation was initially developed, finally completed with the aspects necessary for the real calculation of this technical equipment. There are of interest for a potential user of the convective drying installation for vegetables and fruits, its efficiency indicators, respectively the thermal efficiency of the drying process, the thermal efficiency of the technological process, the specific energy consumption per product unit and the total specific energy consumption per product unit.

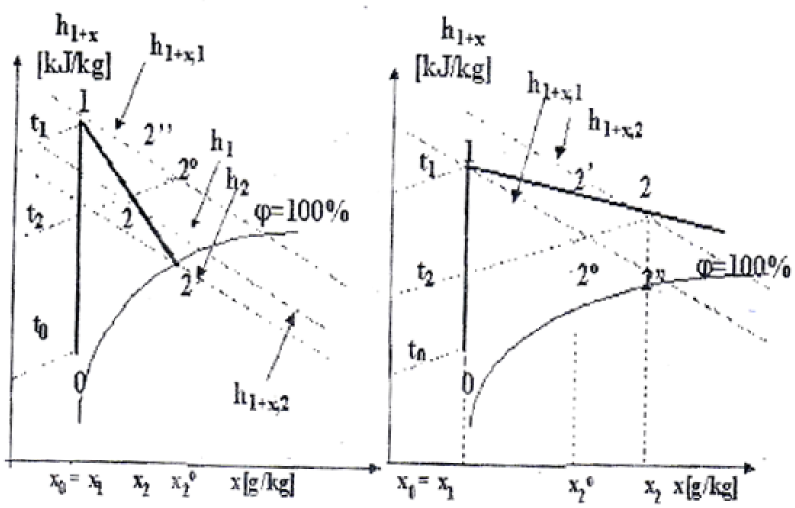

Fig. 4. *Graphical representation of the real drying process in the diagram h_{1+x}-x*

4. Conclusions

✓ The dehydration by drying of vegetables and fruits can also be made by means of specialized installations, which are designed and manufactured according to the principle of convective heat and humidity exchanges. Convective drying is the most widespread procedure of moisture elimination from vegetables and fruits, both due to the simplicity of the procedure, and especially to the multiple possibilities of obtaining good quality, at low cost, in a short amount of time.

- ✓ In this technical equipment, the wet vegetables or fruits come into contact with the drying agent (hot air or combustion gases), from which they receive, by convection, between 80...90% of the total amount of heat necessary for the drying process.
- ✓ The thermal calculation of the dryers for vegetables and fruits aims at establishing the consumptions of thermal agent and heat, in close dependence with the drying technology, operating parameters and installation type.
- ✓ The operating principle of the drying installations for vegetables and fruits, with air or mixture of air-combustion gases supposes the thermal agent to take an amount of moisture from the product to be dried, followed by the total or partial removal of the drying agent from the dryer.
- ✓ In the paper, a complex and complete theoretical calculation, specific to the convective drying installations for vegetables and fruits, was made; thereupon the aspects that arise in the real thermal calculations afferent to this equipment were specified.

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