Contributions to Spray Drying Kinetics Modeling of the Wild Rose Fruits Extract

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In the present paper was realized the spray drying kinetics study of the wild rose fruits extract. Using physical models, existing in the specialized literature and experimental data were calculated the heat and mass coefficients estimation in spray drying process of the wild rose fruits extract. The experimental data was obtained for 10 temperatures of drying agent overwhelm in the range [50; 155]°C and for the 8 classes of the wild rose fruits extract droplet dimensions overwhelm in the range [32; 265] μm.

Keywords: spray drying, kinetics, wild rose fruits extract

The drying operation is a complex phenomenon considering the nature of the heat and mass transfer. Using as intensification technique the spray drying, the matter of drying becomes more complex, by following the optimal droplets dimensions classes, to obtain at the drier exit a solid product, dried until the moisture corresponds the xero-stability state and with an acceptable concentration of active product [1-3].

In the biomaterial drying, the rigorous control of the operating parameters is important, with purpose to maintain the biochemical and biological properties of the finite product. In the particular case of the wild rose fruit extract drying is necessary the control of the temperature and moisture of the product during drying, with purpose to avoid the thermo and xero degradation of the active product, vitamin C [4].

The transfer property (heat and mass) transfer coefficients calculation in the spray drying process uses the mathematical model exsting in the specialty literature. Among these there are noticed the mathematical models which express the heat and mass transfer considering the particle dimensions classes the final moisture of the material and drying agent temperature respectively [5-9].

In the drying kinetics of the considered physical model *Topar* [10], for the constant drying velocity period of the moisture removing of the particle (droplet to solid particle during the drying process transformation, named as follows - volume individual unit - v.i.u), the drying velocity, $\dot{m}_I$, is expressed by the droplet specific mass flow, using the relation [10]:

$$\dot{m}_I = \beta \cdot (u_d - y_{air}) \quad (1)$$

Concomitant with the mass transfer the droplet diameter decreases proportionally with the evaporated water quantity [11, 12]. The instantaneous droplet diameter is expressed by the relation [10]:

$$d_{cl\,i} = d_{cl\,0} \cdot \sqrt[3]{\frac{\rho_{Pwo} - \rho_{wet}}{\rho_{Pw} - \rho_{wet}}} \quad (2)$$

The critical moisture content, u_{cr}, is determined by the drying kinetics experiments, from the drying velocity, m_{II}, expressed like specific mass flow variation during uniform decreasing drying velocity period, by relation [10]:

$$\dot{m}_{II} = \beta \cdot \frac{u - u_e}{u_{cr} - u_e} \cdot (u_d - y_{air}) \quad (3)$$

Surrounding the critical drying point, the droplet surface is gradually changing into a solid layer. Considering the liquid droplet transformed in solid particle, at critical moisture, in the ununiform decreasing velocity of the drying period, take place the porosity and solid particle density modification according to the relation [10]:

$$\frac{d\rho_{Pw}}{dz} = -\frac{6 \cdot \dot{m}_{II}}{\rho_{wet} \cdot d_{cl\,i}}$$
$$\frac{d\varepsilon}{dz} = \frac{6 \cdot \dot{m}_{II}}{\rho_{wet} \cdot d_{cl\,i} \cdot v_t} \quad (4)$$

The heat transfer between the gas and solid particle is characterized by the heat transfer coefficient, α, determined from the Ranz – Marshall equation - used for the Nusselt criteria calculation, in condition of 0<Re<200 [13]:

$$Nu = 2 + 0.6 \cdot Re^{1/2} \cdot Pr^{1/3} \quad (5)$$

The mass transfer partial coefficient, β, is determined considering the Lewis criteria, which is calculated as follow,

$$Le = \frac{a}{D} = \frac{\textit{heat transfer diffusion coefficient}}{\textit{molecular mass transfer diffusion coefficient}},$$

using the relation:

$$\beta = \frac{\alpha}{c_{air\ wet} \cdot Le} \quad (6)$$

The experimental results and the information regarding: the process parameters, the used materials (wild rose fruits extract and the drying agent – air) and the operating parameters of the spray drier, was obtained in a real drier of which scheme is represented in the figure 1.

The experimental determination pursue the heat and mass transfer coefficients calculation for 8 dimensions classes with values overwhelm in range [32; 265] μm and for 10 drying agent temperatures with values overwhelm in range [50; 155]°C.

Experimental part

The experimental plant

The experimental data needed for the spray drying mathematical modeling was obtained in a spray drier (fig. 1) with the following technical characteristics:

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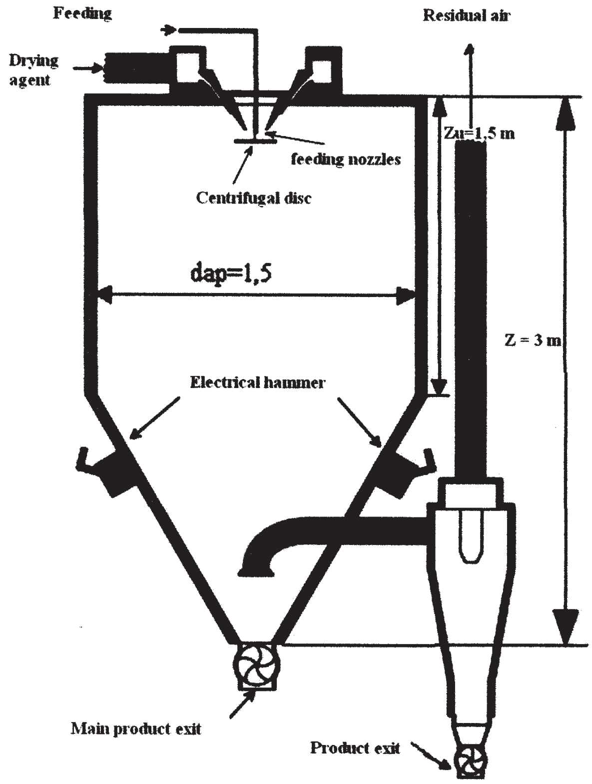

Fig. 1. Spray drier

- the drying room is in cylindrical shape with conical bottom, having the sizes:
 · inlet diameter, d_{ap} = 1.5 m;
 · cylindrical zone height, Z_u = 1.5 m;
 - total height, Z =3 m;
 - the total volume of the drying room: 2.25 m^3.
 - the feeding drying agent flow rate, G_{air} = 0.15 kg/s.

The dried powder separation it is made in two cyclones assembly, serial mounted at the drying room exit. The size of each cyclone and their geometry was established from standard catalogues, in order to concord with drying agent flow rate and to realize the optimal angular velocity allowing a proper separation of the phases (especially for particles with 1 mm minimum diameter).

The drying agent heating is realized by air crossing over an electrical resistance with a total power of 43.2 kW, which allows the air heating until 300°C.

The spray dryer is feed by pumping the liquid suspension through a nozzle with diameter ϕ = 1.5 mm; the dispersion is centrifugal, the liquid solution is pumped into the center of a disc with diameter 100 mm, with the rotation velocity of 30.000 rot/ min at an engine power of 0.55 kW.

The drying agent, the warm air, with transporter role is aspired through a heating battery using a ventilator and enter in the drying chamber through two nozzles with diameter ϕ = 1.5 mm.

The dispersing air pressure is made with a regulator manometer, which allows the pressure establishing between 0 and 5 MPa.

Process parameters

The parameters of the material submissive to the spray drying:

-the feeding flow rate of the wild rose fruit extract subdued to drying is 0,15 kg/s at a temperature of 25°C;

-the moisture content was experimentally determined with a thermo balance; the initial moisture, u_0=2.33 kg water kg dried solid, critical moisture, u_{cr} = 1,7 kg water/ kg dried solid and equilibrium moisture, u_e = 0,01 kg water kg dried solid;

-the wet material density is ρ_{pw} =1140 kg/m^3, and specific heat has the value, c_{pw} = 2090 J/(kg K);

Table 1

THE DROPLET SIZES DISTRIBUTION IN CLASSES

i	d_{cl_i} x10^6 [m]	ψ_i [droplets/sec]
1	32	$3.79 \cdot 10^8$
2	81	$7 \cdot 10^7$
3	110	$2.8 \cdot 10^7$
4	133	$1.58 \cdot 10^7$
5	153	$1.04 \cdot 10^7$
6	174	$7.07 \cdot 10^6$
7	206	$4.26 \cdot 10^6$
8	265	$6.67 \cdot 10^5$

-it was used *i* = 8 variations of the v.i.u.; in function of those sizes varies the number of droplet which pass the nozzle, per second, how is shown in table 1.

The used drying agent parameters

-the drying agent flow rate, G_{air};

-the input air temperature, t_{air} = 135 °C

-the exit air moisture is measured by psychometric method, as shown in table 2; in this table is presented the wet thermometer temperature, t_{wet}, dried thermometer temperature respectively, t_{dried} and the air moisture content corresponding to those two temperatures;

-the initial moisture content of air, y_{air} = 0.0128 kg water vapor/kg dried air, was experimentally determined at drying agent exit from the spray drier without heating system of air; in stationary conditions was measured the dried temperature thermometer, t_{dried} = 24°C and wet

Table 2

THE PROPERTIES OF THE DRYING AGENT – AIR FUNCTION OF THE INPUT TEMPERATURE

j	t_{air} [°C]	t_{wet} [°C]	t_{dried} [°C]	$y_{air\ sat}$ [kg/kg],	$y_{air\ out}$ [kg/kg],
0	50	27.6	17.3	0.0468	0.026
1	60	32	23.1	0.0474	0.028
2	70	35.2	25.2	0.0482	0.0305
3	80	39	29.6	0.0492	0.0333
4	100	43.5	31.7	0.050	0.0376
5	135	45.4	25.6	0.051	0.0415
6	140	45.1	23.8	0.052	0.0446
7	145	44.6	17.8	0.054	0.0492
8	150	43.9	9.2	0.056	0.0530
9	155	43.1	3.9	0.056	0.0580

The operating parameters of the drying process were:

temperature thermometer, t_{wet}=19°C, to establish the initial moisture content of drying agent at drier exit using the psychrometric diagram.

There were proposed ten values for the input drying agent temperature, in range [50-155]°C (table 2). The wet temperature thermometer is one of the parameters which characterizes the wet air condition, being used for the air moisture content measurement.

The properties of the drying agent are presented in table 2, together with the input air temperatures, t_{air}, the wet temperature thermometer, t_{wet}, the dried temperature thermometer, t_{dried}, the saturation moisture content of air, $y_{air, sat}$, and the air moisture content at drier exit, $y_{air,out}$

The operating parameters of the drying process were

-drier pressure, p = 4.9 10^5 [Pa];

-for the v.i.u. having the maximum diameter of d_{max}=3.05 . 10^{-4} m were calculated the axial and tangential velocities of: v_{ax}=81.74 m/s, respectively v_t=43.85 m/s, determined at the bi-extract exit from the distribution nozzles of the spray drier.

Results and discussions

To solve the mathematical model chosen and for the experimental data simulating, there were calculated, function of the processing conditions, the following auxiliary values.

<u>The convection heat transfer coefficient, α</u>, determined with Ranz-Marshall equation (5). For small values of the Reynolds criteria, specific for the spray drying, the Nusselt criteria are NuH≈2 [14, 15].

Function of the corresponding diameter of the v.i.u. fraction, there were obtained eight values of the heat transfer coefficient, each value corresponding to the drying agent temperatures (fig. 2).

From figure 2 it can be observed that at initial drying agent temperature increasing was produce an increasing of the heat transfer coefficient. This modification of the thermal conditions is significantly compared with input drying agent temperature increasing.

To present the influence of the droplets sizes upon the partial coefficient of heat transfer, it is shown in figure 2 the variation of this coefficient function of the drying agent temperature for the considered dimension classes.

From figure 2 we can conclude that for v.i.u. diameters smaller than 100 μm (classes 1 - 3) the heat transfer coefficients have values higher than 500 W/m²K. Thus, for class 1 (3.2 . 10^{-5}m) the heat transfer coefficients are 1700-2300 W/m²K, while for the class 2 and 3 (8.1 . 10^{-5}m, 1.11 . 10^{-4}m) those values half decrease for smaller temperatures (until 80°C) and decrease 2.5 points and 3 points respectively at temperatures varying in the range 80-155°C. For higher sizes than 100 μm of the droplets (classes 4-8) the variation of the heat transfer coefficient with temperature presents a lightly increasing tendency in the range (200-650) W/m²K.

It is ascertained that, concomitantly with v.i.u. sizes increasing, the pronounced influence of temperature upon the heat transfer coefficient variation decrease. This aspect is also evidenced by the slope of line variation of partial coefficient heat transfer function of temperature. The variation function for the heat transfer coefficient versus temperature, obtained at wild-rose extract drying, has the shape:$\alpha = a_1 . t . b_1$.

In table 3 are presented the values of the constants: **a** (the slope) si **b** (origin coordinate) for all dimension classes of v.i.u. considered. The correlation factor between the experimental data and the empirical equations obtained is R^2=1.

Analyzing the variation of the heat transfer coefficient with temperature for different dimensions of v.i.u., we can find that the optimal sizes domain for efficient heat transfer is less than 100 μm, even for low temperatures of the drying agent, used to avoid the biomaterial thermo-degradation.

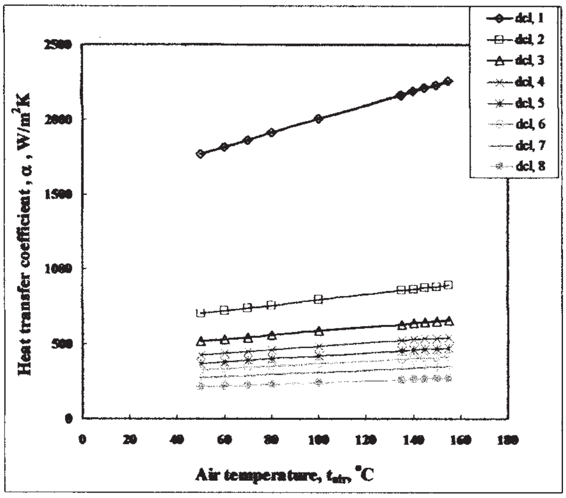

Fig. 2. Variation of heat transfer coeficcient function of drying agent temperature for the considered sizes classes

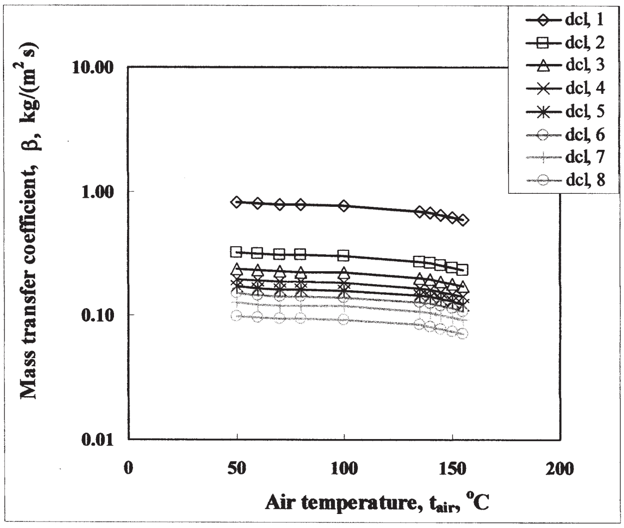

Fig.3. Variation of the mass transfer coefficient function of drying agent temperature for the considered dimension classes

Table 3

i	a_1	b_1	No. equation
1	4.619	1540.7	(8)
2	1.825	608.66	(9)
3	1.344	448.19	(10)
4	1.111	370.69	(11)
5	0.966	322.23	(12)
6	0.849	283.34	(13)
7	0.717	239.33	(14)
8	0.558	186.04	(15)

Table 4

i	a_2	b_2	No. equation
1	-0.0019	0.925	(17)
2	-0.0008	0.366	(18)
3	-0.0006	0.269	(19)
4	-0.0005	0.223	(20)
5	-0.0004	0.1935	(21)
6	-0.0004	0.1702	(22)
7	-0.0003	0.1437	(23)
8	-0.0002	0.1113	(24)

The mass transfer partial coefficient, β, calculated from Lewis criteria using the heat transfer coefficient is:

$$\beta_{ij} = \frac{\alpha_{ij}}{c_{\text{air wet}_j} \cdot Le} \quad (7)$$

In figure 3 is shown the variation of the mass transfer coefficient function of drying agent temperature and the dimension classes.

In this figure it is shown that mass transfer coefficient, obtained from experimental data, is relatively constant for temperatures smaller than 100°C and decreases with temperature increasing, due to the rapid passing from surface evaporation to deeper evaporation of v.i.u.

For v.i.u. with small dimensions (class 1) the mass transfer coefficient has values in range 0.8-0.6 $kg \cdot (m^2 \cdot s)^{-1}$, with approximate constant values up to 100°C in range 0.8-0.76 $kg \cdot (m^2 \cdot s)^{-1}$.

For v.i.u. from class 2 of dimension the variation is less pronounced (between 0.3-0.2 $kg \cdot (m^2 \cdot s)^{-1}$), ascertain a decreasing of 2.5 points at lower temperatures and respectively of 3 points at higher temperatures. The variation is almost constant for temperatures lowest than 100°C and lightly decreasing for temperatures higher than that value.

For dimension classes 3-8 the shape of the variation curves is similar. The variation range of the mass transfer coefficients is overwhelmed between 0.2-0.07 $kg \cdot (m^2 \cdot s)^{-1}$

The experimental data were transformed in linear shape by an logarithmic axis and are presented in a function such as $\lg\beta = a_2 . t . b_2$ as it is shown in figure 3. The coefficients for the obtained functions are presented in table 4. The correlation factor is $R^2 = 0.925$.

The obtained data indicate that, as in heat transfer, the drying operation is efficient also from the mass point of view, in dimension range which has as superior limit the 100 μm size of v.i.u and is recommended temperatures smaller than 100°C for the drying agent.

Conclusions

The present paper has pursued the determination of the simultaneous heat and mass transfer coefficient at wild rose fruits extract drying. The aims were reached by heat and mass transfer coefficient calculation for different dimension classes of v.i.u. and different temperatures of the drying agent. There were chosen eight dimension classes and ten temperatures of the drying agent for which were determined the heat and mass transfer coefficient at spray drying.

The experimental data obtained for the heat transfer between the dying agent and v.i.u. at spray drying has shown a decreasing tendency of the partial heat transfer coefficient with the v.i.u. sizes increasing, as shown in equation (8-15) obtained from experimental data.

The mass transfer coefficient estimation through the moisture mass transfer coefficient for different particle dimension classes and operating temperatures, indicated in experimental conditions, a decreasing of the mass transfer coefficient with temperature increasing, variation presented in equation (17-24) obtained from experimental data.

The obtained data shown that the optimal sizes domain for a simultaneous and efficient heat and mass transfer is less than 100 μm, even at low drying temperatures needed to avoid the biomaterial thermo-degradation.

Notation

Symbol

a - heat conductivity, m^2/s
c - specific heat, J/(kg K)
D - diffusion coefficient, m^2/s
d - diameter , m
G - mass flow rate, kg/s
$\dot{m} = \frac{dG}{d\tau}$ - specific mass flow, kg/(m^2 s),
t - temperature, °C
u - the solid material moisture, (kg water)/(kg dried material)
v - velocity, m/s
y - the moisture content of gas, kg water / kg dried gas
Z - height, m
Z_u - the cylindrical zone height of cyclone, m

Greek

α - partial heat transfer coefficient in gaseous phase, J/(m^2sK)
β - partial mass transfer coefficient , kg/(m^2 s)
ε - the volumetric fraction of the continuous phase (air), (m^3 air) / (m^3 drying room)
η - dynamic density, kg/(m s)
λ - thermal conductivity, J/(m . s . K),
ν - cinematic viscosity m^2/s
ρ - density, kg,m^3
t - time, s
ψ_i - droplets number in ***i*** fraction

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Symbol Signification

cl_i - class i
0 - initial
air - air
ap - apparatus
ax - axial
cr - critic
d - droplet
dried - drying
e - equilibrium
j - temperature index
max - maxim
p - particle
pw - particle wet
t - tangential
w - wet

Dimensionless number

Criteria	Symbol	Realtion
Lewis	Le	$Le = \frac{a}{D} = \frac{\lambda}{\rho \cdot c \cdot D}$

Nusselt	Nu	$Nu = \frac{\alpha \cdot d}{\lambda}$
Prandtl	Pr	$Pr = \frac{c \cdot \eta}{\lambda} = \frac{\nu}{a}$
Reynolds	Re	$Re = \frac{d \cdot v}{\nu} = \frac{d \cdot v \cdot \rho}{\eta}$

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