INVESTIGATION ON KINETICS OF SESAME DRYING AND ROASTING IN ROTATION-PULSED FLUIDIZED BED APPARATUS

by

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An industrial experiment for investigation of kinetics parameters on sesame drying and roasting in rotation-pulsed fluidized bed dryer has been carried out.
The generalized drying curve has been built. The equation describing drying rate depending on the mode parameters has been obtained.

Introduction

The roasting is a high-temperature process of drying and heating the material attended by operations, specific for any object of processing during which characteristic consumative qualities have been formed – taste, colour, aroma, chemical composition changes, structure-mechanical parameters changes, *etc*.

The object of investigation of this paper is roasting of wet-separated sesame-seeds designed for the production of ground roasted sesame-seeds in the industrial-type rotation-pulsed fluidized bed apparatus presented in (Djurkov, 1999). The purpose of this study is to investigate the kinetics of sesame-seeds drying and roasting by means of prognostication the apparatus operation at new technological modes and conditions.

Experimental equipment

The equipment for wet-separated sesame roasting in a rotation-pulsed fluidized bed consists of the main elements, as follows (Fig. 1):

- drying chamber, including gas-distributing chamber 1, driving wheel 2, driving axel 3, gas-distributing disk 4, immovable supporting grid 5, working chamber 14, separation chamber 8, screw feeding device 7 and leading away unit for the final product 15;
- a system for the heating up of the drying air, including electrical 12 and steam 25 air-heaters;
- system for treatment of the waste drying air, including cyclone 10, valve 17 and hopper 18;

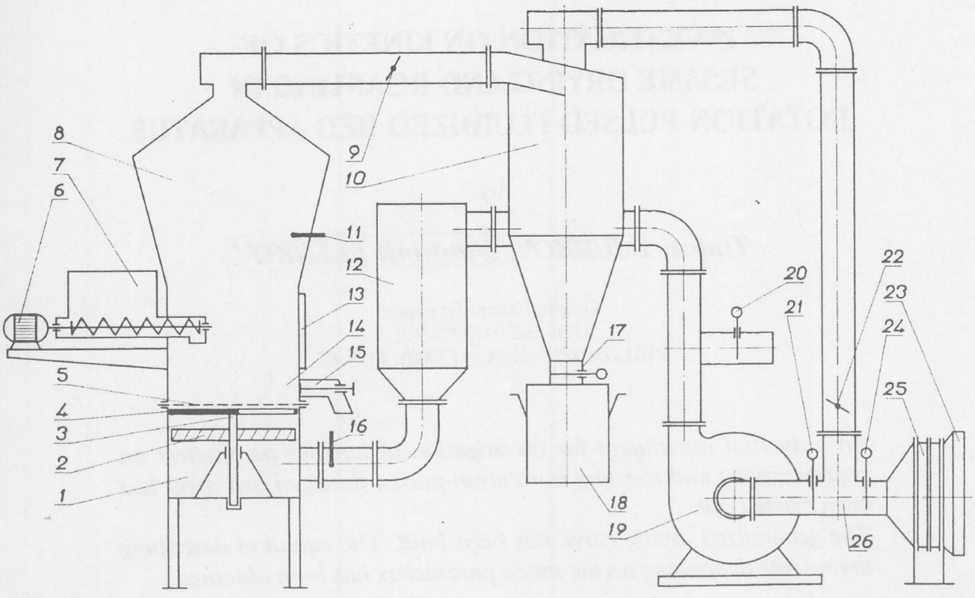

Figure 1

- system for injection and delivery of the drying air through the installation, including fan 19, sucked air cleaning filter 23, valves, flaps and connecting air-pipes;
- power supply and automatic process control system.

The installation works on a batch mode principle, in the following way.

The processed wet product should be poured into hopper 7, whose capacity has been measured up in such a way that it could take one batch of the material. By means of the screw transporter situated in the hopper bottom, the product enters the working chamber 14 upon immovable supporting grid 5. The roasted material is lead out of the working chamber by means of unit 15.

The drying air is sucked by the environment by using fan 19, then it is filtered from mechanical admixtures by passing through filter 23, and is heated up in the steam air-heater 25, then it is mixed with the recirculated air in the mixing chamber 26, and enters the electric air-heater 12 for a final heating up. By using a temperature measurements 16 at the entrance of the drying chamber inlet air temperature is automatically controlled in the range of 120–200 °C. The air heated up in that way enters the gas-distributing chamber 1, then it passes consecutively through the turbine wheel blades 2, through the sector opening of the rotating gas-distributing disk 4, through the apertures of the immovable supporting grid 5, and after entering the chamber 14, it fluidizes the product bed and at the same time dries and roasts the material. The waste drying air passes through the separation chamber 8, where part of the particles taken away by it are separated and fell into the bed again, through the cyclone 10 for the purpose of a final separation of the finer particles, and enters the mixing chamber 26 to be mixed with the fresh air into a pre-set ratio.

When passing through the turbine wheel blades 2, the drying air starts rotating it and by means of the driving axle 3 transmits the motion of the rotating gas-distributing disk 4.

The ratio between the recirculating and fresh air is adjusted by means of the valves 20, 21, 24 and the flap 22. The degree of Sesame roasting can be determined by measuring the output drying air temperature by means of sensor 11.

The gate 13 has two functions – it gives access for the maintenance staff to clean up the working chamber inner surface at idle state of the installation and allows visual observation during operation time, because a sight glass has been mounted on it.

Methodology of investigation of the process of sesame seeds roasting in rotation-pulsed fluidized bed apparatus

Two series of experiments have been carried out – 11 in total. The drying process with partial recycle of gas is shown in Fig. 2. The drying air recirculation rate, the initial temperature, the initial material quantity have been varied. The conditions at which the particular experiments have been carried out are presented in Table 1.

The experiments have been carried out in the following sequence:

- feeding the working chamber with material; the latter consists of well-strained wet-separated sesame-seeds; before feeding the material should be weighed and a sample for determining the initial moisture content should be taken;

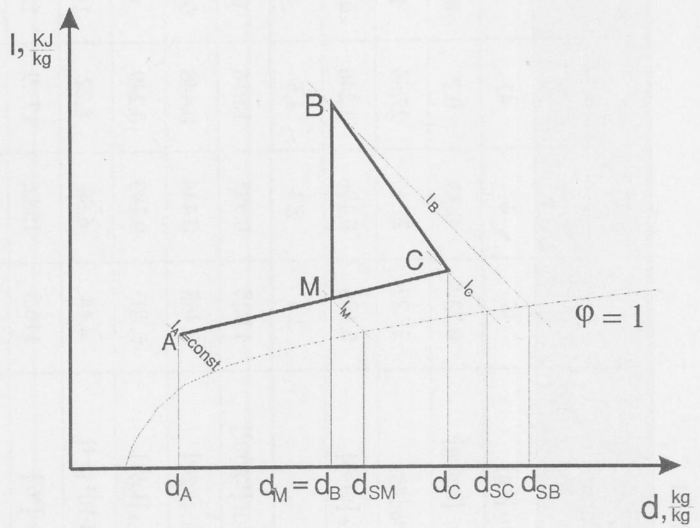

Figure 2. Enthalpy – humidity chart of the drying process

Table 1

Parameter	Experiments										
	1	2	3	4	5	6	7	8	9	10	11
m_I [kg]	48	47	47	32	57	48	48	42.5	45	43	57.8
u_i [kg/kg]	0.732	0.73	0.7	0.702	0.687	0.74	0.696	0.698	0.698	0.698	0.698
m_0 [kg]	27.27	27.17	27.66	18.8	33.79	27.62	28.3	25.03	26.5	25.34	34.04
v_A [m^3/s]	0.196	0.196	0.246	0.134	0.134	0.134	0.196	0.134	0.134	0.134	0.196
h	2.3	2.3	1.8	4.1	4.1	4.1	2.3	4.1	4.1	4.1	2.3
ρ_{SM} [kg/m^3]	1.038	0.985	1.016	0.75	0.816	0.841	0.985	0.805	0.774	0.826	0.923
L_C [kg/s]	0.468	0.444	0.448	0.412	0.448	0.462	0.444	0.442	0.425	0.454	0.416
L_A [kg/s]	0.203	0.193	0.249	0.1	0.109	0.113	0.193	0.108	0.104	0.111	0.181
$N \cdot 10^4$ [s^{-1}]	4.44	6.88	8.22	14.49	7.16	8.39	6.3	8.9	9.69	8.5	6.19
t_B [°C]	116.3	158.6	173.9	182.5	182	188	143	145.5	167.1	158.5	158.6
t_C [°C]	51.8	59.7	61.9	75	71.4	70.3	58.4	69	71.8	68.6	69.3
δt_{max} [K]	64.5	98.5	112	107	110.6	117.7	84.6	76.5	93.3	89.9	95.3
$d_B \cdot 10^3$ [kg/kg]	66.13	102.4	97.18	277.9	225.4	210.6	97.9	214.3	254.9	205.3	124.4
t_{SB} [°C]	51.7	59.7	59.9	73.3	70.7	70	58.3	68.7	71.8	68.6	62.1
$d_{SB} \cdot 10^3$ [kg/kg]	96.6	152.3	154.2	349	293.1	280.9	140.3	260.2	315.2	258.4	174.9

Table 1. *Continuation*

Parameter	Experiments										
	1	2	3	4	5	6	7	8	9	10	11
$d_C \cdot 10^3$ [kg/kg]	92.4	144.5	147.9	344	279.5	262.3	138	264.7	315.3	253.2	175.1
t_{SC} [°C]	51.0	58.9	59.4	73.2	69.9	68.9	58.1	69.0	71.8	68.3	62.2
$d_{SC} \cdot 10^3$ [kg/kg]	92.8	144.9	149.3	345.3	280.4	263.2	138.2	264.7	315.4	253.4	175.7
c_v [kJ(kg·K)]	1.123	1.190	1.181	1.517	1.419	1.392	1.182	1.399	1.474	1.382	1.231
$\frac{c_v}{r_C}\frac{L_C}{m_0}10^6$	7.32	7.43	7.32	12.59	7.17	8.83	7.07	9.42	8.96	9.42	5.73
$\frac{N}{\delta t}10^6$	6.88	6.98	7.34	13.48	6.47	7.13	7.45	11.63	10.16	9.45	6.50
τ [min]	34	22	18	11.5	21	20.5	31	17	21	20	25.5
τ_1 [min]	16	11	9.4	5.2	11.5	9	12	8	9	9	12
u_{kl}	0.256	0.235	0.228	0.236	0.206	0.236	0.235	0.256	0.186	0.231	0.241
k_C	0.075	0.119	0.142	0.172	0.115	0.097	0.067	0.0128	0.089	0.107	0.097
k_B	0.058	0.088	0.089	0.093	0.073	0.041	0.033	0.094	0.09	0.094	0.056

- during the process of roasting the drying agent temperatures should be measured at every minute under the gas-distributor t_B and above the material bed t_C using digital thermometers of the firm "Testoterm" with an accuracy of 0.1 °C;
- samples of the material should be taken periodically from the chamber for determining the moisture content by using the weighing method;
- calibration of the valve of the output drying agent has been preliminarily done – at three fixed positions of the valve the volume capacity of the outflowing air has been determined, the fan capacity and the rate-frequency of recirculation at a working chamber fed with material and temperature equal to the ambient;
- the roasting continues till reaching of preliminarily accepted air temperature after the bed;
- the duration of the process is measured by a stop-watch.

Experimental results

The results obtained by the measurements are presented in Table 1.

This table indicates the average temperature values of the drying air under the gas-distributor t_B and above the material bed t_C, the maximum utilized temperature drop of δt_{max}, for the first roasting period. In this table the following is indicated:

- drying air mass flowrate circulating through the chamber L_C;
- eliminated waste drying air mass flowrate L_A;
- drying rate for the first drying period N;
- moisture content d_B, calculated by the formula:

$$d_B = d_A + \frac{\Delta U'}{L_A} = d_A + \frac{m_0 N}{L_A} \tag{1}$$

- moisture content of the wet air leaving the drying chamber, calculated by the formula:

$$d_c = d_B + \frac{\Delta U'}{L_C} \tag{2}$$

- the duration of drying at the separate experiments τ and the duration of drying by the end of the second sector, which coincides to the first period of drying t_I.

Kinetics of drying. Processing and a general analysis of the experimental results

Because of the small number of moisture measurements during the particular experiment it is not possible to analyse with the individual drying curves. According to the data from all of the experiments the generalized drying curve has been built – Fig. 3. The drying rate for the first period N has been determined by means of the individual drying curve according to the curve slope within the period $\tau = 4 \div 10$ min.

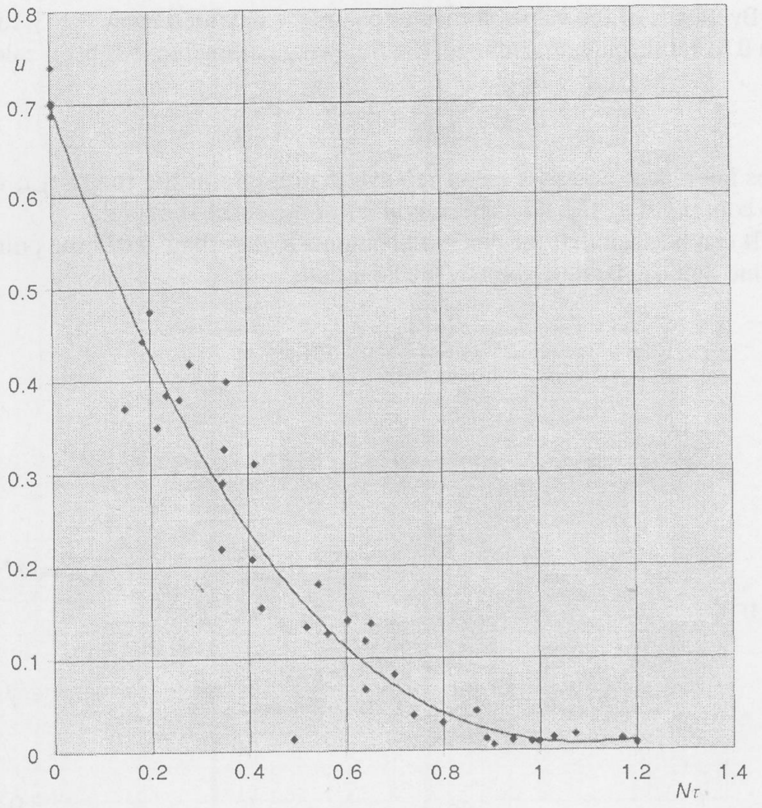

Figure 3. Generalized drying curve

The experimental results can be corrrelated using function of the type given below has been sought for:

$$u = u_0 \exp(-kN\tau) \tag{3}$$

corresponding to the Likov's model. For the experiments carried on the following constants were obtained:

$$u = 0.7 \exp(-3.65N\tau) \tag{4}$$

The equation (4) describes the experimental data with considerable scatter. A better description has been obtained when Olshansky's model has been used (Elenkov, 1995):

$$-\frac{du}{Nd\tau} = \kappa u^n \tag{5}$$

By means of the values for water content u recorded from Fig. 3, for different $N\tau$ from 0 to 1.2 through 0.1 interval, the following parameters has been calculated:

$$\psi = \frac{\Delta u}{N\Delta\tau} = \frac{u_{i-1} - u_{i+1}}{N(\tau_{i+1} - \tau_{i-1})} \tag{6}$$

which has been accepted as a mean relative drying rate in the range τ_{I-1}, τ_{I+1} and at moisture content of u_i. Fig. 4 has been built after the calculation data.

It can be seen that for moisture contents higher than 0.025 the points lie on a straight line that can be described by the equation:

$$\psi = \frac{\Delta u}{N\Delta\tau} = 1.551 u^{0.5} \tag{7}$$

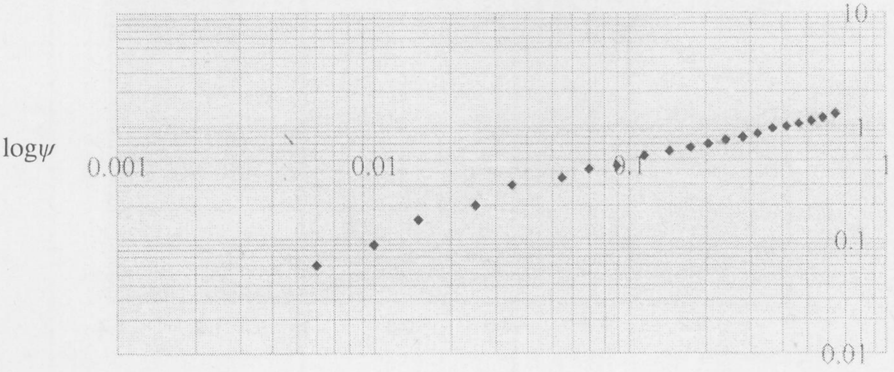

Figure 4. Relative drying rate curve

For the values less than $u = 0.025$ the curve is broken – the slope of the curve increases – the moisture evaporation is accelerated because of the seeds temperature increase.

From the equation (5) by means of integration the equation of the generalized drying curve can be obtained:

$$u = (0.837 - 0.776\,N\tau)^2 \tag{8}$$

being valid in the range $0.75 > u > 0.025$ or for $0 < N\tau < 0.88$.

The equation (8) has been utilized for engineering computations of the drying rate N in function of the process parameters. Having in mind the temperature curve type commented in (Djurkov, 1999), especially in its second section, it can be stated that in this period a process of adiabatic air saturation with moisture can be observed.

This can be confirmed by the fact that the values of the calculated t_{SB} coincide practically with the measured temperatures t_C (Table 1). The intensity of evaporation can be determined by the degree of drying agent cooling-$\delta t_{\max} = t_B - t_C = t_B - t_{SB}$, and not by the kinetics of the outer heat - and mass-exchange:

$$r_C \Delta U' = r_C m_0 N = L_C c_v (t_B - t_C) \tag{9}$$

or

$$\frac{N}{\delta t} = \frac{c_v}{r_C} \frac{L_C}{m_0} \tag{10}$$

In Fig. 5 the values of $N/\delta t$ and $c_v L_C / r_C m_0$ taken from Table 1 have been shown in binary logarithmic coordinate system.

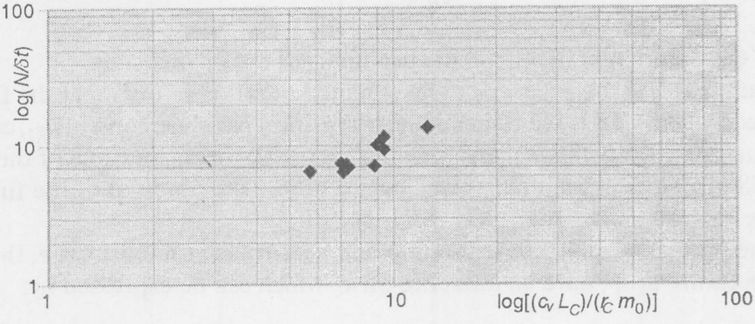

Figure 5. Relationship between drying kinetics and equilibrium process parameters

Using the method of least squares a linear regression equation has been obtained:

$$\frac{N}{\delta t} = 0.903 \left(\frac{c_v L_C}{r_C m_0} \right)^{1.055} \tag{11}$$

The power function is close to the linear one which confirms the supposition that the heat – and mass-transfer can be at equilibrium conditions considered and their intensity can be determined by the temperature drop $\delta t = t_B - t_{SB}$ available, mainly.

Kinetics of heating and roasting of the material

The speed of heating the material and the maximum temperatures that have been reached at the end of the process are the parameters themselves having a considerable significance for carrying out the roasting process.

From Fig. 2–12 (Djurkov, 1999) it can be seen that at the second stage, the drying agent temperatures before and above the bed have changed almost linearly as a function of time.

Having in mind the strongly developed heat- and mass-transfer surface of the bed, the high speed of flowing around the separate grains and the low values of Biot's criterion, it can be considered that the material mean temperature in the bed θ and temperature of the drying agent leaving it t_C are equal. Consequently, θ will also be a linear function of time.

$$\theta = t_C = t_{SC} + k_C \tau_{II} \tag{12}$$

Table 1 shows empirically obtained values of the constants in front of the argûment τ_{II}– k_B and k_C, determining the temperature growth rates t_B and t_C at the second stage of sesame roasting. Time period τ_{II} is defined as:

$$\tau_{II} = \tau - \tau_I \tag{13}$$

where: τ_I is the duration of drying till the beginning of the second stage.

From Table 1 the experimentally obtained duration of drying at the first stage τ_I can be recorded, as well as the values of the first critical moisture content u_{k1}, calculated by using equation (8). By the mean value of $u_{kI} = 0.232$, the mean value of the product $N \cdot \tau_I = 0.458$, can be determined, as well, which allows the duration of the first drying period to be calculated, depending on the drying rate.

The process of moisture separation and heat-transfer intensity, *i. e.* the change of the temperature drop, have an influence on k_C which can be expressed by:

$$\frac{\delta t}{\delta t_{\max}} = f\left[\left(\frac{\alpha F}{mc}\right), \left(\frac{du}{d\tau}\right)\right] \tag{14}$$

as well as on the drying agent temperature change, which at a constant air-heater power depends on the heat-accumulating ability of the unit as a whole and on the atmospheric air parameters.

The effect of the drying rate upon the relative temperature drop $\delta t/\delta t_{\max}$ at the second drying period has been studied. In Fig. 6, 7 and 8, as an illustration the dependency of $\delta t/\delta t_{\max} = f(N \cdot \tau)^{-n}$ for experiments № 1, 7 and 10, has been shown. Constants A and n in equation of the type:

$$\frac{\delta t}{\delta t_{\max}} = A(N \cdot \tau)^{-n} \tag{15}$$

were calculated using the linear regression (Table 2).

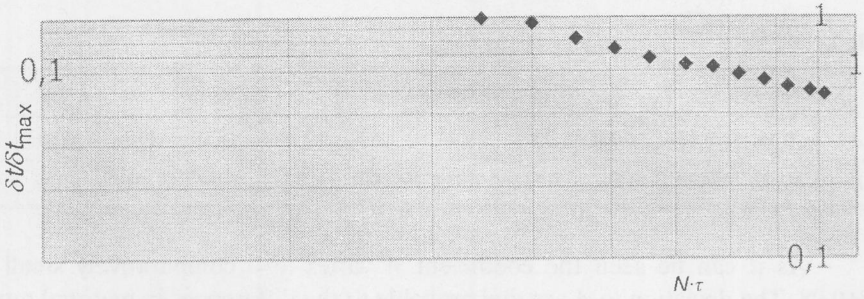

Figure 6. Relationship between drying rate and relative temperature drop for Experiment 1

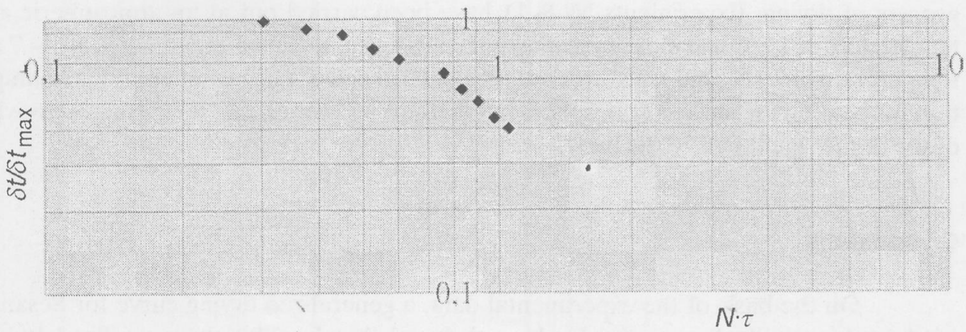

Figure 7. Relationship between drying rate and relative temperature drop for Experiment 7

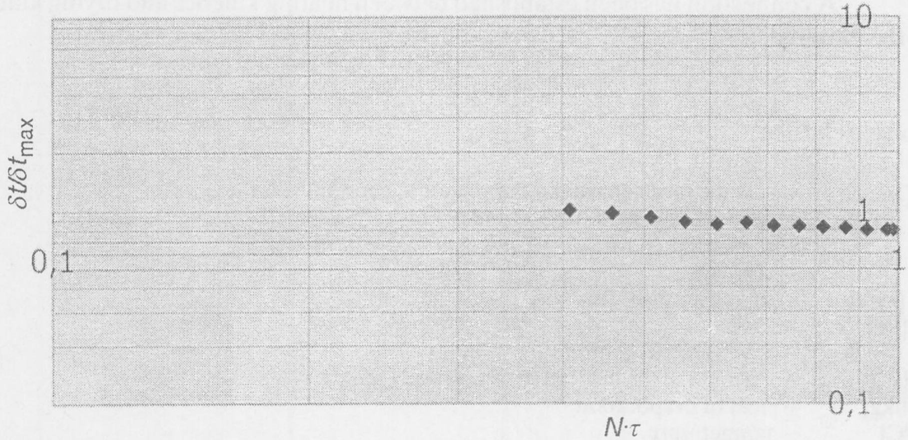

Figure 8. Relationship between drying rate and relative temperature drop for Experiment 10

Table 2

	1	2	3	4	5	6	7	8	9	10	11
A	0.35	0.47	0.35	0.48	0.40	0.37	0.37	0.30	0.40	0.30	0.37
n	0.732	0.696	0.756	0.712	0.714	1.00	0.773	0.206	0.314	0.185	0.418

As it can be seen the coefficient A varies in a comparatively small range 0.38±0.08. The deviation in A are due probably to the differences in material moisture, with which it enters the second drying period.

The exponent n for experiments № 1–7 (n_{mean} = 0.77) differs considerably from n for experiments № 8–11 (n_{mean} = 0.28). An explanation of that circumstance can be sought for in the difference between the atmospheric air parameters, utilized during the process of drying. Experiments № 8–11 have been carried out at an atmospheric air temperature of 15 °C and moisture content of 0.008 kg/kg, while the experiments № 1– 7 at temperature of 7.1 °C and moisture content of 0.0055 kg/kg. The higher energy consumption for heating the sucked atmospheric air leads to a lower rate of temperature growth of the drying agent before the bed t_B.

Conclusions

On the basis of the experimental data, a generalized drying curve for Sesame seeds has been built. An equation has been deduced, that describes the generilized drying curve.

The drying kinetics has been bound by the drying process balance task parameters.

A connection has been established between heating kinetics and drying kinetics of the material.

Nomenclature

c_v [J/kgK]	– specific heat capacity of the wet air at constant volume
d	– air humidity, kg water/kg humid air
h	– re-circulation rate ($h = L_C/L_A$)
k	– constant
L [kg/s]	– drying air mass flowrate
m [kg]	– mass
n	– rate of re-circulation
N [s^{-1}]	– drying rate for the first drying period ($-du/d\tau = N$)
r [J/kg]	– heat of evaporation
t [°C]	– temperature
u [kg/kg]	– water content
$\Delta U'$ [kg/s]	– evaporated water
v [m^3/kg]	– specific volume

Greek symbols

α [W/m^{2}K] – heat transfer coefficient
δ – difference
ρ [kg/m^3] – density
τ [s] – drying time
θ [°C] – temperature of the material
ψ – relative drying rate ($1/N \cdot du/d\tau$)

Subscripts

i – initial
0 – absolutely dry material

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