EVALUATING THE EFFICIENCY OF DRYING WITH VARIOUS MEANS OF ENERGY SUPPLY

L. M. Boikov

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We present results from experimental research into the drying of cardboard roofing material under various forms of energy input. We have undertaken a comparative analysis of various means of drying in terms of energy efficiency. We have demonstrated the usefulness of an expanded industrial application of the convective method of energy supply in the drying of fiber strand materials.

For the continuous drying of cellulose, paper, and cardboard, contact drying installations have presently gained the greatest acceptance, with the heat in such devices transferred directly from the heated cylinder surfaces to the moist material. However, the development of contact drying installations dictated by the effort to increase productivity led to a situation in which contemporary design of paper- and cardboard-making machinery are excessively complex and require the use of an excessive amount of metal. Operational experience in the use of this machinery demonstrates that the contact drying installation design is less than optimum and associated with extensive energy consumption. In this connection, projects have recently been undertaken to find other methods of drying fiber strand materials.

Results are presented in [1-8] from studies into the drying kinetics of cardboard roofing material with various means of energy supply: contact, convective, radiation, radiation-convective, and filtration. Comparative analysis of the kinetic characteristics (Figs. 1 and 2) makes it possible qualitatively and quantitatively to estimate the efficiency of each drying method. The slowest moisture-evaporation process is noted in the contact and convective means of energy supply, while the accelerated process of thermal fabric desiccation is characteristic of radiation-convective and filtration drying.

In order to evaluate drying efficiency for the various methods of energy influx, we need coefficients which would be identically valid for each drying method, regardless of the energy-supply scheme. We know [9] that in order to evaluate the thermal efficiency of various convective heat-exchange surfaces we resort to the energy factor $\varepsilon = Q/N$, which represents the quantity of transferred heat, referred to the energy expended on overcoming resistance. The higher ε, the more efficient the heating surface from the standpoint of energy. However, this method is unsuited to a comparison of the efficiencies of various drying methods. The efficiency of the drying process is defined by two indices: the total specific rate of energy flow expended on drying and the average intensity of the process.

The total specific rate of energy flow $Э_\Sigma$ expended on the drying is composed of the expenditures of energy in the form of heat $Э_h$ and electrical energy $Э_N$:

$$Э_\Sigma = Э_h + Э_N, \ \text{kW/kg of moisture}$$

As a universal characteristic for purposes of comparing the various drying methods we proposed the utilization of the drying energy efficiency factor (DEEF), which is made up of the total expenditures of energy referred to a unit of dried fabric surface:

$$E = Э_\Sigma (\overline{m\tau})_\Sigma, \ \text{kW/m}^2 \tag{1}$$

The DEEF, after removal of 1 kg of moisture by evaporation:

$$E_0 = E/P_{df}(U_0 - U_2), \ \text{kW/kg of moisture}$$

The lower the coefficients E and E_0, the lower the energy expenditures on drying and the more effective the given method. Calculations demonstrated that E falls within a range of 0.27-1.11 kW/m^2, while E_0 = 0.52-2.12 kW/kg of moisture. Higher values are characteristic of contact drying, while lower values are characteristic of convective and radiation-convective heat supply (Table 1).

For filtration drying (E = 0.33 kW/m^2 and E_0 = 0.64 kW/kg of moisture) we require the use of special perforated (honeycombed) cylinders and, consequently, the design of the drying installation is made considerably more complex. Moreover, the filtration drying method is used for a markedly limited range of fiber materials, most specifically for sanitary-hygienic paper.

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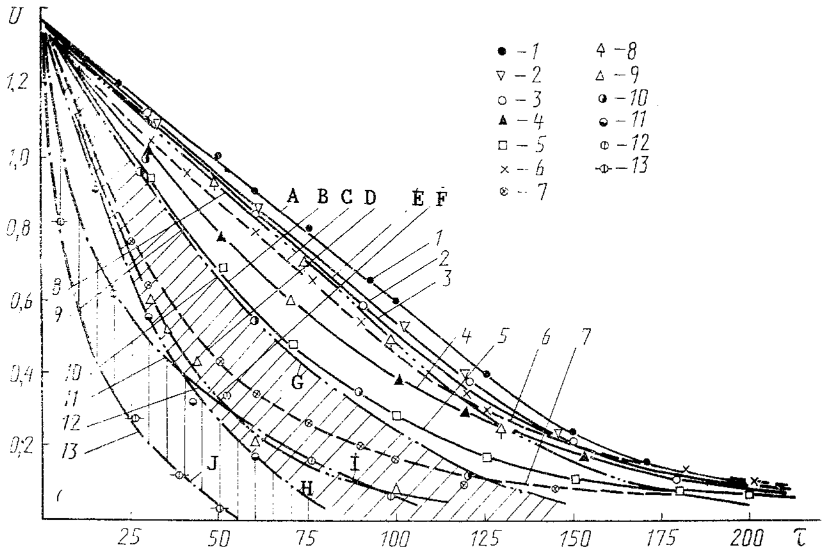

Fig. 1. Kinetics of drying cardboard roofing material with various methods of energy supply: 1-5) contact drying at the Kiev Cardboard-Making Machinery [CMM] Combine "Stroiindustriya," the K-2 type CMM of the No. 1 Krasnodar Combine "Stroimaterialy," the "Kartontol'" CMM of the Leningrad factory, the K-3M and K-2M type CMM of the Ryazan' cardboard—ruberoid factory [CRF]; 6, 7) convective drying of cardboard, repsectively, at t_a = 120°C, v_a = 5 m/sec and t_a = 160°C, v_a = 15 m/sec; 8, 9) radiation drying of cardboard at t_{rad} = 400 and 500°C; 10, 11) radiation-convective drying of material at t_{rad} = 300°C, v_a = 15 m/sec, t_a = 100 and 160°C; 12, 13) filtration drying of cardboard roofing material at ΔP = 2.5 kPa, t_a = 20 and 100°C. Drying: A—B, C—D, E—F, G—H, I—J) contact, convective, radiative, radiative-convective, filtration. Research results at positions 6-13 were obtained under laboratory conditions. τ, sec.

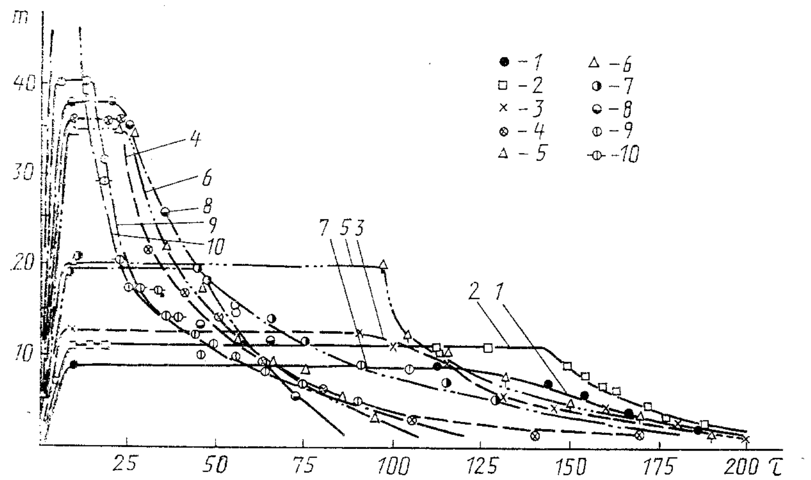

Fig. 2. Intensity of drying cardboard roofing material with various means of energy supply: 1, 2) contact drying of cardboard on CMM of the Kiev Combine "Stroiindustriya," and on the K-2M type CMM of the Ryazan' CRF; 3, 4) convective drying of cardboard at t_a = 120°C, v_a = 5 m/sec, and t_a = 160°C, v_a = 15 m/sec; 5, 6) radiation drying at t_{rad} = 400 and 500°C; 7, 8) radiation-convective drying at t_{rad} = 300°C, v_a = 15 m/sec, t_a = 100 and 160°C; 9, 10) filtration drying at ΔP = 2.5 kPa, t_a = 20 and 100°C. m, kg/(m^2·h).

Radiation-convective drying can take place at low DEEF (E = 0.30-0.33 kW/m^2 and E_0 = 0.57-0.63 kW/kg of moisture) only when use is made of a radiator with a temperature in excess of 400°C, which is an unacceptable solution from the standpoint of fire safety. Moreover, the design of the drying installation is significantly more complex.

Thus, from the standpoint of energy consumption the convective drying method is the most promising, since it is characterized by insignificant expenditures of energy E = 0.27-0.29 kW/m^2 and E_0 = 0.52-0.56 kW/kg of moisture, by low values for the total

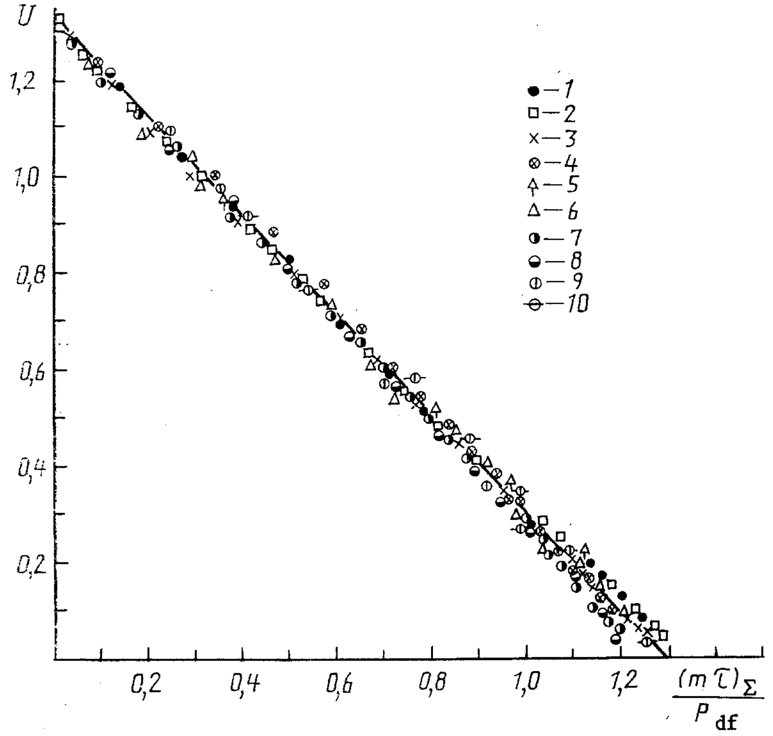

Fig. 3. Generalized characteristic for the drying of cardboard roofing material with various means of energy supply and in a variety of regimes; drying: 1, 2) contact drying on CMM of the Kiev Combined "Stroiindustriya" and the CRF factory at Ryazan'; 3, 4) convective drying at t_a = 120°C, v_a = 5 m/sec, and t_a = 160°C, v_a = 15 m/sec; 5, 6) radiation drying at t_{rad} = 400 and 500°C; 7, 8) radiation-convection drying at t_{rad} = 300°C, v_a = 15 m/sec, and t_a = 100 and 160°C; 9, 10) filtration drying at ΔP = 2.6 kPa, t_a = 20 and 100°C; $U = U_0 - 1.033(\overline{m\tau})_\Sigma/P_{df}\cdot U$; $(m\tau)_\Sigma/P_{df}$, kg/kg.

TABLE 1. Efficiency of Drying A-420 Cardboard Roofing Material with Various Methods of Energy Supply

Drying characteristic	Cardboard roofing material drying method								
	Contact	Convective drying at t_a and v_a		Radiation drying at t_{rad}		Radiation-convective drying at t_{rad} = 300°C, v_a = 15 m/sec; t_a		Filtration drying at ΔP = 2.5 kPa and t_a	
	K-2M type CMM	120°C, 5 m·sec^{-1}	160°C, 15 m·sec^{-1}	400°C	500°C	100°C	160°C	20°C	100°C
$\overline{m}\cdot 10^3$, $\frac{\text{kg of moisture}}{\text{m}^2\cdot\text{sec}}$	2,7	2,4	3,4	3,5	4,4	2,9	5,6	3,6	5,2
Q_d, kW	2154	1960	2736	2822	3576	2326	4529	2908	4200
q_N, $\frac{\text{kW}}{\text{kg of moisture}}$	37,8	10,4	14,7	15,6	28,1	12,5	24,4	15,7	22,5
q_h; $\frac{\text{kW}}{\text{m}^2}$	20,2	1,2	2,3	8,1	14,7	5,1	6,3	—	1,2
τ, sec	195	195	140	195	105	175	85	115	115
$Э_\Sigma$, $\frac{\text{kW}}{\text{kg of moisture}}$	2,14	0,58	0,62	0,85	0,82	0,66	0,63	0,24	0,54
E, $\frac{\text{kW}}{\text{m}^2}$	1,11	0,27	0,29	0,58	0,38	0,33	0,30	0,12	0,33
E_o, $\frac{\text{kW}}{\text{kg of moisture}}$	2,12	0,52	0,56	1,10	0,73	0,63	0,57	0,23	0,64
m_m, $\frac{\text{kg of metal}}{\text{kg of moisture}}$	887	172	171	93	136	286	305	1125	767
K	1,00	0,19	0,19	0,11	0,15	0,32	0,34	1,26	0,85
$(\overline{m\tau})_\Sigma$, $\frac{\text{kg of moisture}}{\text{m}^2}$	0,52	0,46	0,47	0,68	0,47	0,50	0,48	0,49	0,60

specific energy expended on evaporation of 1 kg of moisture $Э_\Sigma = 0.58\text{-}0.62$ kW/kg of moisture and since it takes place at intensive specific moisture removal $(\bar{m}\tau)_\Sigma = 0.46\text{-}0.47$ kg of moisture/m^2.

The calculations which we have carried out demonstrated that the amount of metal used in the convective installation is smaller by a factor of 4-5 than the contact-type unit.

Qualitative indices for the material being dried depend in considerable measure on the methods and regimes of drying. Experimental research [7, 8] leads to the conclusion that the qualitative characteristics of the cardboard roofing material in the case of a convective energy supply are higher than those in the case of the contact method.

The convective drying method which is characterized by low expenditures of energy, limited use of metal, and improved qualitative indices for the cardboard roofing material can thus be recommended as the basic method to be used in this branch.

The coefficients E and E_0 depend significantly on the average intensity of the drying process, while on the other hand the moisture content of the material is also dependent on the intensity of the process. Moreover, drying intensity is associated with the design characteristics of the drying unit. Thus, drying intensity serves as a universal criterion with which to evaluate the effectiveness of any drying method.

In processing the kinetic curves for the drying processes we can generalize all of the experimental data with a single drying characteristic for various means of energy supply and for various thermal regimes (Fig. 3). The resulting graphic relationship is well approximated by an equation of the form

$$U = U_0 - \beta \frac{(\overline{m\tau})_\Sigma}{P_{df}} . \tag{2}$$

The value of the complex $(\bar{m}\tau)_\Sigma$ is determined graphoanalytically with the aid of Fig. 2.

The familiar function $\varepsilon = Q/N$ does not allow us to choose an optimum drying-unit design nor to ascertain the efficiency and advantage of one drying method over another.

The duration of the drying process is comprised of the material heating time, the duration of the first and second drying periods:

$$\tau = \tau_h + \tau_1 + \tau_2' + \tau_2''.$$

In each period the intensity of drying varies and depends on the time of the process $m_i(\tau_i)$. On the whole, for any stage in the drying the average intensity of moisture vaporization from 1 m^2 of fabric is

$$\overline{m_i\tau_i} = \int_0^\tau m_i(\tau_i)\, d\tau_i, \ \text{kg of moisture/m}^2$$

The relationship $S_i = m_i(\tau_i)d\tau_i$ represents the area beneath the line of the drying process (Fig. 2). During the heating period this relationship is linear in nature: $m_h = 2a\tau$. Then

$$S_h = (\overline{m}_h\tau)_h = \int_0^{\tau_h} m_h\, d\tau = a\tau_h^2 .$$

In the first drying period the intensity is constant, as a consequence of which

$$S_1 = (\overline{m_1\tau_1})_\Sigma = m_{max}\int_0^{\tau_1} d\tau = m_{max}\tau_1.$$

Mathematical processing of the drying curves with the aid of a computer made it possible to find the approximate exponential relationships for the first and second intervals of the second period:

$$m_2' = Ae^{-B\tau_{21}}; \tag{3}$$

$$m_2'' = C\,e^{-D\tau_{22}}, \tag{4}$$

where A, B, C, and D are the experimental coefficients (Table 2).

The areas S_2' and S_2'' beneath the curves m_2' and m_2'' (Fig. 2) are obtained by integration of (3) and (4):

TABLE 2. Drying-Installation Design Data for Various Means of Energy Supply

Drying characteristic and recalculation factors	Drying method for cardboard roofing material A-420									
	K-2M CMM contact drying	Convective drying at t_a and v_a		Radiation drying at t_{rad}		Radiation-convective drying at t_{rad} = 300°C, v_a = 15 m/sec and t_a		Filtration drying at ΔP = 2.5 kPa and t_a	
		120°C, 5 m·sec^{-1}	160°C, 15 m·sec^{-1}	400°C	500°C	100°C	160°C	20°C	100°C
τ_h, sec	9,3	9,0	5,5	8,0	7,0	9,0	5,1	5,0	2,0
τ_1, sec	98,1	81,0	14,5	63,0	18,0	37,0	15,9	8,0	2,0
τ_2', sec	32,7	45,0	50,0	32,0	40,0	55,0	35,0	22,0	17,0
τ_2, sec	87,6	105,0	120,0	99,0	80,0	130,0	64,0	122,0	107,0
τ_d, sec	195,0	195,0	140,0	170,0	105,0	175,0	85,0	135,0	115,0
U_{k1}, kg/kg	0,49	0,49	0,88	0,53	0,82	0,72	0,80	0,86	0,77
m_1, $\frac{kg}{m^2 \cdot h}$	11,3	12,5	35,9	20,0	34,2	19,8	37,9	40,6	112,5

$$m_2' = A \cdot e^{-B\tau_2'}, \quad kg/m^2 \cdot h$$

A, $\frac{kg}{m^2 \cdot h}$	11,403	13,420	28,395	15,422	31,320	18,643	40,517	39,100	75,00
$B \cdot 10^2$	0,169	1,878	2,587	2,66	3,093	1,672	3,039	5,060	14,80

$$m_2'' = C \cdot e^{-D\tau_2''}, \quad kg/m^2 \cdot h$$

C, kg/m^2·h	11,611	5,361	7,548	6,415	10,965	9,013	20,643	14,624	19,04
$D \cdot 10^2$	2,764	1,613	2,053	1,690	4,268	2,077	9,110	2,182	20,83

$$S_\Sigma = (\overline{m}\tau)_\Sigma = a\tau_h^2 + B\tau_1 + c\,(1 - e^{-d\tau_2'}) + g\,(1 - e^{-f\tau_2''}), \ kg/m^2$$

$a \cdot 10^4$	1,680	1,928	9,066	3,694	6,333	3,437	9,600	11,277	156,25
$b \cdot 10^3$	3,139	3,472	9,972	5,555	9,500	5,550	10,530	11,280	31,25
$c \cdot 10$	1,873	1,985	3,049	1,610	2,813	3,097	3,704	2,147	1,39
$d \cdot 10^3$	1,692	1,878	2,587	2,6[illegible]0	3,093	1,672	3,039	5,060	14,98
$g \cdot 10^2$	0,117	9,232	10,213	10,5[illegible]0	7,136	12,060	6,290	18,620	25,38
$f \cdot 10^2$	2,764	1,613	2,053	1,690	4,268	2,077	9,110	2,182	2,83

$$S_2' = \overline{m}_2' \tau_2' = \frac{A}{B}\,(1 - e^{-B\tau_2'});$$

$$S_2'' = \overline{m}_2'' \tau_2'' = \frac{C}{D}\,(1 - e^{-D\tau_2''}).$$

The total area beneath the line of drying intensity is equal throughut the entire process to the sum of the mean specific intensities at each segment:

$$S_\Sigma = S_h + S_1 + S_2' + S_2'' = \overline{m}_h \tau_h + \overline{m}_1 \tau_1 + \overline{m}_2' \tau_2' + \overline{m}_2'' \tau_2''. \tag{5}$$

Expanding (5), we obtain a generalized equation for all instances of energy supply in finite form

$$S_\Sigma = (\overline{m}\tau)_\Sigma = a\tau_h^2 + b\tau_1 + c\,(1 - e^{-d\tau_2'}) + g\,(1 - e^{-f\tau_2''}), \tag{6}$$

where a, b, c, d, g, and f are experimental coefficients (Table 2).

Having jointly solved (2) and (5), we can derive the equation which links the moisture content of the material to the duration of the drying process. The results from the computer calculations demonstrated that system of equations (2)-(5) is in good agreement with the experimental kinetic curves for any drying method. The error does not exceed 1.5%.

Equations (2) and (5) allow us:

to make the transition from the description of one drying method to the description of another;

to find the average value of intensity for each period of drying and for the entire process as a whole;

to determine the thermal efficiency and advantages of one method of energy supply over another.

The transition from the description of one drying method to the description of another is accomplished analytically on the basis of an equation of the form

$$U_2 = U_1 - \beta \left[\left(\frac{(\bar{m}\tau)_\Sigma}{P_{df}} \right)_2 - \left(\frac{(\bar{m}\tau)_\Sigma}{P_{df}} \right)_1 \right],$$

where the subscripts 1 and 2 pertain to the first and second drying methods.

CONCLUSIONS

We have validated the effectiveness of convective energy supply, and this can be recommended for an extensive range of applications in drying technology. We have obtained graphic and analytical generalizing relationships which allow us to determine the effectiveness of any drying method.

NOTATION

ε, energy coefficient of convective heat exchange; Q, quantity of transmitted heat; N, expenditures of energy on overcoming resistance; $\ni_\Sigma$, total specific rate of energy flow expended on drying; $\ni_h$ and $\ni_N$, specific expenditures of energy in the form of heat and electrical energy; $\bar{m}$, mean intensity of the drying process; τ, duration of the process; $(\bar{m}\tau)_\Sigma$, total specific removal of moisture, referred to 1 m^2 of fabric; E and E_0, coefficients of drying efficiency, referred to 1 m^2 of fabric or to 1 kg of evaporated moisture; U_0 and U, initial and instantaneous moisture content in the material; P_{df}, mass of 1 m^2 of dry fabric; β, correction factor; τ_{df} and τ_1, duration of the process during the heating period and during the first drying period; τ_2' and τ_2'', duration of the process in the first and second intervals of the second drying period; m_i, instantaneous intensity of drying; τ_i, instantaneous time; S_i, area beneath the drying intensity line expressed in coordinates of intensity and time; A, B, C, D and a, b, c, d, g, f, experimental factors; S_h and S_1, areas beneath lines of process intensity during the heating period and in the first drying period; S_2' and S_2'', areas beneath the process intensity lines in the first and second intervals of the second drying period; S_Σ, total area beneath the entire drying intensity line from the onset of the process; CMM, cardboard-making machine; t_a and v_a, temperature and velocity of air; t_{rad}, radiator temperature; ΔP, pressure difference; Q_d, heat expended on drying; $\bar{v}$, mean drying rate; q_N, specific heat flux referred to 1 kg of moisture; q_h, specific heat flux; m_m, specific amount of metal consumed in the drying installation; $K = m_m/m_{con}$, relationship, in terms of metal consumption, for the given drying method relative to the contact method.

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