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HEAT AND MASS TRANSFER IN THE DRYING OF DISPERSE MATERIALS IN COCURRENT DRUM DRIERS

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Heat and mass transfer which accompanies the process of drying of disperse materials in cocurrent drum driers has been studied. The results of modeling of moisture removal from dried disperse material under the effect of a temperature field with account for the hydrodynamic situation in the drum drier allow one to run the process with minimum deviations of the final humidity and temperature of particles from specified values. A system of control over the drum driers, which considerably decreases the consumption of energy carriers and improves the efficiency of the equipment used, has been developed and implemented.

At present, drying of disperse materials is used in many convection-based technologies. The removal of moisture from dried particles under the effect of the temperature field produced by the heat carrier is characterized by a rather high consumption of electric energy and of gaseous, liquid, and solid fuels. Due to the continuous growth of the cost of energy carriers, the problem of their economical use and savings is pressing for all technologies without exception. Heat and mass transfer in the drying of different capillary-porous materials which have the shape of a sphere or allow its conventional adoption with the required level of adequacy can be described by the known system of differential equations [1, 2]

$$\frac{\partial T}{\partial \tau} = a_T \left(\frac{\partial^2 T}{\partial r^2} + \frac{\Phi}{r} \frac{\partial T}{\partial r} \right) + \varepsilon r_{\text{lat}} \frac{\partial U}{\partial \tau} \,, \tag{1}$$

$$\frac{\partial U}{\partial \tau} = a_{\text{m}} \left(\frac{\partial^2 U}{\partial r^2} + \frac{\Phi}{r} \frac{\partial U}{\partial r} \right) + a_{\text{m}} \delta_{\text{h.m.t}} \left(\frac{\partial^2 T}{\partial r^2} + \frac{\Phi}{r} \frac{\partial T}{\partial r} \right) . \tag{2}$$

The corresponding initial and boundary conditions, equations of material and thermal balance, and solutions of the system of equations of heat and moisture transfer in cocurrent motion of the heat carrier and processed particles under the conditions of ideal displacement for the periods of constant and decreasing rates of drying are given in [3], where the solutions obtained by the author are adequate for many technologies of drying of disperse materials. For them to be applicable to description of the technology of dehydration in drum-type apparatuses, it seems necessary to allow for the hydrodynamics of the process. The laws governing changes in the time of particle motion in a rotating cylindrical drum are adequately expressed by the following empirical relation:

$$\tau = \frac{2.076\,(kl)^{0.61} z_1^{0.34} d^{0.526}}{T_{\text{in}}^{0.425} \left[\dfrac{U_{\text{fin}}}{U_{\text{in}}\,(U_{\text{in}} - U_{\text{fin}})} \right]^{0.34} \left(\dfrac{f^2}{1800} \right)^{z_2} (\rho v)^{0.864} D^{z_3} \sin \beta^{z_4} \left(\dfrac{T_{\text{fin}} - 30}{T_{\text{in}} - T_{\text{fin}} + 10} \right)^{0.5}} \,. \tag{3}$$

In Eq. (3), the finite moisture content of the dried material is found from the formula

$$U_{\text{fin}} = a_0 + a_1 T_{\text{in}} + a_2 T_{\text{f.g}} + a_3 K_{\text{or}} + a_4 K_{\text{f}} + a_5 P_{\text{comb}} + a_6 P_{\text{mix}} + a_7 U_{\text{in}} + a_8 U_{\text{sur}} + a_9 T_{\text{sur}} + a_{10} T_{\text{atm}} +$$

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TABLE 1. Change in the Humidity Field of a Wood Particle

τ, sec	$r \cdot 10^{-3}$, m						U_{mean}, kg/kg
	0	0.8	1.6	2.4	3.2	4	
0	0.8	0.8	0.8	0.8	0.8	0.8	0.8
18	0.7518	0.7518	0.7517	0.7517	0.7517	0.7517	0.750158
78	0.6915	0.6915	0.6914	0.6914	0.6914	0.6913	0.686679
138	0.6312	0.6312	0.6311	0.631	0.631	0.6309	0.623769
198	0.5709	0.5709	0.5708	0.5707	0.5706	0.5706	0.561485
258	0.5107	0.5106	0.5105	0.5104	0.5103	0.5102	0.499804
318	0.4504	0.4503	0.4501	0.45	0.4499	0.4498	0.439106
378	0.3901	0.39	0.3898	0.3897	0.3896	0.3894	0.375498
438	0.3298	0.3297	0.3295	0.3293	0.3292	0.329	0.315292
474	0.2997	0.2995	0.2993	0.2992	0.299	0.2988	0.284148
570	0.2292	0.2289	0.2285	0.2282	0.2278	0.2274	0.215104
648	0.1765	0.176	0.1754	0.1749	0.1743	0.1738	0.163715
708	0.1372	0.1366	0.136	0.1354	0.1348	0.1342	0.125858
768	0.1079	0.074	0.1068	0.1062	0.1056	0.1049	0.097986
828	0.0861	0.0856	0.085	0.0845	0.0839	0.0833	0.0773891
888	0.0699	0.0694	0.0689	0.0684	0.0679	0.0674	0.0624091
948	0.0578	0.0573	0.0569	0.0565	0.056	0.0556	0.048311
1008	0.0487	0.0484	0.048	0.0476	0.0473	0.0469	0.0382533
1068	0.042	0.0417	0.0414	0.0411	0.0408	0.0405	0.038501
1128	0.037	0.0367	0.0365	0.0362	0.036	0.0357	0.0350294
1188	0.0332	0.033	0.0328	0.0326	0.0324	0.0322	0.0317858
1248	0.0305	0.0303	0.0301	0.03	0.0298	0.0296	0.0294492

$$+ a_{11}T_{in}^2 + a_{12}T_{f.g}^2 + a_{13}K_{or}^2 + a_{14}K_f^2 + a_{15}P_{comb}^2 + a_{16}P_{mix}^2 + a_{17}T_{in}T_{f.g} + a_{18}T_{in}K_{or} + a_{19}T_{in}K_f +$$

$$+ a_{20}T_{in}P_{comb} + a_{21}T_{in}P_{mix} + a_{22}T_{f.g}K_{or} + a_{23}T_{f.g}K_f + a_{24}T_{f.g}P_{comb} + a_{25}T_{f.g}P_{mix} + a_{26}K_{or}K_f +$$

$$+ a_{27}K_{or}P_{comb} + a_{28}K_{or}P_{mix} + a_{29}K_fP_{comb} + a_{30}K_fP_{mix} + a_{31}P_{comb}P_{mix} + a_{32}U_{in}^2 + a_{33}U_{sur}^2 + a_{34}T_{sur}^2 + a_{35}T_{atm}^2 . \quad (4)$$

The numerical values of the quantities P_{comb} and P_{mix} are determined by the degree of opening of air ducts. The closed position of the air ducts corresponds to the zero value of these parameters, while the fully opened position corresponds to unity.

The process terminates when the moisture content U_{mean}, integral-mean over the particle volume, corresponds to U_{fin}. In this case, for reasons of fire safety or special properties of the processed material, the volume-mean particle temperature at the end of the process must not exceed a value which is determined by the relation

$$T_{fin} = b_0 + b_1T_{in} + b_2T_{f.g} + b_3K_{or} + b_4K_f + b_5P_{comb} + b_6P_{mix} + b_7U_{in} + b_8U_{sur} + b_9T_{sur} + b_{10}T_{atm} +$$

$$+ b_{11}T_{in}^2 + b_{12}T_{f.g}^2 + b_{13}K_{or}^2 + b_{14}K_f^2 + b_{15}P_{comb}^2 + b_{16}P_{mix}^2 + b_{17}T_{in}T_{f.g} + b_{18}T_{in}K_{or} + b_{19}T_{in}K_f +$$

$$+ b_{20}T_{in}P_{comb} + b_{21}T_{in}P_{mix} + b_{22}T_{f.g}K_{or} + b_{23}T_{f.g}K_f + b_{24}T_{f.g}P_{comb} + b_{25}T_{f.g}P_{mix} + b_{26}K_{or}K_f +$$

$$+ b_{27}K_{or}P_{comb} + b_{28}K_{or}P_{mix} + b_{29}K_fP_{comb} + b_{30}K_fP_{mix} + b_{31}P_{comb}P_{mix} + b_{32}U_{in}^2 + b_{33}U_{sur}^2 + b_{34}T_{sur}^2 + b_{35}T_{atm}^2 . \quad (5)$$

TABLE 2. Change in the Temperature Field of Chips during the Drying

τ, sec	$r \cdot 10^{-3}$, m						T_{mean}, °C
	0	0.8	1.6	2.4	3.2	4	
0	20	20	20	20	20	20	20
48	33.89	33.99	34.08	34.18	34.29	34.39	32.96
108	48.57	48.75	48.93	49.12	49.31	49.5	48.4534
168	60.75	60.98	61.22	61.45	61.7	61.94	61.7351
228	70.85	71.11	71.38	71.64	71.91	72.19	75.0166
288	79.23	79.5	79.78	80.06	80.34	80.62	84.4838
348	86.18	86.45	86.73	87.01	87.29	87.57	92.0056
408	91.95	92.21	92.48	92.75	93.02	93.3	98.1334
468	96.73	96.98	97.24	97.49	97.75	98.01	103.186
498	99.8	99.05	99.3	99.55	99.79	100.04	105.541
528	100.7	100.93	101.17	101.41	101.65	101.89	107.346
588	103.99	104.21	104.43	104.65	104.87	105.09	110.788
648	106.72	106.92	107.12	107.32	107.52	107.72	113.629
708	108.98	109.16	109.34	109.53	109.71	109.89	115.976
768	110.86	111.02	111.19	111.35	111.51	111.67	117.917
828	112.42	112.56	112.71	112.85	113.0	113.14	119.521
888	113.71	113.84	113.97	114.1	114.23	114.35	120.849
948	114.78	114.9	115.01	115.12	115.24	115.35	121.944
1008	115.67	115.77	115.87	115.97	116.07	116.17	122.849
1068	116.41	116.5	116.59	116.67	116.76	116.85	123.601
1128	117.02	117.1	117.18	117.25	117.33	117.4	124.219
1188	117.53	117.6	117.66	117.73	117.8	117.86	124.732
1248	117.95	118.01	118.07	118.13	118.18	118.24	125.155

The coefficients a_i and b_i are found empirically by the active-experiment method and depend on the numerical values of the quantities U_{in}, U_{sur}, T_{sur}, and T_{atm}. To obtain specified values of U_{fin} and T_{fin} which provide high efficiency of the drying, the operating parameters T_{in}, $T_{f.g}$, K_{or}, K_f, P_{comb}, and P_{mix} are determined in the course of the optimization of functions (4) and (5). In this case, restrictions corresponding to a specific technology of drying and dependent on the individual properties of the dried material are imposed on the numerical values of these parameters.

In construction of the curves for different values of r, due to the small numerical difference between the values of the moisture content and the temperature relative to the values of these parameters there occurs imposition (convergence) of the graphs on each other, which makes it difficult to visually determine U and T in controlling the processes. Therefore, numerical examples of calculation of these equations for the process of drying of wood particles which have certain thermophysical characteristics are presented in Tables 1 and 2.

Thus, the results of determination of the laws governing the removal of moisture from disperse material under the effect of a temperature field (1) and (2) with account for the hydrodynamics of the drum apparatus (3) allow drying with minimum deviations of the final humidity and temperature of particles from specified values. A system of control over drums has been developed and implemented on the basis of these relations. The principle of the operation system is as follows. With objective change in the values of U_{in}, U_{sur}, T_{sur}, and T_{atm} the optimum values of the operating parameters T_{in}, $T_{f.g}$, K_{or}, K_f, P_{comb}, and P_{mix} are found and determined using this system. In controlling the process of drying of wood particles using this system of control, the deviation of the final moisture content of wood particles from the given value U_{fin} = 0.03 kg/kg was 0.001 kg/kg, whereas in traditional manual control over drying U_{fin} varied from 0.025 to 0.038 kg/kg. The final temperature of wood particles T_{fin} is the criterion of fire hazard. Due to its subjectivity, manual control of the process leads, more often at night, to ignition of the dried material. When the developed system of control was used, T_{fin} did not exceed a fire-safety level of 125^{o}C, which is stipulated by the properties of wood.

Use of the system allows one to stabilize the final humidity of the material dried, to guarantee the technologically required final temperature of the heat carrier, to substantially decrease the consumption of energy carriers, and to improve the efficiency of the equipment used, which is of utmost importance at present.

NOTATION

T, running temperature of a particle of dried material, ^{o}C; τ, running time of drying, sec; a_T, thermal diffusivity, m^2/sec; r, running radius, m; Φ, form factor; ε, criterion of phase transition; r_{lat}, latent heat of evaporation, J/kg; U, running moisture content of a particle of dried material, kg/kg; a_m, coefficient of diffusion of moisture, m^2/sec; $\delta_{h.m.t}$, coefficient of heat and moisture transfer, 1/deg; k, filling factor of the drum, %; l, drum length, m; z_1, z_2, z_3, and z_4, empirical coefficients; d, mean equivalent diameter of particles, m; T_{in} and T_{fin}, initial and final temperatures of the heat carrier, ^{o}C; U_{in} and U_{fin}, initial and final moisture contents of a particle, kg/kg; f, rotation frequency of the drum, 1/sec; ρ, density of the heat carrier, kg/m^3; v, velocity of the heat carrier, m/sec; D, drum diameter, m; β, slope angle of the drum to the horizon, ^{o}; a_i and b_i, coefficients of regression; $T_{f.g}$, temperature of the fuel gas in the furnace, ^{o}C; K_{or} and K_f, amount of the supplied original material and fuel, kg/sec; P_{comb} and P_{mix}, air flow rate in combustion and mixing of the fuel gas with air for obtaining a heat carrier of specified temperature, rel. units; U_{sur} and T_{sur}, moisture content and temperature of the air surrounding the drier, kg/kg and ^{o}C; T_{atm}, atmospheric-air temperature, ^{o}C; U_{mean} and T_{mean}, integral-mean moisture content and temperature of a particle, kg/kg and ^{o}C. Subscripts: lat, latent; m, moisture; h.m.t, heat and moisture transfer; in, initial; fin, final; i, ordinal number of the coefficient of regression, i = 0, ..., 35; f.g, fuel gas; or, original; f, fuel; comb, combustion; mix, mixing; sur, surrounding; atm, atmosphere; mean, integral-mean.

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