APPROXIMATE CALCULATION OF THE RATE AND THE TIME OF CONVECTIVE DESICCATION IN THE VARIABLE MODE

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A method is proposed for calculating the rate and the time of the convective desiccation process in parallel-flow and in counterflow apparatus, using the kinetic constants based on desiccation with a drying agent whose parameters remain constant. The theoretical principles and the experimental verification of this method are described.

Modern methods of calculating the rate and the time of convective desiccation as well as modern research concerning the attendant heat transfer encompass only those process modes where the parameters of the drying agent remain constant throughout [1-7].

In industrial convective continuous-operation apparatus, as a result of the heat transfer between dried material and drying agent, the parameters (temperature and humidity) of the drying agent vary. Therefore, the dried material inside the apparatus is in contact with a drying agent of variable parameters. This makes it difficult to extrapolate the test data obtained for a process with constant parameters to a process with variable parameters in actual desiccators.

This study is an extension of the earlier one [8] and an engineering method will be developed here for calculating the desiccation rate and time in parallel-flow and in counterflow convective apparatus, the results then being checked out experimentally.

The following assumptions are made for the derivation of formulas:

1. The desiccation process inside a drying chamber is almost adiabatic. The mean temperature of the drying agent and the mean moisture content in the material at any desiccator section are related approximately according to Eqs. (1)-(3) [8]:

for parallel flow

$$\frac{T_i - T}{T_i - T_f} = \theta, \tag{1}$$

for counterflow

$$\frac{T_i - T}{T_i - T_f} = 1-\theta, \tag{2}$$

$$\theta = \frac{u_i - u}{u_i - v_f}. \tag{3}$$

2. The desiccation process consists of two stages corresponding to two different ranges of the moisture content in the dried material: the first stage $u_{cr1} \le u \le u_i$ with the material at an approximately constant temperature and the second stage $u_e \le u \le u_{cr1}$ with the temperature of the material rising. The second stage generally breaks down into two periods: the first period when $u_{cr2} \le u \le u_{cr1}$ and the second period when $u_e \le u \le u_{cr2}$. There is no warmup period.

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3. The critical values of moisture content u_{cr1} and u_{cr2} do not depend on the process mode and remain the same for a given material, whether the parameters of the drying agent remain constant or vary.

4. The expressions for the relative desiccation rate at constant parameters of the drying agent are valid also when those parameters vary during the process, namely [4, 6]:

when $u_{cr1} \leq u \leq u_i$

$$\psi = 1, \tag{4}$$

when $u_{cr2} \leq u \leq u_{cr1}$

$$\psi = \frac{\frac{du}{d\tau}}{N} = -[1 - \chi_1(u_{cr1} - u)], \tag{5}$$

when $u_e \leq u \leq u_{cr2}$

$$\psi = \frac{\frac{du}{d\tau}}{N} = -\chi_2(u - u_e). \tag{6}$$

5. During the first stage of the process the desiccation rate depends on the parameters of the drying agent as follows [5]:

$$N = k(v\rho)^n (T - T_{\text{м}}). \tag{7}$$

6. The flow rate of the drying agent and the cross section of the apparatus are assumed constant. Changes in the mass flow rate of the drying agent due to evaporation of moisture from the dried material will be disregarded. The relative desiccation rate under conditions (4)-(6) with variable parameters of the drying agent is defined as the ratio of the desiccation rate at a given apparatus section to the desiccation rate during the first stage under external conditions corresponding to this apparatus section.

It must be noted that the choice of formulas (4)-(6) for the relative desiccation rate is dictated by the desire to obtain the simplest possible expressions for the desiccation rate and time when the parameters of the drying agent are variable. They contain the minimum number of constants to be determined by tests. The use of other formulas for the relative desiccation rate as those in [5], for example, leads generally to differential equations which are difficult to integrate.

A relation between the desiccation rate and the relative moisture content during the first stage of the process with variable parameters of the drying agent can be easily established on the basis of conditions (1)-(4) and (7):

for parallel flow

$$N = N_i[1 - (1 - \varepsilon)\theta], \tag{8}$$

for counterflow

$$N^* = N_i[\varepsilon + (1 - \varepsilon)\theta]. \tag{9}$$

Considering that $N = -du/d\tau$ and expressing u in terms of θ according to formula (3), we obtain equations which describe the desiccation rate during the first stage:

for parallel flow

$$\frac{d\theta}{d\tau_1} = \frac{N_i}{u_i - u_f}[1 - (1 - \varepsilon)\theta], \tag{10}$$

for counterflow

$$\frac{d\theta}{d\tau_1^*} = \frac{N_i}{u_i - u_f}[\varepsilon + (1 - \varepsilon)\theta]. \tag{11}$$

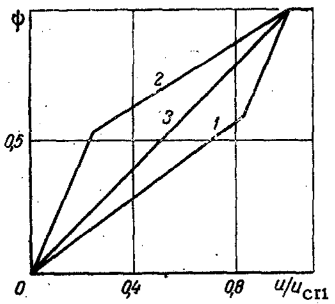

Fig. 1. Curves of relative desiccation rate: filter paper (1), asbestos sheet (2), lead chromate paste (3). Relative moisture content u/u_{cr1}.

In Eqs. (10), (11) ε denotes the utilization factor of the desiccation potential defined as the ratio:

$$\varepsilon = \frac{N_f}{N_i} = \frac{T_f - T_M}{T_i - T_M}. \tag{12}$$

Integrating (10) and (11), we obtain formulas for calculating the desiccation curve for the first stage of the process with variable parameters of the drying agent:

for parallel flow

$$\Pi_1 = \frac{\tau_1 N_i}{u_i - u_f} = \frac{2.3}{1-\varepsilon} \log\left[\frac{1}{1-(1-\varepsilon)\theta}\right], \tag{13}$$

for counterflow

$$\Pi_1^* = \frac{\tau_1^* N_i}{u_i - u_f} = \frac{2.3}{1-\varepsilon} \log\left[\frac{\varepsilon + (1-\varepsilon)\theta}{\varepsilon}\right]. \tag{14}$$

The length of the first stage will follow from (13) and (14) at $\theta = \theta_{cr1}$. The value of θ_{cr1} is calculated according to the formula

$$\theta_{cr1} = \frac{u_i - u_{cr1}}{u_i - u_f}. \tag{15}$$

In order to derive formulas for the desiccation rate and time in the first period of the second stage of the process, we will write condition (5) in new variables with u expressed in terms of θ according to formula (3):

$$(u_i - u_f)\frac{\frac{d\theta}{d\tau}}{N} = 1 - \chi_1^*(\theta - \theta_{cr1}). \tag{16}$$

Inserting expressions (8) and (9) for N into (16), we obtain a formula for the desiccation rate during the second stage of the process with variable parameters of the drying agent:

for parallel flow

$$\frac{d\theta}{d\tau_2} = \frac{N_i}{u_i - u_f}[1-(1-\varepsilon)\theta][1 - \chi_1^*(\theta - \theta_{cr1})], \tag{17}$$

for counterflow

$$\frac{d\theta}{d\tau_2^*} = \frac{N_i}{u_i - u_f}[\varepsilon + (1-\varepsilon)\theta][1 - \chi_1^*(\theta - \theta_{cr1})]. \tag{18}$$

Integrating (17) and (18), we obtain formulas (19) and (20) which will yield desiccation curves for the first period of the second stage with variable parameters of the drying agent:

for parallel flow

$$\Pi_2 = \frac{\tau_2 N_i}{u_i - u_f} = \frac{2.3}{\Delta_1} \log\left\{\left[\frac{1-(1-\varepsilon)\theta}{1-(1-\varepsilon)\theta_{cr1}}\right]\left[\frac{1}{1-\chi_1^*(\theta-\theta_{cr1})}\right]\right\}, \tag{19}$$

for counterflow

$$\Pi_2^* = \frac{\tau_2^* N_i}{u_i - u_f} = \frac{2.3}{\Delta_1^*} \log\left\{\left[\frac{\varepsilon + (1-\varepsilon)\theta}{\varepsilon + (1-\varepsilon)\theta_{cr1}}\right]\left[\frac{1}{1-\chi_1^*(\theta-\theta)_{cr1}}\right]\right\}. \tag{20}$$

The numerical values of Δ_1, Δ_1^*, and χ_1^* are calculated according to the formulas:

$$\Delta_1 = \chi_1^*[1-(1-\varepsilon)\theta_{cr1}] - (1-\varepsilon), \tag{21}$$

$$\Delta_1^* = \chi_1^*[\varepsilon + (1-\varepsilon)\theta_{cr1}] + (1-\varepsilon), \tag{22}$$

$$\chi_1^* = \chi_1(u_i - u_f) \tag{23}$$

TABLE 1. Constants for Calculating the Desiccation Rate and Time for Various Materials

Indicators	Asbestos sheet	Grade F-1 filter paper	Yellow lead chromate
Specimen dimensions, mm	50×100	67×83	100×100
Thickness, mm	1,5	20	20
Initial moisture content, kg/kg	0,6	1,8	1,0
First critical moisture level, kg/kg	0,32	1,1	0,2
Second critical moisture level, kg/kg	0,07	0,9	—
Rate coefficients:			
χ_1	1,8	2	4
χ_2	7,25	0,67	—
Desiccation modes:			
Blow rate, kg/m^2·sec	1,8	3,0	3,0
Process temperature, T° K	373—525	373—473	373—673

Formulas (19) and (20) are valid when Δ_1 and Δ_1^* are not equal to zero. The length of the first period of the second stage is easily determined from (19) and (20) by letting $\theta = \theta_{cr2}$, where θ_{cr2} is defined as follows:

$$\theta_{cr2} = \frac{u_i - u_{cr2}}{u_i - u_f}. \tag{24}$$

Analogously, from conditions (6), (8), and (9) we obtain formulas for the desiccation rate in the second period of the second stage with variable parameters of the drying agent:

for parallel flow

$$\frac{d\theta}{d\tau_3} = \frac{N_i}{u_i - u_f}\chi_2^*[1-(1-\varepsilon)\theta](k_1-\theta), \tag{25}$$

for counterflow

$$\frac{d\theta}{d\tau_3^*} = \frac{N_i}{u_i - u_f}\chi_2^*[\varepsilon+(1-\varepsilon)\theta](k_1-\theta). \tag{26}$$

Integrating (25) and (26), we obtain formulas which will yield desiccation curves for the second period of the second stage:

for parallel flow

$$\Pi_3 = \frac{\tau_3 N_i}{u_i - u_f} = \frac{2.3}{\Delta_2\chi_2^*}\log\left\{\left[\frac{1-(1-\varepsilon)\theta}{1-(1-\varepsilon)\theta_{cr2}}\right]\left[\frac{k_1-\theta_{cr2}}{k_1-\theta}\right]\right\}, \tag{27}$$

for counterflow

$$\Pi_3^* = \frac{\tau_3^* N_i}{u_i - u_f} = \frac{2.3}{\Delta_2^*\chi_2^*}\log\left\{\left[\frac{\varepsilon+(1-\varepsilon)\theta}{\varepsilon+(1-\varepsilon)\theta_{cr2}}\right]\left[\frac{k_1-\theta_{cr2}}{k_1-\theta}\right]\right\}. \tag{28}$$

The values of Δ_2, Δ_2^*, k_1, and χ_2^* are calculated according to the formulas:

$$\Delta_2 = 1 - k_1(1-\varepsilon), \tag{29}$$

$$\Delta_2^* = \varepsilon + k_1(1-\varepsilon), \tag{30}$$

$$k_1 = \frac{u_i - u_e}{u_i - u_f}, \tag{31}$$

$$\chi_2^* = \chi_2(u_i - u_f). \tag{32}$$

Formulas (27) and (28) are valid when Δ_2 and Δ_2^* are not equal to zero.

Thus, the derived formulas make it possible to plot a desiccation curve for the process with variable parameters of the drying agent: formula (13) or (14) for the interval $\theta_{cr1} \geq \theta \geq 0$, formula (19) or (20) for the interval $\theta_{cr2} \geq \theta \geq \theta_{cr1}$, and formula (27) or (28) for the interval $1 \geq \theta \geq \theta_{cr2}$.

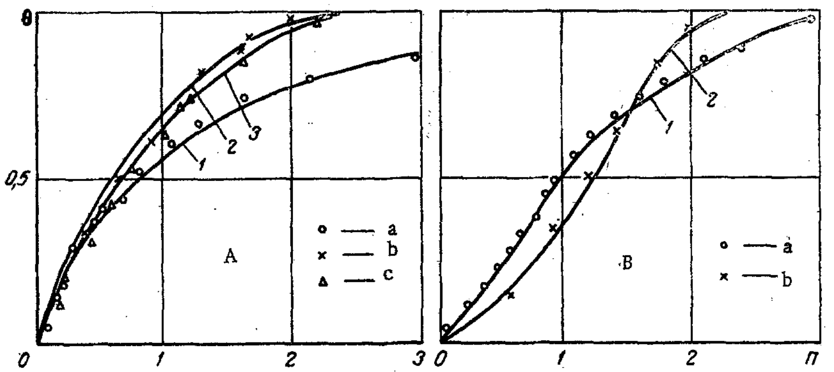

Fig. 2. Dimensionless desiccation curves. (A) Parallel flow: filter paper $T_i = 435°K$, $T_f = 373°K$, $T_M = 321°K$, $v\rho = 3.0\ kg/m^2 \cdot sec$ (1, a), asbestos sheet $T_i = 583°K$, $T_f = 373°K$, $T_M = 330°K$, $v\rho = 1.8\ kg/m^2 \cdot sec$ (2, b), yellow lead chromate $T_i = 598°K$, $T_f = 398°K$, $T_M = 331°K$, $v\rho = 3.0\ kg/m^2 \cdot sec$ (3, c). (B) Counterflow: filter paper $T_i = 473°K$, $T_f = 383°K$, $T_M = 321°K$, $v\rho = 3.0\ kg/m^2 \cdot sec$ (1, a), asbestos sheet $T_i = 505°K$, $T_f = 366°K$, $T_M = 324°K$, $v\rho = 1.8\ kg/m^2 \cdot sec$ (2, b). The solid curves are based on formulas (13), (14), (19), (20), (27), (28), the dots represent test points.

The total desiccation time within the interval $1 \geq \theta \geq \theta_{cr2}$ is calculated as follows:

for parallel flow

$$\Pi = \frac{\tau N_i}{u_i - u_f} = \frac{2.3}{1-\varepsilon} \log \left[\frac{1}{1-(1-\varepsilon)\theta_{cr1}}\right] + \frac{2.3}{\Delta_1} \log \left\{\left[\frac{1-(1-\varepsilon)\theta_{cr2}}{1-(1-\varepsilon)\theta_{cr1}}\right] \times \left[\frac{1}{1-\chi_1^*(\theta_{cr2}-\theta_{cr1})}\right]\right\} + \frac{2.3}{\Delta_2 \chi_2^*} \log \left\{\left[\frac{1-(1-\varepsilon)\theta}{1-(1-\varepsilon)\theta_{cr2}}\right]\left[\frac{k_1-\theta_{cr2}}{k_1-\theta}\right]\right\}, \tag{33}$$

for counterflow

$$\Pi^* = \frac{\tau^* N_i}{u_i - u_f} = \frac{2.3}{1-\varepsilon} \log \left[\frac{\varepsilon+(1-\varepsilon)\theta_{cr1}}{\varepsilon}\right] + \frac{2.3}{\Delta_1^*} \log \left\{\left[\frac{\varepsilon+(1-\varepsilon)\theta_{cr2}}{\varepsilon+(1-\varepsilon)\theta_{cr1}}\right] \times \left[\frac{1}{1-\chi_1^*(\theta_{cr2}-\theta_{cr1})}\right]\right\} + \frac{2.3}{\Delta_2^* \chi_2^*} \log \left\{\left[\frac{\varepsilon+(1-\varepsilon)\theta}{\varepsilon+(1-\varepsilon)\theta_{cr2}}\right]\left[\frac{k_1-\theta_{cr2}}{k_1-\theta}\right]\right\}. \tag{34}$$

The obtained formulas become much simpler when $u_{cr1} = u_{cr2}$, i.e., when $\theta_{cr1} = \theta_{cr2}$ and $\chi_1^* = \chi_2^*$.

The formulas were verified experimentally with various moist materials in various desiccation modes.

For specimens we selected asbestos sheets 1.5 mm thick, grade F-1 filter paper, and yellow lead chromate paste. All specimens were dried convectively on both sides in the laboratory apparatus which had been described earlier in [8].

In the first test series the specimens were dried with the parameters of the drying agent set at various values, in order to thus determine the basic kinetic constants χ_1, χ_2, u_{cr1}, and u_{cr2} needed for calculating the desiccation time with variable parameters of the drying agent.

In Fig. 1 is shown the relative desiccation rate for asbestos (curve 2), for yellow lead chromate (curve 3), and for filter paper (curve 1), plotted according to formulas (4), (5), and (6). The values of the basic constants were calculated from the desiccation curves for fixed parameters of the drying agent by the method which had been proposed in [4], and these values are shown in Table 1. The accuracy of the values obtained for χ_1 and χ_2 was checked by comparing the test curves with the calculated curves in the case of a drying agent with fixed parameters. The calculated values deviated from the test points by not more than 10%.

The functional relation, according to formula (7), between the desiccation rate and the parameters of the drying agent during the first stage of the process in the constant mode was verified experimentally for each material. The mass flow rate of drying agent was held constant for each material during desiccation with either fixed or variable parameters of the drying agent. This made it possible to determine the desiccation rate N_i, corresponding to the initial values of variable parameters of the drying agent, directly from the test data pertaining to the process with the parameters of the drying agent fixed.

The values of the kinetic constants describing the desiccation rate in the first and the second period of the second stage, as also the values of the critical moisture levels, were found to be independent of the process mode for each of the tested materials.

In the second test series similar specimens were dried in various parallel-flow and counterflow process modes. Desiccation with variable parameters of the drying agent was achieved by the method which we had proposed earlier in [8]: during an adiabatic desiccation of a stationary test specimen of moist material the temperature of the drying agent was varied automatically according to relation (1) in the parallel-flow mode and according to relation (2) in the counterflow mode by means of a special tracking system. The humidity of the drying agent was regulated with reference to the wet-bulb temperature, while the latter was held constant in any given test by addition of water vapor to the drying agent.

The desiccation curves in dimensionless coordinates $\Pi = f(\theta)$, which are shown in Fig. 2A, B for various process modes, have been calculated according to formulas (13), (14), (19), (20), (27), (28), and data from Table 1. The warmup period was eliminated for the comparison between calculated and measured values. The maximum deviation of test points from calculated values did not exceed ±12% and, evidently, depended on the kinetic constants used for the calculations.

For calculating the desiccation time in parallel-flow and in counterflow modes, therefore, one may use the kinetic constants which apply to the process with constant parameters of the drying agent and which can be easily determined in single tests with simple laboratory apparatus with those parameters held fixed.

NOTATION

u_i	is the initial moisture content, kg/kg;
u	is the instantaneous moisture content, kg/kg;
u_f	is the final moisture content, kg/kg;
u_e	is the equilibrium moisture content, kg/kg;
T_i	is the initial temperature of drying agent, °K;
T	is the instantaneous temperature of drying agent, °K;
T_f	is the final temperature of drying agent, °K;
u_{cr1}	is the first critical moisture level, kg/kg;
u_{cr2}	is the second critical moisture level, kg/kg;
ψ	is the relative desiccation rate;
N	is the desiccation rate during the first stage under constant ambient conditions, kg/kg·h;
χ_1, χ_2	are the relative desiccation coefficients for the first period and the second period respectively of the second stage;
v	is the linear velocity of the drying agent, m/sec;
ρ	is the density of the drying agent, kg/m^3;
T_M	is the wet-bulb temperature;
N_i, N_f	is the desiccation rate of moist material during the first stage, at the initial and the final temperature of the drying agent respectively, kg/kg·h;
ε	is the utilization factor of the drying agent;
$\Pi = \tau N_i/(u_i - u_f)$	is the dimensionless time parameter for parallel-flow desiccation;
$\Pi^* = \tau^* N_i/(u_i - u_f)$	is the dimensionless time parameter for counterflow desiccation;
τ_1	is the desiccation time during the first stage in parallel flow, h;
τ_1^*	is the desiccation time during the first stage in counterflow, h;
τ_2, τ_3	are the desiccation time in the first and the second period of the second stage in parallel flow, h;
τ_2^*, τ_3^*	are the desiccation time in the first and the second period of the second stage in counterflow, h;
θ	is the relative change in moisture content.

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