DRYING OF PEAT IN AN ATMOSPHERE OF SUPERHEATED STEAM UNDER PRESSURE

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Results are presented of experimental investigations into the high-temperature drying of lowland peat in an atmosphere of superheated steam under pressure. The influence on shrinkage, drying kinetics and the associated thermal decomposition of the peat of the parameters of the drying agents and the basic characteristics of the moist material is examined.

A significant number of papers has been devoted to the drying of various materials in an atmosphere of superheated steam. However, these investigations were carried out mainly at low superheats and at atmospheric pressure. Data on temperatures above 200° C and under pressure are practically nonexistent.

This paper examines the results of experiments on drying peat in an atmosphere of superheated steam under pressure conducted in the following intervals of variation of the parameters: temperature of medium from 150° to 450° C, pressure from 0.98×10^5 to 9.8×10^5 N/m^2, flow rate of drying agent from 0.49 to 1.2 m/sec. The majority of experiments was carried out on sedge peat with degree of decomposition 35–40% and initial moisture content 1.74–7.0 kg/kg. The sample was in the form of a briquet (basic dimensions $12 \times 6 \times 2.4$ cm) and the drying agent flowed around it parallel to the main surfaces. The initial hydraulic radius of the sample $R = 4V/F$ varied from 1.76 to 3.12 cm.

The experimental investigations were carried out on two identical test beds; the first bed was reserved for the investigation of drying at atmospheric pressure, the second (Fig. 1) at pressures up to 9.8×10^5 N/m^2.

For continuous recording of the weight of the sample during drying, a special asymmetrical balance was developed. The gravimetric apparatus was mounted in a separate compartment, which during the experiment was easily and hermetically connected to the drying compartment. The carriage with the sample was suspended from a rod fastened to the long arm of the balance beam. A counter-weight was moved along to the arm to establish equilibrium with the initial sample weight. On drying, equilibrium was disturbed and the rod rose. Movement of a mark on the rod was observed through a gauge glass with a reticule. The

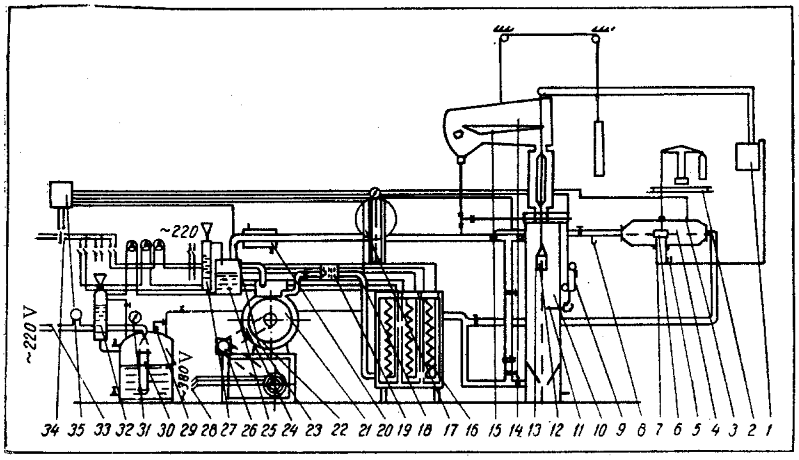

Fig. 1. Test setup for investigating drying under pressure. 1) EPP-09 automatic potentiometer for recording the temperature of the material; 2, 15) balances; 3, 11) thermocouples for regulation and measurement of temperature; 4) compartment for investigation of transfer potentials; 5, 8, 9, 31) manometers; 6, 12) samples; 7, 13) thermocouples for measurement of material temperature; 10) drying compartment; 14) device for measuring weight under pressure; 16) superheater; 17) differential manometer; 18, 23) thermocouples; 19) oil filter; 20) cooler; 21) pump; 22) electric motor; 24) boiler heater; 25) boiler; 26) pump gear box; 27, 32) devices for supplying water to the system under pressure; 28) high-pressure regulating boiler, 29) safety valve; 30) water heater; 33) electronic potentiometer for measuring and regulating temperatures in drying compartments; 34) magnetic boiler switch; 35) automatic magnetic system switch.

weight of the sample was recorded with an accuracy of up to 9.8×10^{-3} N (i.e., ~0.5%).

The procedure was as follows. The apparatus was warmed up to eliminate condensation of water vapor in the gravimetric apparatus and to attain normal operating temperature in the drying compartment. Then the system was repeatedly blown through with steam from the regulating boiler. After this, the drying compartment was isolated from the circulating system and the sample quickly introduced. At the same time, steam from the regulating boiler brought the pressure in the system to the normal operating level and the temperature to a value slightly lower than normal. Time measurements began from the moment the drying compartment was connected into the system. Normal operating temperature in the compartment was established in approximately 2 min (equalization of pressure was practically instantaneous). During the course of the experiment the temperature in the drying compartment was maintained correct to $\pm 0.05 \times 10^5$ N/m². Upon termination of the experiment the drying compartment was again isolated from the circulating system, the weight of the sample recorded, and the pressure slowly released. The gravimetric device was disconnected from the drying compartment at atmospheric pressure, and the sample, to prevent ignition, transferred to a vessel containing inert gas. After cooling, the weight, moisture content, and dimensions of the dried product were measured more accurately.

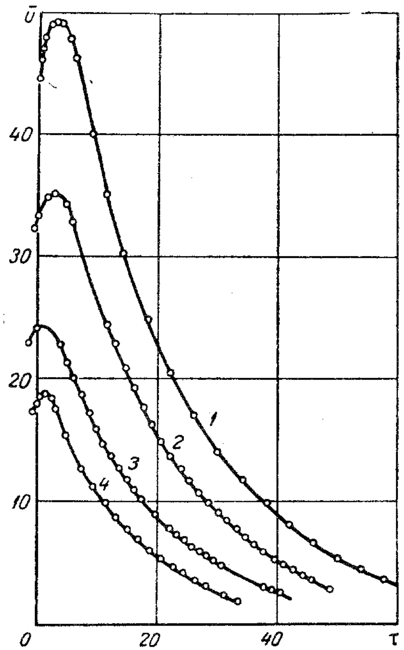

Fig. 2. Drying curves for warm-up period ($p = 4.49 \times 10^5$ N/m², $t_c = 250°$ C): 1) $\bar{u}_i$—4.39; 2) 3.24; 3) 2.29; 4) 1.75 kg/kg.

Investigation of the drying process included a study of the problems of shrinkage of peat, drying kinetics and the thermal decomposition of the peat during drying.

Investigations of the shrinkage showed that the change in the dimensions of the samples during high-temperature drying under pressure ceases to be linear. During drying and heat treatment peat changes its structure and properties [1, 2, 3], as a result of which the volume coefficient of shrinkage β_V usually used in the empirical relationship $V = V^{dry}(1 + \beta_V \bar{u})$ also changes. The same holds for the surface and linear coefficients of shrinkage. Therefore the further use of relations of this type has no particular advantage compared with the use of other types of relationship. For drying under pressure, when determination of the sample dimensions during drying is very difficult, it is more convenient to use values of the relative shrinkage, i.e., to express the change in volume in terms of the coefficient $\varkappa_V = V_i/V_f$, in surface in terms of $\varkappa_F = F_i/F_f$ and in linear dimensions in terms of $\varkappa_L = R_i/R_f$.

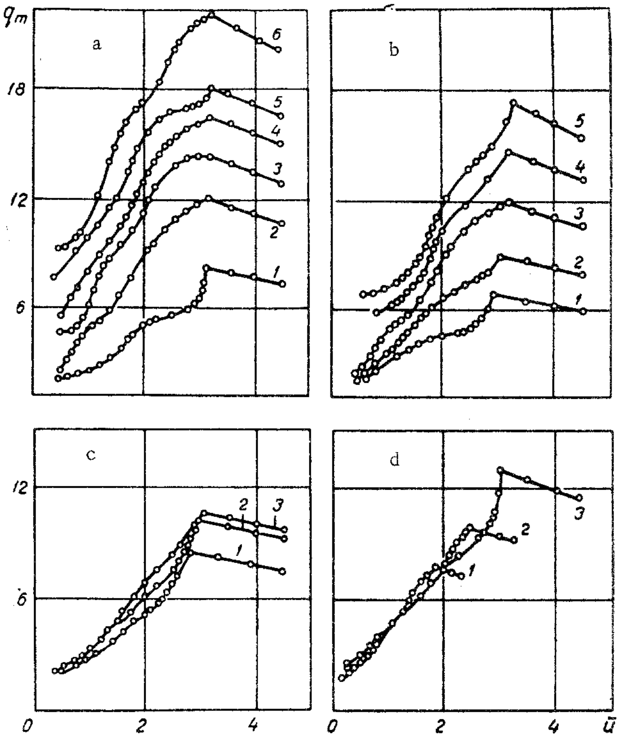

Fig. 3. Drying rate (kg/m²·hr) for peat in superheated steam as a function (a) of the temperature of the medium (1) 200; 2) 250; 3) 300; 4) 350; 5) 400; 6) 450° C) (b) of pressure (1) 0.98; 2) 2.94; 3) 4.90; 4) 6.86; 5) 8.82×10^5 N/m²); (c) of flow rate of drying agent (1) 0.49; 2) 0.86; 3) 1.06 m/sec); (d) of initial moisture content (1) 2.39; 2) 3.24; 3) 4.39 kg/kg).

The investigations carried out were used to determine the influence on the shrinkage of peat of the parameters of the superheated steam, the initial and final moisture contents of the peat, and its specific weight and initial dimensions. Thus, empirical relationships for the relative shrinkage of sedge peat can be represented by the equations

$$\varkappa_V = u_i^{*} u_f^{*} R^{*} t^{*} p^{*} w^{*} \gamma^{*} \tag{1}$$

$$\varkappa_F \quad u_i^{+} u_f^{+} R^{+} t^{+} p^{+} w^{+} \gamma^{+}. \tag{2}$$

Here

$$u_{\mathrm{i}}^{*} = 0.531 + 0.523\,\bar{u}_{\mathrm{i}};\quad u_{\mathrm{i}}^{+} = 0.92 + 0.22\,\bar{u}_{\mathrm{i}};$$
$$u_{f}^{*} = (100\,\bar{u}_{f})^{-0.403};\quad u_{f}^{+} = 2.88 - 0.71\ \lg 100\,\bar{u}_{f};$$
$$R^{*} = 1.70 + 2{,}12/R_{\mathrm{i}};\quad R^{+} = 2.13 - 0.09\,R_{\mathrm{i}};$$
$$t^{*} = 0.118 - 2.0\cdot 10^{-5}(t_{\mathrm{c}} - t_{\mathrm{s}});\quad t^{+} = 0.045 - 15\cdot 10^{-6}(t_{\mathrm{c}} - t_{\mathrm{s}});$$
$$p^{*} = 1.94 + 0.106\,p;\quad p^{+} = 1.70 + 0.03\,p;$$
$$w^{*} = 2.35 - 0.18\,w;\quad w^{+} = 1.87 - 0.16\,w;$$
$$\gamma^{*} = 3.74 - 1.19\cdot 10^{-4}\gamma_{\mathrm{i}};\quad \gamma^{+} = 2.01 - 0.143\cdot 10^{-4}\gamma_{\mathrm{i}}.$$

The deviation from the experimental data of the data calculated from (1) is 2.3%, and from (2) 1.4%.

Parameters connected with the material and the pressure of the medium have strongest influence on the shrinkage of peat. In relation to the final moisture content and sample dimensions, shrinkage is nonuniform. For example, the volume and surface of a sample for a final moisture content of 0.2–0.88 kg/kg change, respectively, 7.7 and 4.8 times more than for a moisture content of 2.2–4.5 kg/kg, and the change of volume at an hydraulic radius R = 1.76–1.84 cm is 2.6 times greater than at R = 2.24–2.84 cm. The temperature of the drying agent affects shrinkage only slightly and at atmospheric pressure has practically no influence in the investigated temperature range.

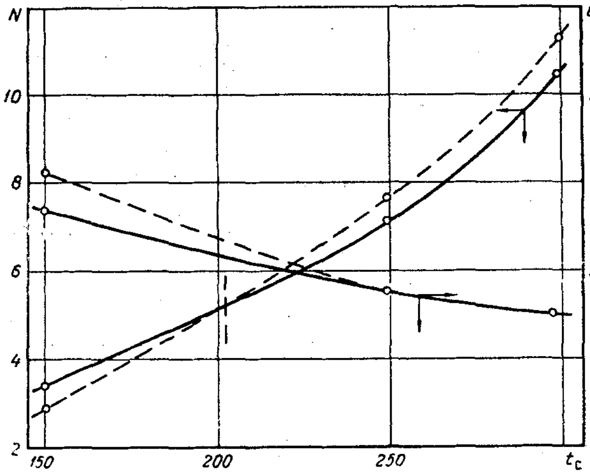

Fig. 4. Influence of temperature of drying agent on drying rate N, %/min and critical moisture content of peat ($\bar{u}_{c\lambda}$ kg/kg) in a superheated steam atmosphere (broken line) and in air (continuous line).

The coefficient of relative change of linear dimensions $\varkappa_L$ is expressed in terms of the coefficients $\varkappa_V$ and $\varkappa_F$ by the relation $\varkappa_L = \varkappa_V/\varkappa_F$. On the whole, the same parameters have a similar influence on $\varkappa_L$ and $\varkappa_V$. A number of authors have recorded relations between the shrinkage coefficients $\varkappa_L^{3} = \varkappa_F^{3/2} = \varkappa_V$, which, as shown by our investigations, hold only at atmospheric pressure and low drying agent temperatures.

Shrinkage during drying of peat in air is higher than during drying in superheated steam. At the same time, the ratio of the mean "temperature gradients" of relative shrinkage for the two drying agents $\left(\frac{\partial \varkappa_{V(F)}}{\partial t_c}\right)_{\text{steam}} : \left(\frac{\partial \varkappa_{V(F)}}{\partial t_c}\right)_{\text{air}}$ remains constant over the entire temperature interval investigated: for volume this ratio is equal to 0.82 and for surface, to 0.67. In a superheated steam atmosphere the peat, on the whole, dries more uniformly than in air atmosphere.

Experimental data on the drying kinetics of peat in superheated steam show that the overall character of drying does not differ significantly from drying in air and flue gases. There are three periods of drying: warm-up, constant drying rate and decreasing drying rate. The conclusion agrees with the findings of other authors.

The warm-up period, on the average, comprises 10% of the over-all drying time. The dependence of the duration of this period on the initial moisture content can be determined from the empirical equation

$$\tau_0 = -16.39 + 9.01\ \lg 100\bar{u}_{\mathrm{i}}. \tag{3}$$

A special feature of the warm-up period during drying in a superheated steam atmosphere is the presence of steam condensation and wetting of the sample (Fig. 2). From the very beginning of the process the mean moisture content of the sample increases and attains a maximum, which depends on the parameters of the drying agent and the characteristics of the material, after which it begins to decrease. Wetting of the sample lasts approximately half the warm-up period; this is far from corresponding with the results of the theoretical investigations of Van der Held [4]. The maximum moisture content of the peat during wetting, as a function of the initial moisture content, can be expressed by the relation

$$\bar{u}_{\max} = \bar{u}_{\mathrm{i}} + 0.0632\cdot 10^{0.205\bar{u}_{\mathrm{i}}}. \tag{4}$$

With increase in pressure, the duration of the warm-up period and the amount of wetting quickly increase. For example, an increase in pressure from 0.98×10^5 to 4.9×10^5 N/m^2 (t_c = 250° C) increases the warm-up period by a factor of 3.8, and the wetting of the peat by a factor of 12. An increase of temperature reduces these characteristics, and at t_c = 300° C ($p = 0.98 \times 10^5$ N/m^2) wetting is no longer observed. Analysis of the experimental data shows that, at a constant value of the initial moisture content, the amount of wetting is determined not by the temperature and pressure separately, but by a single characteristic, the superheat $t_c - t_s$. With increase in superheat the amount of wetting quickly decreases.

The next period of drying sets in mainly before the sample regains the initial moisture content (Fig. 2); however, the shift in moisture content does not exceed 4% and quickly decreases with decrease in $\bar{u}_i$. In the range of operating parameters investigated, the period of constant drying rate is clearly observed up to t_c = = 450° C. With increase in the temperature of the superheated steam, the drying rate increases; however, the most significant acceleration of drying is observed at low temperatures. Thus, increase in t_c from 200° to 300° C increases the drying rate by 171%, and from 300° to 400° C by 128% ($p = 4.9 \times 10^5$ N/m^2, $w = 0.82$ m/sec, $\bar{u}_{i1} = 4.18$ kg/kg). On the whole, the drying rate depends on the temperature of the atmosphere to the power 1.22. Increase in pressure also leads to increase in drying in the form of the relationship $N = N(p)$ for $p > 3.9 \times 10^5$ N/m^2 being linear. The influence of the individual factors on the drying rate, with an accuracy of up to 5%, can be approximated by the expression

$$N = 0.3917\,(t_c - t_s)^{0.592} w^{0.429}\,\bar{u}_{i1}^{1.435} \exp(0.147\,p)/R^{1.994}. \quad (5)$$

Preliminary heat treatment of the peat in a liquid or saturated-vapor medium decreases the initial moisture content of the material, which in turn leads to reduction in the duration of drying. Thus, samples obtained from a peat mass after heat treatment and mechanical dehydration have drying times, respectively, 22% ($t_{ht} = 200°$ C) and 41% ($t_{ht} = 250°$ C) less than samples from mechanically dehydrated but thermally untreated peat.

With increase of treatment temperature, the relative length of the period of constant drying rate increases and the first critical moisture content is displaced toward lower moisture contents, although the absolute value of the drying rate decreases.

For the investigated parameters, the intensity of drying lay in the range 6–24 kg/m^2·hr (Fig. 3), which significantly exceeds the intensity of convective drying for similar samples using the usual conditions. The drying intensity curves differ in character from the familiar curves: in the period of constant drying rate the intensity of drying increases linearly with decrease in moisture content and attains a maximum at the first critical point. The new character of the relationship can be explained by incomplete allowance for the surface of evaporation in accordance with the shrinkage data. In fact, since, according to experiments, N = const, and the dry mass B^{dry} in this period decreases only slightly (~1%), the increase in intensity of drying ($q_{ml} = B^{dry} N/100F$) is determined only by the decrease in the surface area of the sample F due to shrinkage. General physical considerations also show that the intensity of mass transfer to the medium in this period is determined mainly by the capacity of the drying agent to take up evaporated water: if the operating parameters are constant this capacity does not decrease, i.e., the drying rate must be constant. Consistency with theory can be maintained by assuming that decrease in the observed geometrical surface area of the sample due to shrinkage is compensated by increase in the internal surface of evaporation due to extension of evaporation into the bulk of the material.

Comparison of the results of drying peat in air and superheated steam show that at low temperatures drying in air is more intense, at $t_c = 200°$ C ($p = 0.98 \times 10^5$ N/m^2) the rates are comparable, and, subsequently, the drying rate in steam begins more and more to exceed the drying rate in air (Fig. 4). It is necessary to point out that drying in air at temperatures above 200° C is very difficult on account of ignition of the peat, in a superheated steam atmosphere such ignition was not observed even at $t_c = 500°$ C. At drying-agent temperatures up to 200° C the critical moisture contents of peat in an air atmosphere are lower; however, even at temperatures around 200° C they are comparable, and subsequently practically the same. Thus, with increase in temperature, and especially pressure, the advantages of superheated steam over air become significant.

The value of the critical moisture content working the transition from the period of constant to the period of decreasing drying rate can be approximated by the equation

$$\bar{u}_{cr} = 0.888\,\Delta t^* p^* w^* \frac{u^*}{R^{0.0852}}, \quad (6)$$

where

$$\Delta t^* = (t_c - t_s)/[7 + 3.06\,(t_c - t_s)]; \quad u^* = \bar{u}_i/(0.98 + 0.11\bar{u}_i);$$
$$w^* = 908 + 84w; \; p^* = 1.02p/(29 + 313p).$$

For a definite thickness and initial moisture content of the peat, the critical moisture content is a linear function of the intensity drying rate in the period of constant drying rate. For example, at $\bar{u}_i = 4.5$ kg/kg and R = 2.84 cm this relation, with an accuracy of 2.1%, is given by

$$\bar{u}_{cr} = 2.73 + 0.0274N.$$

We note that on the basis of investigations of sand dried in a superheated steam atmosphere the same conclusions were reached by L. Wenzel and R. White [5].

Dependence of Intensity of Drying on the Parameters of the Process

Gradient	Interval of variation of parameter	Period of drying			
		Constant	Decreasing		
		$\bar{u}=4.0$ kg/kg	$\bar{u}=2.5$	$\bar{u}=2.0$	$\bar{u}=1.0$
$\frac{\Delta d\bar{u}/d\tau}{\Delta t_c}$	200—250 °C	0.078	0.096	0.072	0.034
	300—350 °C	0.040	0.030	0.044	0.030
$\frac{\Delta d\bar{u}/d\tau}{\Delta p}$	$(0.98 \div 2.94) \cdot 10^5$ N/m^2	0.77	0.83	0.60	0.13
	$(4.90 \div 6.86) \cdot 10^5$ N/m^2	0.99	0.50	0.43	0.30

Beyond the critical moisture content a sharp decrease in drying rate is observed. The period of decreasing drying rate is nonuniform.

In connection with the preferential expulsion from the material of water with a particular form of binding energy, the drying intensity curves show several points of inflection (Fig. 3). The influence of the individual parameters on the intensity of drying in this period, in comparison with the period of constant drying rate, is much the same. However, the relation between the change in rate or intensity of drying per unit change of temperature, pressure, and other parameters, as follows from the table, is different. The data presented show that the most rapid change of the mean gradients, relative to the operating parameters, is observed at the very beginning of the period. For example, in the temperature intervals of 200°–250° C and pressure $0.98–4.9 \times 10^5$ N/m^2, the values of the mean gradients are higher than the values of the corresponding gradients for the period of constant drying rate. With increase in temperature and pressure these gradients decrease, and their values for different intervals of change of moisture content converge.

A peculiarity of the high-temperature drying of moist substances of organic origin in general, and the drying of peat in superheated steam in particular, is decomposition of the dry mass. In contrast to the period of constant drying rate, where this process in the range of operating parameters investigated seems unimportant, thermal decomposition of peat in the period of decreasing rate of drying can be significant. Thus, at $t_c = 450°$ C the thermal degradation is about 20% of the dry mass. It should be noted that, together with temperature and pressure, at high flow rates of drying agent an important role in the loss of dry mass begins to be played by crumbling of the overdried surface of the peat, which becomes particularly significant in countercurrent drying of small peat particles [6].

Comparison of the loss of dry mass upon drying peat in air and steam shows that, in the first case, this loss is more significant on account of smoldering and even ignition of the peat. Whereas for drying in air at $t_c = 180°$ C it comprises 5.5%, for drying in superheated steam such losses of dry mass are incurred only at 300° C.

Analysis of experimental data on the thermal decomposition of sedge peat yields the following formula for calculating the loss of dry mass:

$$\alpha^{\mathrm{dry}} = 100\,\frac{B_{\mathrm{i}}^{\mathrm{dry}} - B_{\mathrm{i}}^{\mathrm{dry}}}{B_{\mathrm{i}}^{\mathrm{dry}}} = 0.33 + 0.00264\,w \exp(-2.66\bar{u}_f) \times \times p^* t^* u^* R^* \gamma^*. \tag{7}$$

Here

$$p^* = 0.96 + 1.30p;\quad R^* = 7.8 - 0.485R;$$
$$t^* = -8.9 + 0.065t_c;\quad \gamma^* = -9.1 + 15.1\cdot 10^{-4}\gamma_{\mathrm{i}};$$
$$u^* = 20.6 - 4.07\bar{u}_{\mathrm{i}}.$$

The complex nature of the drying rate curve in the third period prompts the use in approximate kinetics calculations of suitably selected straight lines. The slope of these lines determines the drying coefficient. Analytical treatment of the empirical data allows the drying coefficient to be expressed in terms of the individual parameters:

$$K = 127\,(t_c - t_s)^{0.673} p^+ w^+ u^+ R^+ \gamma^+, \tag{8}$$

where

$$p^+ = 5.9\cdot 10^{-4} + 2.86\cdot 10^{-4}p;\quad w^+ = 0.601 + 0.384\,w;$$
$$u^+ = -0.0618 + 0.0421\,\lg(100\bar{u}_{\mathrm{i}});$$
$$\gamma^+ = 0.0771 - 0.0342\cdot 10^{-4}\gamma_{\mathrm{i}};$$
$$R^+ = 0.150 - 0.244\,\lg R_{\mathrm{i}}.$$

Numerous investigations at low temperatures have shown that the drying coefficient is proportional to the rate of drying, i.e., $K = \chi N/100$. The dimensionless proportionality factor χ is called the relative drying coefficient. Our investigations show that this relation also holds for high-temperature operation. However, for a given initial state of the peat, legitimate approximation of all the operating parameters by one straight line is possible only over a reasonable interval of variation. This observation relates primarily to the flow rate of drying agent and, to a somewhat lesser degree, to the pressure.

Having numerical values of N, K (and hence χ) and $\bar{u}_{\mathrm{cr}}$ it is easy to calculate the over-all drying time for moist material in a superheated steam atmosphere. The necessary relations for the individual drying periods are determined in the usual way [7]. The over-all drying time $\tau = \tau_0 + \tau_1 + \tau_2$ can be determined from the equation

$$\tau = \tau_0 + (100/N)\left[\bar{u}_{\mathrm{i}} - \frac{1}{\chi}\,(1 + 2.3\,\lg \chi\,\bar{u}_{\mathrm{cr}})\right], \tag{9}$$

where τ_0 is the duration of the warm-up period, which for approximate calculations can be estimated from (3).

NOTATION

τ) time; t) temperature; p) pressure; W) flow rate of drying agent; R) hydraulic radius; F) surface area of sample; V) volume of sample; B) mass of sample; $\bar{u}$) moisture content; γ) specific weight; N) drying rate; q_m) intensity of drying; K) drying coefficient; χ) relative drying coefficient; α^{dry}) coefficient of loss of dry mass; β_V) volume shrinkage coefficient; x) relative shrinkage coefficient. Indices: i and f) initial and final state, respectively; 1) period of constant drying rate; dry) dry mass; c) medium; s) saturated state; ht) heat treatment; cr) critical moisture content.

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