INTENSIFICATION OF DRYING PROCESS DURING ACTIVATED CARBON REGENERATION

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Abstract. Heat-mass exchange processes during regenerated activated carbon drying was studied to determine the minimum height of heat-mass exchange zone and termination time of hot heating agent supply based on criterion equations and heat balance calculations. The heating agent temperature changes with time and the adsorbent bed height, as well as the time of moisture content change and drying rate were studied experimentally. Minimum height of a wet material layer ensuring rational use of the heating agent was determined. Heat amount which can be saved and amount of the energy accumulated by a part of the adsorbent bed for further drying were calculated. Regeneration method allows to reduce the amount of consumed specific energy.

Keywords: adsorbent, drying, cooling, temperature regime, heat energy, heat-mass transfer zone.

1. Introduction

In chemical technology a considerable part of technological processes proceeds in a fixed bed of dispersed material. Such processes involve adsorption-desorption processes, which are widely used in chemical, food, pharmaceutical and other industries.

Adsorption plants with the fixed bed of adsorbent, working under a periodic mode sorption – desorption, are most widespread in industry. After a target product recovery the fixed bed of an adsorbent is subjected to regeneration.

Regeneration of the adsorbent can be carried out by steaming with saturated water vapor or by treatment with hot water [1-4]; by electrical [5] and electrochemical methods [6-9, 10, 11]; by microwave radiation [12, 13, 14]; by thermal [15, 16], chemical [15] or ultrasonic methods [17-19]; by means of catalyst addition [20]; by ultraviolet irradiation [21].

In consideration of the fact that much more energy is consumed by the adsorbent regeneration process compared to the adsorption process itself, theoretical and experimental studies of drying and cooling processes are very urgent.

In industry adsorbents are reusable materials. After adsorbent saturation with an adsorbate the process is discontinued and the adsorbent used is regenerated with the aim of removing the adsorbed components. Water steam or hot water with the temperature of 373 K are most often used as desorbing agents, and regeneration of the adsorbents without their consequent drying leads to a considerable decrease of their adsorption capacity. According to [22-24], the adsorbent regeneration consists of the following stages:

- – heating of the bed by hot air;
- – steaming of the bed by saturated water vapor;
- – drying of the adsorbent;
- – cooling of the adsorbent bed to 293 K.

It is stated in [23] that after finishing the adsorbent drying its adsorption capacity can become equal to the capacity of fresh adsorbent. Such phenomena depend on size of pores and capillaries and on the amount of moisture condensed in them.

S. Ukhanov *et al.* [24] state that activated carbon (AP-B and AG-3 grades) is dried within the temperature range of 423–473 K. The experimental results of drying the AG-3 adsorbent are also represented in the mentioned paper. Drying at 423 K allows to exceed initial characteristics of fresh carbon, namely: to achieve adsorption capacity 0.185 g/g, the degree of gasses purification 94.7 and 70.6 % at the beginning and at the end of the process, respectively. These values for fresh carbon were 0.133 g/g, 80.2 % and 68.5 %, respectively.

In study [25] regeneration of natural zeolites after their activation is heavily emphasized. The activation is carried out using NaOH solution, afterwards regeneration by a thermal treatment in the oven at 573 K is carried out. Adsorption capacity of the activated zeolite is 0.137 g of water vapor per 1 g of the adsorbent. Thermal method is also used for removing toluene by two-stage technique including treatment with acid and thermal treatment at 473 K [15]. Nitrophenol is desorbed by combination of gasification and thermal treatment [16].

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Methods of removing pharmaceuticals [1], phenol [2] or hydrogen sulfide [3-4] by microwave radiation (MWR) are widespread. Such processes proceed at adsorbent temperature of 573 K. Pentachlorophenol [12] and trichlorobiphenyl [13] are also removed from adsorbents by MWR. The adsorbent is dried at 376 K and regenerated in a quartz reactor [13].

In paper [26] orange-peels dried in a convective dryer with a heating agent velocity of 1 m/h for 4 h at 306 K and for 1 h at 365 K are used as moisture adsorbent. Orange press-cake, which is dried in the convective drier at 363 K for 1.5 h before use, is considered by authors of [27] as an adsorbent for wastewater. Carbon adsorbents – carbon aerogel (CA) and carbon xerogel (CX) [7] obtained by a sol gel method and dried at 423 K are used for wastewater treatment too.

In paper [29] physics of filtration drying during regeneration of industrial adsorbents, in particular the adsorbent activated carbon, is considered. During filtration drying, similarly to adsorption processes, the heat-mass exchange occurs not in the whole layer but only at certain height which is called a mass transfer front.

Heating agent filtrating through a porous structure of wet material gives its heat to the material and becomes saturated with moisture. With time the internal moisture evaporation in upper layers is over and the equilibrium between the dispersed material and the heating agent is established. There appears a layer of dry material, which does not take part in the mass exchange but only warms up and accumulates considerable amount of energy. At the same time the temperature of heating agent coming out of the layer approaches to the temperature of heating agent coming into the layer, resulting in the waste of heat energy.

As can be seen, high temperatures [1-4, 12-13, 18, 25, 28] or considerable process durations [26, 27] are required for drying the adsorbents mentioned above.

Electrochemical methods to remove toluene [6, 8], phenol [7, 11] or acids [9], as well as ultrasonic methods [17-19], ultraviolet irradiation methods [21], catalyst addition [20] allow to achieve high removal efficiency. However, such methods are not always efficient in industrial scale for large amounts of adsorbents and not always applicable for combustible adsorbates.

It is known that low temperatures facilitate adsorption processes. That is why the adsorbent having been dried at high temperatures has to be cooled down. In available scientific and technical literature insufficient attention is paid to a cooling processes research. For example, in [30] it is stated that drying and cooling processes are carried out sequentially and, according to experimental data, the drying time is equal to the cooling time. Processes realized by such method require a lot of time and, accordingly energy consumed.

T. Tevyashev *et al.* [31] discuss the method of adsorbate removal from the adsorbent by the electric field energy, when the adsorbate is moved in several layers of the adsorbent by an electric field energy when raising voltage and reducing current strength layer by layer in an adsorbate flow direction. Simultaneously the adsorbent with a low content of adsorbate is cooled. Such method allows to reduce total time of regeneration but requires considerable energy.

Method of drying the capillary porous materials is discussed in [32]. Periodic alternation of infrared irradiation and rapid cooling of particles surface allows to reduce total drying time by 2–4 times and increase the consumed energy efficiency coefficient up to 70–80 %.

Thus, based on literature data it can be concluded that the adsorbent layer regeneration intensity is determined by the way of heat energy supply, velocity of particles washing by a gas flow, heating agent temperature and, consequently, expenditure of energy for the process. In available scientific and technical literature insufficient attention is paid to regeneration of industrial adsorbents with combustible adsorbates. One of the stages of such adsorbents regeneration – the drying process – is carried out by the thermal treatment in the oven by the convection or by the gas flow filtration through a porous structure of the adsorbent fixed bed due to a pressure difference (depression or overpressure). Taking into consideration that in industrial plants the adsorbent layer height is 1 m and more [32], and drying time must be 3–4 times less than the adsorption duration [33], considerable expenditure of energy to ensure high temperature and high rate of the heating agent is necessary. Consequent cooling process, the duration of which is almost equal to the duration of drying, also requires energy expenditure. This problem can be solved by varying temperature regimes and, consequently, efficient use of heating agent energy.

2. Experimental

2.1. Materials

Activated carbon, used in this study as the research object and supplied by Sigma Aldrich, was Carbotrap Adsorbent matrix, 20–40 mesh grade. Its main characteristics are given in Table 1. Granulometric composition of the carbon is given in Table 2.

Main characteristics of Carbotrap Adsorbent matrix

Average particle diameter $d_p \cdot 10^3$, m	Apparent density ρ_{ap}, kg/m^3	Single particle porosity e, m^3/m^3	Adsopbent bed porosity e_{bed}, m^3/m^3	Specific surface are of single particle s_0, m^2/m^3	Specific surface area of adsorbent bed s, m^2/m^3	Particle form factor F	Surface screening factor K_n
2.26	240	0.614	0.375	1165	597	0.8	0.82

Granulometric composition of carbon

$d_p \cdot 10^3$, m	0–0.16	0.16–0.315	0.315–0.63	0.63–1.25	1.25–2.5	2.5–5	>5
%	0.25	0.32	0.64	9.51	26.12	62.23	0.93

2.2. Experimental Technique

Activated carbon was loaded into a cylindrical container purchased from Sigma Aldrich (Fig. 1). The container is made of thermal insulating material (polytetrafluoroethylene film) with the thickness of 0.005 mm, length 0.1 m, coil width 450 mm. It consists of six 30 mm high sections with perforated bottoms. Thermocouples are mounted into each section. Other two thermocouples are used to measure temperature at the inlet and outlet of the container. Temperature is registered by eight-way thermoelectric transducer PT-108 (CEM R&D, China) capable of displaying measured values on the screen after 1.8 s. Change of weight of the container filled with the activated carbon during drying was measured by the electronic balance AXIS-3000 (AXIS, Poland) with accuracy of 0.01 g. Gas flow rate is measured by the rotameter PM–II (Arzamas, Russia).

Wet adsorbent, regenerated by steaming with a saturated water vapor, with the temperature of 373 K was loaded into six sections of the cylindrical container (Fig. 1). Total height of the adsorbent bed in the container was 180 mm. The rate of heating agent filtered through the bed was 2 m/s. Researches were carried out at the heating agent temperature of 373 K, which was kept constant at the container inlet. Change of heating agent temperature across the adsorbent layer height during filtration drying was registered by thermocouples situated in the middle of each section and at the container outlet.

Weight of the container with activated carbon was measured after definite periods of time (30 s). If the container weight remained constant for 120–180 s and if the heating agent temperature at the container outlet was 373 K, the experiment was discontinued. The weight of dry carbon was 640 g.

The experimental set-up scheme and its principle of operation are described in [34].
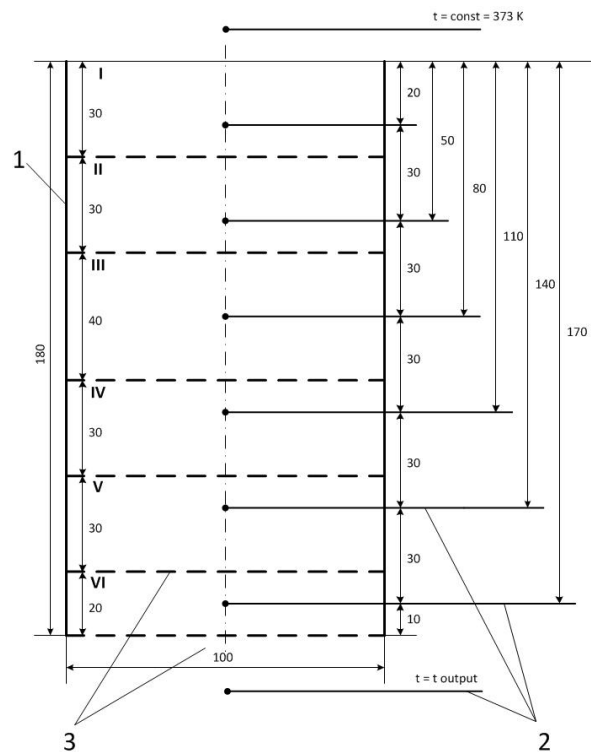

Fig. 1. Arrangement of thermocouples mounted into sections of thecontainer for dispersed adsorbent: 1 – container; 2 – thermocouples; 3 – perforated partitions

3. Results and Discussion

Kinetic curve of drying and dependence of drying time on time for activated carbon (180 mm layer) at heating agent temperature of 373 K are shown in Fig. 2.

Filtration drying has a zonal character, the mechanism of which is described in [35]. As can be seen from Fig. 2, *curve* 1 consequently represents periods of moisture mechanical displacement (first 30 s), total and

partial saturation with moisture. The equilibrium between the dried material and the heating agent is reached after 1000 s that corresponds to the curves of heat agent temperature change (Fig. 3). The period of total saturation with moisture is 30–450 s, which is characterized by a constant drying rate (Fig. 2, *curve* 2). After 450 s the period of partial saturation with moisture begins, and the drying rate decreases. Approximately after 750 s the drying rate slightly decreases and kinetic *curve* 1 (Fig. 2) tends to equilibrium.
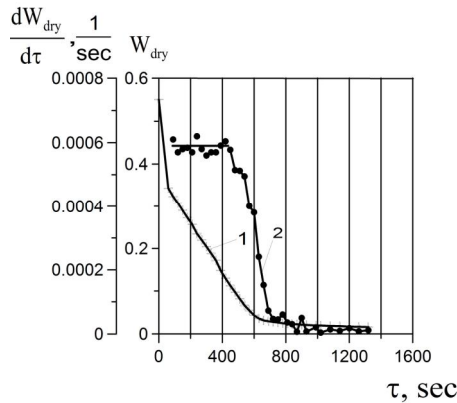

Fig. 2. Kinetic curve of activated carbon drying (1) and dependence of drying time on time (2) at 373 K
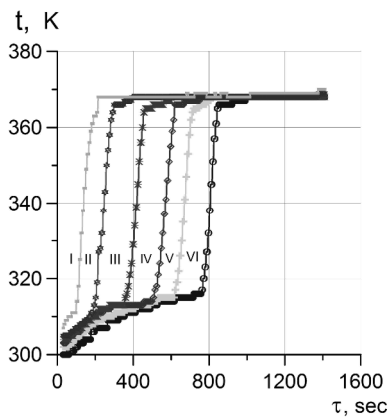

Fig. 3. Change of the heating agent temperature in time across the adsorbent layer height (m): 0.03 (I); 0.06 (II); 0.1 (III); 0.13 (IV); 0.16 (V) and 0.18 (VI)

Change in time of the heating agent temperature across the adsorbent layer height during filtration drying is shown in Fig. 3. These results confirm the mechanism of filtration drying.

Let us consider the upper layer of 30 mm height (Fig. 3, *curve* I). Initially (first 50 s) the heating agent filtrated through the layer becomes completely saturated with moisture, consequently, its relative humidity and moisture content increase, and its temperature decreases

becoming equal to a wet thermometer temperature (405 K). Drying proceeds until the heating agent becomes completely saturated with moisture.

Then the upper layer contacts with a fresh heating agent, which becomes partially saturated with moisture, *i.e.* its relative humidity increases to the values less than 100 %. At the same time the heating agent temperature decreases to the values higher than the wet thermometer temperature. After 120 s the heating agent temperature in the upper layer reaches 325 K, after 140 s – 343 K, and after 175 s – 358 K (Fig. 3, *curve* I). After 210 s, when the temperature in the layer becomes equal to 373 K, the equilibrium between the upper layer and the heating agent is established. Thus, during further drying this layer does not take part in the heat-mass exchange. At this time the second layer (Fig. 3, *curve* II) starts to dry under total saturation conditions. After 390 s the second layer discontinues participation in the heat-mass exchange in the same way as the first layer. The drying proceeds similarly in the lower layers (Fig. 3, *curves* III–VI). The layer VI achieves an equilibrium state with the heating agent after 1000 s.

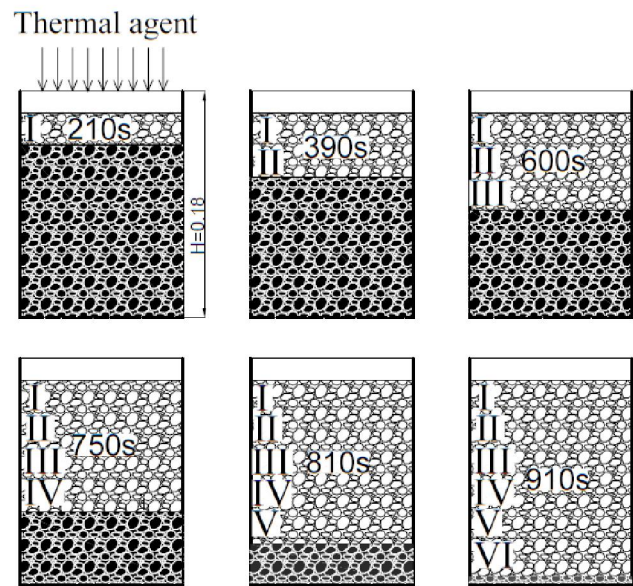Time of reaching equilibrium dryness for each layer of activated carbon is represented in Fig. 4.

Fig. 4. Filtration drying of activated carbon conventionally divided into six layers by height (m): 0.03 (I); 0.06 (II); 0.1 (III); 0.13 (IV); 0.16 (V) and 0.18 (VI)

So, the experimental data show that the heat-mass exchange zone moves in a heating agent flow direction. After certain time intervals an adsorbent layer appears, which does not take part in the heat-mass exchange process and accumulates heat energy in itself.

Taking this fact into consideration, it is reasonable to use the energy accumulated by a dried layer to dry the remaining wet material by filtration of cold air through a hot dried layer. Thus, due to such organization of the process a part of heat energy can be saved and total duration of the adsorbent regeneration can be reduced.

New concept of regeneration of activated carbon layer is suggested in the paper. The essence is drying of hot layer of adsorbent with the temperature of 373 K by the heating agent with the same temperature. The driving force in this case is the difference of partial pressures of saturated water vapor on the surface of adsorbent and heating agent particles.

The mechanism of the suggested method is as follows: the moisture from the activated carbon particles is evaporated and moved out by the heating agent flow due to the pressure difference. Complex heat-mass exchange proceeds during this action. The activated carbon particles are cooled because of moisture evaporation and, at the same time, heated up by the heating agent. So, the temperature of the first layer in heating agent flow direction is kept constant and equal to 373 K.

Further heat-mass exchange proceeds only due to the cooling wet particles of the adsorbent lower layers. Due to the heating agent cooling and its saturation with moisture the evaporation intensity steadily decreases in the heating agent flow direction until its total saturation with moisture. Thus, the mass exchange zone is expanded. After total saturation of the heating agent with moisture corresponding to its temperature at certain height $h_{\min}$, it is heated up when filtrating through wet layer of the adsorbent with the temperature of 373 K. Thus, the heating agent "gets its second wind", *i.e.* its extra saturation of water vapors becomes possible. Moisture content of the heating agent coming out from the adsorbent layer is determined by its temperature.

With time, if the adsorbent bed is rather high, the mass exchange zone will move in the heating agent flow direction toward the perforated partition, where the adsorbent is situated. Simultaneously, in upper layers of the adsorbent which are the first to contact with the heating agent, a thermal front of particles heated up to 373 K is formed. This front will be also expanded in the heating agent flow direction. Due to such process both the layer of dry material with the temperature of 373 K and the layer of wet material with the temperature below 373 K will simultaneously exist in the adsorbent bed. At certain height ratio of hot dry and wet layers, when the energy accumulated by the dry layer is sufficient to dry the wet layer, it is reasonable to supply cold air into the container that will cool the upper layers of the adsorbent and dry wet material.

Taking into consideration that the actual velocity of gas flow between adsorbent particles is high, the heat-transfer coefficient is also high. This allows to use the heat energy accumulated by dry upper layers, and dry a wet material. Consequently, the upper layer will be cooled, that results in decreasing not only heat energy consumption but also the total time of the adsorbent cooling.

Based on the experimental data it is necessary to determine the amount of energy accumulated by the upper layers, which is required to dry the lower wet layers without heating of the agent filtrated through the activated carbon. Let us plot the dependence of layer height on time needed to reach equilibrium moisture content (Fig. 5).
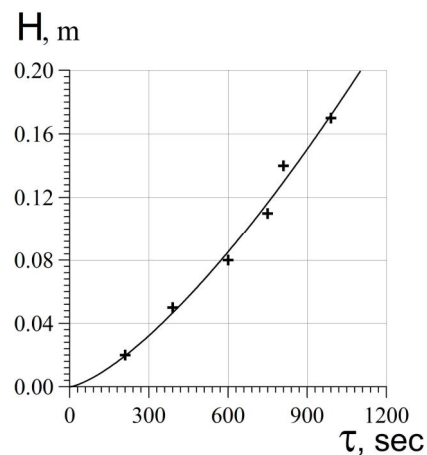

Fig. 5. Dependence of layer height on time needed to reach equilibrium moisture content

As a result of the experimental data approximation by a power function (Fig. 5) the Eq. (1) was obtained.

$$H = 1.1 \cdot 10^{-5} \cdot t^{1.4} \tag{1}$$

Eq. (1) allows to calculate the height of the dry layer of activated carbon in any time, and, respectively, the time needed to reach equilibrium moisture content of any layer within studied range of height.

It is important to determine the way the heating agent passes until its total saturation with moisture, *i.e.* to determine a minimum height of wet material layer $h_{\min}$ providing an efficient use of the heating agent. Initially the layer of wet activated carbon contains a lot of free moisture, which evaporates during the first stage. According to [36] the minimum height of wet material layer, which is dried during the first stage, can be calculated by the following equation:

$$h_{\min} = \frac{2 \cdot u_0 \cdot r \cdot c}{a \cdot s} \tag{2}$$

where u_0 – apparent velocity of the hot heating agent, m/s; ρ – density of the heating agent, kg/m^3; c – heat capacity of heating agent, J/(kg·K); a – heat-transfer coefficient, W/(m^2·K); σ – specific surface of the adsorbent layer, m^2/m^3.

Heat-transfer coefficient a for wet activated carbon can be calculated according to the criterion equation, obtained by V. Atamanyuk *et al.* [29]:

$$Nu = 0{,}033 \cdot \mathrm{Re} \cdot \mathrm{Pr}^{0.33} \tag{3}$$

Substituting numerical values determined by experimental and theoretical researches into Eq. (2) we got $h_{\min} = 0.055$ m – a numerical value of the minimum way passed by the heating agent through the layer of wet activated carbon under the experimental conditions until its total saturation with moisture.

When using Eq. (1) we calculate the time of total saturation of the heating agent with moisture: $t_{\min} = 440$ s. This value is confirmed by the experimental results represented in Fig. 3. A period of the heating agent total saturation with moisture lasts 450 s (Fig. 3, *curve* 2).

At time $t_{\min} = 440$ s a layer with the height $h_{\min} = 0.055$ m and temperature of 373 K is formed, which does not take part in the heat-mass exchange but accumulates some part of heat resulting in waste of energy. It means that after 440 s the supply of heating agent may be terminated and the energy of dry hot layer may be used to dry lower wet layers. More precise termination time of the hot heating agent supply can be determined based on the heat balance. This time must be above or equal to $t_{\min}$.

Let us construct heat balance equations based on above described mechanism of filtration drying of activated carbon with the temperature of 373 K in the case of the heating agent temperature of 373 K.

Let us subdivide the process into time intervals from t to $t+\Delta t$. Heat generation occurs at time t, and heat consumption – at time $t+\Delta t$.

Heat balance equation of the filtration drying at the initial time ($t = 0$) is:

$$
\begin{aligned}
Q_{h.a.} &+ Q_{dry\,carb.(t)} + Q_{water(t)} = \\
&= Q_{evap(t+\Delta t)} + G_{h.a.} \cdot c_{h.a.} \cdot t_{out(t+\Delta t)} + \\
&+ Q^{d.l.}_{dry\,carb.(t+\Delta t)} + Q^{w.l.}_{dry\,carb.(t+\Delta)} + Q_{water(t+\Delta t)}
\end{aligned}
\tag{4}
$$

Heat balance equation of a further filtration drying is:

$$
\begin{aligned}
Q_{h.a.} &+ Q^{d.l.}_{dry\,carb.(t)} + Q^{d.l.}_{dry\,carb.(t)} + Q_{water(t)} = \\
&= Q_{evap(t+\Delta t)} + G_{h.a.} \cdot c_{h.a} \cdot t_{out(t+\Delta t)} + \\
&+ Q^{d.l.}_{dry\,carb.(t+\Delta t)} + Q^{w.l.}_{dry\,carb.(t+\Delta t)} + Q_{water(t+\Delta t)}
\end{aligned}
\tag{5}
$$

Heat balance equations (4), (5) were constructed based on the experimental data represented in Figs. 2 and 3 and the mechanism of filtration drying of activated carbon, consisting of the hot layer of the adsorbent with the temperature of 373 K drying by the heating agent with the same temperature.

Let us assume as a first approximation, that average temperature of the heating agent $\bar{t}$ in the drying zone changes linearly and can be calculated as the arithmetical mean of the initial temperature of the heating agent and its temperature when coming out the adsorbent layer, *i.e.* $\bar{t} = (373 + t_{out})/2$.

In general, filtration drying by analogy with periodic adsorption (desorption) processes [37] is a complex non-stationary heat and mass transfer process, in which parameters change periodically both in coordinates and in time.

Fig. 6 shows the flow diagram of the heat balance in the filtration drying apparatus, which has a cross-sectional area S. We select the elementary layer with dz height in the apparatus z height.

The heat-balance equation in the elementary region dz in the form of the differential equation of the periodic process of filtration drying in the stationary layer of the adsorbent has a view:

$$
\begin{aligned}
S \cdot dz \cdot r_{ad} \cdot \frac{\partial W^c}{\partial t} \cdot r \cdot dt &= S \cdot dz \cdot r_{ad} \cdot \frac{\partial t_{ad}}{\partial t} \cdot c_{ad} \cdot dt + \\
&+ S \cdot dz \cdot r_{t.a.} \cdot \frac{\partial t_{t.a.}}{\partial t} \cdot c_{t.a.} \cdot dt
\end{aligned}
\tag{6}
$$

where S – cross-sectional area of the layer, m^2; dz – height of the layer elementary part, m; $\rho_{ad.}$ – adsorbent density, kg/m^3; $\dfrac{\partial W^c}{\partial t}$ – change in the moisture content of the heat agent during time $d\tau$; r – specific heat of vaporization J/kg; $\dfrac{\partial t_{ad}}{\partial t}$ – change in the temperature of the wet adsorbent during time $d\tau$; $c_{ad.}$ – heat capacity of the adsorbent, J/(kg·K); $\rho_{t.a.}$ –the thermal agent density, kg/m^3; $\dfrac{\partial t_{t.a.}}{\partial t}$ – change in the thermal agent temperature during time $d\tau$; $c_{t.a.}$ – heat capacity of the thermal agent J/(kg·K).

To determine the termination time of the hot heating agent supply, the amounts of heat of the heating agent ($Q_{h.a.}$), heat of water evaporation (Q_{evap}) and heat accumulated by the layer of activated carbon ($Q_{layer} = Q^{d.l.}_{dry\,carb.} + Q^{w.l.}_{dry\,carb.} + Q_{water}$) have been calculated. Calculations results are given in Table 3.
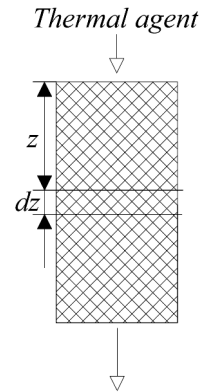
Thermal agent

Fig. 6. Scheme of heat flow during filtration drying in an apparatus with a stationary layer of an adsorbent

Table 3

Amounts of heat of heating agent ($Q_{h.a.}$), heat of water evaporation (Q_{evap})
and heat accumulated by the layer of activated carbon

t, s	Q_{layer}, kJ	Q_{evap}, kJ	$Q_{h.a.}$, kJ
0	177.656	0	0
30	122.030	30.624	40.874
60	127.705	28.185	34.927
90	114.962	22.652	30.414
120	106.960	24.549	25.584
150	100.147	24.933	23.566
180	93.794	22.742	22.583
210	88.856	31.482	21.126
240	102.442	20.755	24.088
270	109.619	22.358	20.940
300	116.057	23.149	20.037
330	117.398	23.058	19.949
360	116.183	33.763	19.867
390	109.763	25.791	25.141
420	87.566	24.662	23.502
450	78.632	21.952	22.176
480	73.626	21.861	20.130
510	70.540	21.116	19.266
540	**67.213**	17.096	18.507
570	65.425	**16.238**	**15.817**
600	65.314	**10.276**	**14.408**
630	48.321	**6.504**	**10.210**
660	47.563	**3.117**	**6.637**
690	49.844	**2.010**	**3.537**
720	52.205	**1.942**	**2.080**
750	53.064	**2.597**	**1.711**
780	41.329	**1.536**	**2.076**
810	39.291	**1.310**	**1.419**
840	30.001	**0.294**	**1.143**
870	29.585	**2.145**	**0.377**
900	29.376	**0.339**	**1.597**
930	28.639	**1.762**	**0.435**
990	29.000	**0.181**	**2.775**
1020	37.224	**1.220**	**0.118**
1080	23.786	**0.836**	**0.222**
1140	36.815	**1.536**	**0.111**
1200	36.759	**0.700**	**0.111**
1260	36.562	**0.994**	**0.111**
1320	36.592	**0.988**	**0.111**
		$Q_{evap\sum}$ = **56.522**	$Q_{h.a\sum}$ = **64.897**

One can see from Table 3 that after 540 s the amount of energy accumulated by the adsorbent layer Q_{layer} = 67.213 kJ, whereas the amount of energy required to evaporate water until the final moisture content in the adsorbent is

$$Q_{evap\sum} = \sum_{Q_{evap}^{t=570}}^{Q_{evap}^{t=1320}} Q_{evap.} = 56.522 \text{ kJ}$$

It means that after 540 s, the amount of energy accumulated by the adsorbent layer is enough to evaporate the amount of water, which must be removed during the next 750 s.

So, the obtained time 540 s is more than the above calculated value t_{min}= 440 s.

According to the experimental and calculated data, after 540 s of drying it is reasonably to supply the heating agent with the temperature of 293 K and carry out drying for the following 750 s with cold air. This allows both to dry and to cool the adsorbent. One can see from Table 3 that amount of the heating agent energy equal to 64.897 kJ is used inefficiently.

The next step to ascertain the real heat saving is the supply of the heating agent with the temperature of 293 K into the activated carbon layer.

Heat amount of cooling air:

$$Q_{h.a.cool} = G_{h.a.} \cdot c_{h.a.} \cdot (t_{out} - 293)$$

In case of applying the conventional approach to the activated carbon regeneration, the process consists of drying the layer of activated carbon with the temperature of 373 K by the heating agent of the same temperature until equilibrium humidity during 1320 s, followed by its air cooling at the temperature of 293 K during the same time. Amount of energy consumed for such process is:

$$Q_1^{h.a.} = Q_1^{h.a.\ dry} + Q_1^{h.a.\ cool} = 497.79 + 1567.2 = 2064.99 \text{ kJ}$$

In case of the adsorbent regeneration according to the method suggested in the present paper, the process consists of drying the activated carbon layer during 540 s followed by its cooling during the next 750 s. Amount of energy consumed in such a case is:

$$Q_2^{h.a.} = Q_2^{h.a.\ dry} + Q_2^{h.a.\ cool} = 448.49 + 933.65 = 1382.14 \text{ kJ}$$

Thus, 682.85 kJ of heat energy is saved per 640 g of dry activated carbon. Specific consumption of heat energy for regeneration of activated carbon by a suggested technique is less by 1066.95 kJ/kg.

4. Conclusions

Mechanism of filtration drying of activated carbon, consisting of drying a hot layer of the adsorbent with the temperature of 373 K by the heating agent of the same temperature, has been grounded. Based on experimental results and grounded drying mechanism, the reasonability of using the energy accumulated by the dried layer for drying the remaining wet material by filtration cold air through it, has been demonstrated. Minimum termination time of the hot heating agent supply, as well as minimum height of hot layer, energy of which would be enough to dry the lower wet layers, have been determined based on experimental data and criterion equations.

Exact time of the hot heating agent supply termination has been calculated based on the heat balance, which under the experimental conditions is equal to 540 s. Amount of energy consumed for the conventional process of adsorbent regeneration and amount of energy consumed for the regeneration process suggested in the paper have been calculated.

It has been proved that the suggested regeneration method allows to reduce the amount of consumed specific energy by 1066.95 kJ/kg$_{\text{dry adsorbent}}$.

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ІНТЕНСИФІКАЦІЯ ПРОЦЕСУ ВИСУШУВАННЯ ПІД ЧАС РЕГЕНЕРАЦІЇ АКТИВОВАНОГО ВУГІЛЛЯ

Анотація. *Досліджено тепломасообмінний процес під час регенерації активованого вугілля. Обґрунтовано механізм фільтраційного висушування активованого вугілля за умов однакової його температури з тепловим агентом. Згідно обґрунтованому механізму, тепловому балансу та критеріальних рівнянь встановлено час припинення подачі теплового агенту. Доведено, що енергії акумульованої частини висушеного шару активованого вугілля буде достатньо для довисушування шару до кінцевої вологості. Запропонований спосіб регенерації дає змогу зменшити кількість затраченої питомої енергії.*

Ключові слова: *адсорбент, висушування, охолодження, температурний режим, теплова енергія, зона тепло-масоперенесення.*