Представлені результати експериментального дослідження теплообміну між газовим середовищем і щільним шаром гранульованого матеріалу. Визначено, що при деякому наближенні температури матеріалу до температури повітря на вході темп нагріву різко знижується, що слід враховувати при розрахунках теплоакумуляторів. Встановлено, що зміна коефіцієнта міжкомпонентного теплообміну в часі підпорядковується рівнянню класу сигмоїд

Ключові слова: теплообмін, гранульований матеріал, рухомий шар, нерухомий, газовий потік, температурні криві

Представлены результаты экспериментального исследования теплообмена между газовой средой и плотным слоем гранулированного материала. Определено, что при некотором приближении температуры материала к температуре воздуха на входе темп нагрева резко снижается, что следует учитывать при расчетах теплоаккумуляторов. Установлено, что изменение коэффициента межкомпонентного теплообмена во времени подчиняется уравнению класса сигмоид

Ключевые слова: теплообмен, гранулированный материал, движущийся слой, неподвижный, газовый поток, температурные кривые

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INVESTIGATION OF HEAT EXCHANGE IN A BLOWN DENSE LAYER OF GRANULAR MATERIALS

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1. Introduction

Employment of heat carriers in the heat power industry in the form of granular materials makes it possible to substantially intensify the processes of heat and mass exchange [1]. The field of research of this work directly relates to optimization of heat accumulators of regenerative type. For example, in food industry, heated gas from the exhaust devices transfers its warmth when passing through a dense layer of granular material. Accumulated heat can then be used for a variety of purposes.

Regenerative heat exchangers with a dense packing layer, both moving and stationary, are characterized by high thermal efficiency, compactness, small mass, simplicity of design and reliability. All this ensures high productivity [2, 3]. The potential for applicability of granular material as an intermediate heat carrier in heat accumulators and heat recovery units is significant [4]. It seems expedient to use heat accumulators and heat recovery units with a granular packing in the industries characterized by a relatively low temperature level of waste gases. However, for industrial implementation, there are too few reliable data on heat exchange between a dense layer of granules and gas. This determines relevance of studying the processes of intercomponent heat exchange in a layer of granular material.

2. Literature review and problem statement

Heat transfer to the particles from the gas flow passing through the layer of dispersed material determines in many cases velocity and stability of the processes occurring between solid and gaseous components [4]. When designing heat exchangers as regenerative systems, it is essential to have information about influence of numerous factors on the heat exchange between solid particles and gas. Heat exchange is subjected to a decisive influence from the flow of heat carriers, cycle duration [5], size of particles and peculiarities of their packing [6, 7]. To optimize the process, work [7] considers operation of heat exchangers that use packing of materials having various geometries: spherical particles, Raschig rings, briquettes).

The results of individual studies show that intensity of heat exchange in the static layer is higher than that in the moving layer which is explained by some loosening of the layer density during its movement [8]. However, there is no mentioning of at what speed the described effects begin to arise. It should be noted that materials of strict geometry are not common which limits the scope of applicability of the results.

Of a particular complexity is acquisition of stable analytical or empirical relationships that would ensure assessment of thermal characteristics, such as amount of heat to be recycled (input) and coefficient of intercomponent heat transfer. For some cases, this problem has been already solved. Regularities of the processes of unsteady heat exchange between a gas stream and a stream of granular material were theoretically studied in [9]. As a result, relation between the heat transfer rate and the design and process parameters was determined. A cellular mathematical model of regenerative processes in heat exchangers with a moving granular packing has been developed [9]. To perform calculations of heat transfer using the analytical dependences obtained on the basis of mathematical models [9, 10], reliable data on the coefficients of intercomponent heat exchange are needed. A model was proposed [11] that enables obtaining of data on the layer thermal state when applying the numerical net-point method. Data on the coefficients of intercomponent heat transfer are also required for calculations. Theoretical and experimental study of heat transfer in a dense layer [12] showed that when using a dense layer for effective accumulation of thermal energy, the Biot number should be as low as possible lest thermal resistance inside the solid should become dominant. It is worth notion that accuracy of the Biot number determination depends on the accuracy of values of the heat transfer coefficients. Comparative evaluation of data on generalized dependences for the coefficient of intercomponent heat exchange obtained by various authors is given in [13]. In most cases, they point out that the criterion determining heat exchange is the Reynolds number. The defining parameters can also include Archimedes number, Stanton number and Froude number. Dependences were obtained for bodies of a simple geometry, such as ball and cylinder [13].

The need for carrying out heat-exchange studies in a blown dense layer is caused by the following. At present, there are no concrete data on the features of heat exchange for a layer of granular material with particles of arbitrary shape, such as claydite or gravel. At the same time, these materials are attractive in terms of their thermophysical properties, availability and cost for their use as a granular heat accumulating packing. Besides, as can be seen from the analysis of the literature data, in order to perform thermal calculations, it is necessary to have values of coefficients of intercomponent heat exchange. Determining them constitutes a separate scientific challenge.

3. The aim and objectives of the study

This study objective was to determine conditions of intensification of heat exchange between a dense layer of particles and air flown in a heat accumulator with a granular packing. This will make it possible to efficiently utilize heat from exhaust devices in the industries that are characterized by a relatively low temperature of exhaust gases.

To achieve this goal, the following tasks were accomplished:

– based of experimental research, work out recommendations on selection of rational operating conditions for heat accumulators;

– determine influence of process duration, speed of movement, gas temperature and type of granular material on intensity of heat exchange;

– compare the heat exchange rate for moving and stationary layers using claydite and gravel as granular materials;

– determine nature of variation in time of the coefficient of intercomponent heat exchange and the key parameters affecting the value of the coefficient of intercomponent heat exchange.

4. Materials and methods of research

4. 1. Characteristics of materials

Gravel and claydite were chosen for research as granular materials. First, the main geometric characteristics of the layer and particles were evaluated. Important characteristics of the layer of granular materials that are necessary for calculating thermal characteristics of the heat exchange process and analyzing the results obtained are as follows: porosity ε of the layer and the equivalent particle diameter $\bar{d}_e$ [14]. It was established that the claydite layer porosity ε_k=0.47, porosity of the gravel layer ε_r=0.5. The properties of granular materials necessary for calculating thermal characteristics of heat exchange between air and a layer of material are given in Table 1.

Table 1

Basic properties of granular materials

Material	Heat capacity, J/(kg·K)	Thermal conduction, W/(m·K)	Density, kg/m^3	Packing height, m	Cross section area, m^2
Gravel	840	0.4-0.93	1,950	0.25–0.52	0.1
Claydite	750	0.16-0.2	816–950		

The material used in the experiment was a polydisperse material with equivalent particle diameter defined as a weighted average over the surface in accordance with the relationship (1):

$$\bar{d}_e = \left(\sum_{i=1}^{n} \frac{m_i \phi_i}{d_i} \right)^{-1}, \qquad (1)$$

where n is the number of fractions in the mixture, m_i is the weight content of the i-th fraction in the mixture, kg/kg; d_i is the particle size of the i-th fraction; ϕ_i is the particle shape factor. The ϕ_i factor which characterizes deviation of the particle shape from spherical shape is equal to one for balls and can be found according to recommendations of [14] for particles of other shapes as follows:

$$\phi_i = \frac{F}{F_0},$$

where F_0 is the surface area of the ideal body (sphere), F is the real surface area of the i-th fraction granule. Initial data and results for claydite are given in Table 2.

Table 2

Geometric characteristics of claydite fractions

No. of the i-th fraction	d_i, m	F_0, m^2	F, m^2	φ_i	$m \cdot 10^2$, kg	n	m_i, kg
1	0.032	$1.52 \cdot 10^{-3}$	$22 \cdot 10^{-2}$	1.45	4.43	30	0.525
2	0.028	$1.02 \cdot 10^{-3}$	$16 \cdot 10^{-2}$	1.57	2.53	29	0.2897
3	0.025	$0.82 \cdot 10^{-3}$	$13 \cdot 10^{-2}$	1.58	1.77	13	0.0908
4	0.019	$0.51 \cdot 10^{-3}$	$7.5 \cdot 10^{-2}$	1.47	0.87	16	0.0549
5	0.018	$0.5 \cdot 10^{-3}$	$7 \cdot 10^{-2}$	1.4	0.84	12	0.0398

The results obtained in calculation of geometric characteristics of gravel fractions are given in Table 3.

Table 3

Geometrical characteristics of gravel fractions

No. of the i-th fraction	d_i, m	F_0, m^2	F, m^2	φ_i	$m \cdot 10^2$, kg	n	m_i, kg
1	0.0267	$1.45 \cdot 10^{-3}$	$18 \cdot 10^{-4}$	1.24	1.01	33	0.367
2	0.0317	$1.54 \cdot 10^{-3}$	$22 \cdot 10^{-4}$	1.43	1.11	19	0.2323
3	0.0276	$1.51 \cdot 10^{-4}$	$19 \cdot 10^{-4}$	1.26	1.07	20	0.2357
4	0.0266	$1.29 \cdot 10^{-3}$	$17 \cdot 10^{-4}$	1.31	0.85	11	0.103
5	0.0203	$0.69 \cdot 10^{-3}$	$9.5 \cdot 10^{-4}$	1.37	0.33	17	0.0618

From the data on fractions (Table 2, 3), it was found that the equivalent diameter $\overline{d}_e = 0.018$ m for claydite and $\overline{d}_e = 0.021$ m for gravel.

4. 2. The experimental setup diagram and the method of investigation

The experimental setup diagram developed by the authors of this paper for the study of heat exchange in a dense layer of a granular material is shown in Fig. 1.

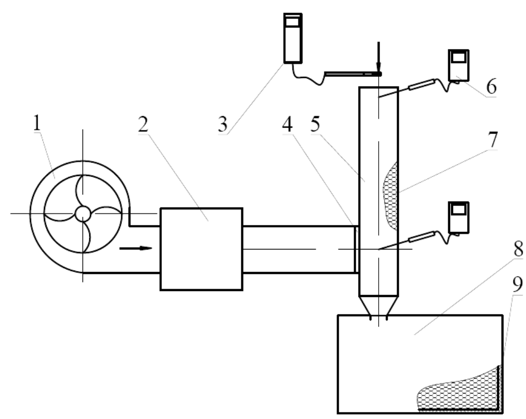

Fig. 1. Experimental setup for the study of heat exchange in a dense layer of a granular material: fan (1); heater (2); anemometer (3); mesh (4); working chamber (5); thermometer (6); granular material (7); container for collecting disperse material (8); insulation (9)

The experimental procedure was as follows. Desired air temperature was set on the regulator and fan 1 and heater 2 were switched on. Air flow was regulated by the gate at the fan inlet. After the experimental setup gained operation mode, material of a specified weight was filled in and temperature measurements started. Mesh 4 prevented the grains from entering the air duct. Anemometer 3 was used to measure air velocity. In all experiments, incoming air temperature t'_a and outcoming air temperature t''_a incoming material temperature t'_m (at the top of the apparatus) and outcoming material temperature t''_m (at the bottom of the apparatus) and the material temperature at a distance of 0.12–0.52 m from the level of filling the heat exchange section was measured. The maximum height of the layer was 0.52 m, the channel diameter was 0.1 m. The temperature measurements were made with a time interval of 30 s. Air temperature at the inlet varied from 50 °C to 80 °C. Based on the results obtained, the main characteristics of heat exchange between air and disperse material were determined.

5. Results of the study of heat exchange in a dense blown layer of granular material

5. 1. Investigation of heat exchange in a dense stationary layer of granular material heated by an air flow

The experiments which were carried out using above procedure have shown that the material temperature varied greatly in height (which was especially noticeable when the stationary mode was attained) due to thermal losses to environment. Fig. 2 shows dependences of the heat carrier (air and claydite) temperature on time. These dependences were typical for all experiments. The material temperature in the outlet section did not exceed 71 °C and the intense heating of the material ended after 600 s at a temperature of 68 °C. Intensity of material heating in the inlet section decreased after 240 s of operation.

In all experiments (Fig. 2), intensity of material heating in the inlet section wss substantially higher than that in the outlet section. The decrease in weight also led to increase in the heating intensity, both in the inlet and outlet sections. At $t'_a = 80$ °C, the heating rate in the outlet section was 0.065 K/s, at $t'_a = 60$ °C, the heating rate in the outlet section was 0.044 K/s for the load weight m=2.01 kg, and 0.059 K/s for the load weight m=1.7 kg.

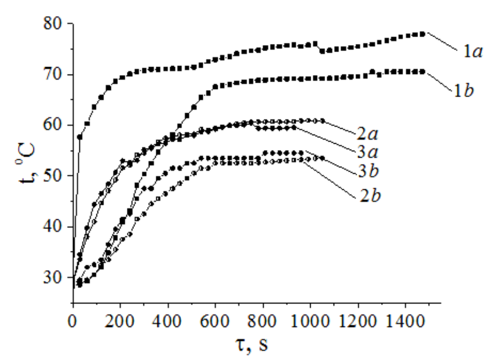

Fig. 2. Change of claydite temperature in the inlet (a) and outlet (b) sections of the apparatus: initial air temperature $t'_a = 80$ °C (1), initial air temperature $t'_a = 60$ °C (2, 3), load weight m=2.01 kg (1, 2); load weight m=1.7 kg (3)

At the same load weight (Curves 1, 2) and the same material heating temperature corresponding to the curve 2a break point (t=53 °C), the heating rate was 0.83 K/s for the curve 1a (Fig. 2), and 0.12 K/s for the curve 2a (Fig. 2). This is an indication of a significant effect of temperature of the heat carrier (air) on intensity of heat-exchange processes: a 1.3-fold growth of the inlet temperature led to a 7-fold increase in the heating rate. For the stabilizing section, the rate of claydite heating at $t'_a = 80$ °C was 1.8 tines higher than the rate of heating at $t'_a = 60$ °C.

Fig. 3 shows the course of temperature curves for air and material. The average filtering rate was w_f =1.2 m/s.

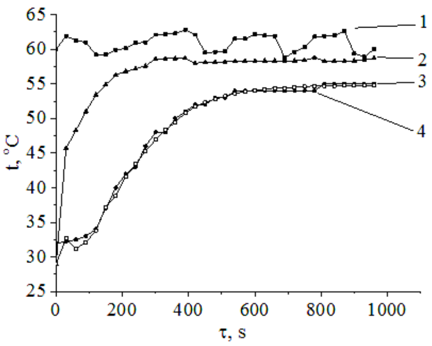

Fig. 3. Temperature of the material (claydite) and air at the inlet and outlet of the apparatus: inlet air temperature (1), material inlet temperature (2), outlet air temperature (3), input material temperature (top of apparatus) (4)

It is evident from Fig. 3 that the air temperature at the exit from the working section practically corresponds to the material temperature. This indicates a complete absorption of heat transferred by air. Curve 2 is smoothed in comparison with curve 1 since it is the result of averaging the temperature data for three repeated experiments.

Three heating zones were most clearly visible at the outlet section: initial, short zone in which temperature varied insignificantly, then a zone of intense heating with a constant speed was observed and finally a stabilizing zone where the material temperature did not practically change.

Primary experimental data were used to calculate the heat transferred from air to material and estimate the coefficient of intercomponent heat exchange. Under the studied conditions, absorption of heat from heated air was materially reduced in all cases after 600 s of heating, i. e., its thermal potential was used ineffectively.

The character of dependence of the average heat transfer coefficient on the process duration is shown in Fig. 4 for all experimental conditions under consideration.

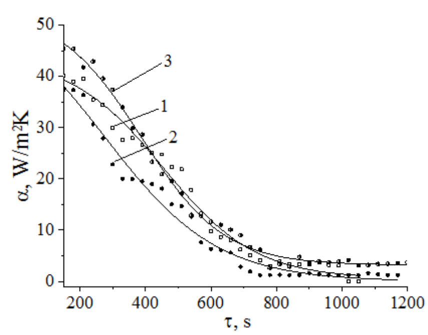

Fig. 4. Average heat transfer coefficient vs. time: inlet air temperature $t'_a = 60$ °C (1, 2); inlet air temperature $t'_a = 80$ °C (3), load weight m=2.01 kg (1,3); load weight m=1.7 kg (2). Average filtering rate w=1.2 m/s

In accordance with Newton-Rikhman's law, when $\bar{\alpha}_{ic}$ was calculated, surface area of the intercomponent heat transfer F_s was taken into account. That is, the surface area of all particles in the working chamber. F_s can be determined in accordance with the procedure [15]. Calculation of F_s for the claydite packing resulted in the following data: F_s=0.67 m² at the layer height L=0.52 m; F_s=0.51 m² at the layer height L=0.39 m. The corresponding data for gravel were as follows: F_s =0.59 m² at at the layer height L=0.52 m; F_s=0.44 m² at the layer height L=0.39 m.

All curves are described with high accuracy by sigma equations:

$$\bar{\alpha}_{ic} = \frac{A_1 - A_2}{1+e^{(\tau-b)/c}} + A_2. \quad (2)$$

Coefficient A_2 indicates the degree of approximation to the equilibrium state. The value of this coefficient was higher at $t'_1 = 80$ °C, A_2=3.2. At $t'_1 = 60$ °C and the same weight of filling m=2.01 kg, A_2=2.2. Reduction in weight to m=67 kg led to a decrease in heat losses and, respectively, a decrease in the coefficient: A_2=0.6. Coefficient $A1$ shows the maximum possible value of the heat transfer coefficient. Coefficients b and c were also determined empirically and take into account influence of the process duration. Thus, for $t'_1 = 80$ °C (Curve 1), b=498.3, c=101.7. For $t'_1 = 60$ °C (Curve 2), b=440.0; c=130.9. For $t'_1 = 60$ °C at a smaller weight (Curve 3), b=388.0; s=125.7. The decrease in coefficient b indicates that the period of change of $\bar{\alpha}_{ic}$ from the maximum to the minimum value which corresponds to the onset of the stationary state decreases.

5. 2. Study of heat exchange between a moving dense layer of granular material and an air flow

In the study of heat exchange between preheated air and a moving dense layer of granular material, the average air filtering rate was 3.5–0.63 m/s for claydite and 0.5–3.5 m/s for gravel at the layer height 0,12 m; velocity of the material layer $0.8 \cdot 10^{-3}$–$4.4 \cdot 10^{-3}$. The ambient temperature varied in the range (13–20) °C. The nature of the temperature change in material (gravel) as a function of the filtering rate is shown in Fig. 5. Speed growth promotes intensification of heat exchange and at a speed w=1 m/s the material practically ceased to be heated after 330–360 s reaching a temperature of t≈55 °C. The heating efficiency was lower at lower speeds.

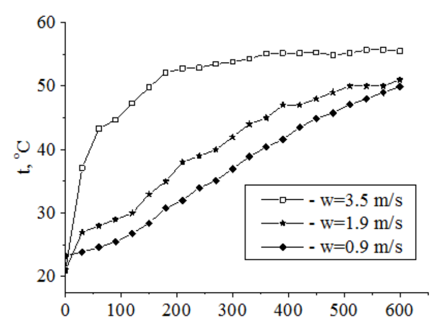

Fig. 5. Heating of gravel in the working chamber at various air filtering rates w_f

Fig. 6 shows the temperature curves obtained for a claydite layer at various air filtering rates. The influence of speed when heating claydite packing was much less than for gravel.

It can be seen (Fig. 6) that starting from a certain time interval, a steady-state mode was established at which the material temperatures practically did not change. For a moving layer, this mode started at τ=300 s, and at τ=500 s for a stationary layer. Comparison of the data on kinetics of gravel heating (Fig. 5) and claydite heating (Fig. 6) shows that claydite was heated in the working chamber much more intensively. In experiments with a moving claydite packing, the time to onset of the stationary mode was reduced by a factor of 2.4 (air speed range: 0.5–3.5 m/s, average velocity of the material layer: $0.9\cdot10^{-3}$ m/s) and in 2,2 times for stationary mode. In order that efficiency of heat exchange with gravel is comparable to that of claydite, air filtering rate must be significantly increased [16].

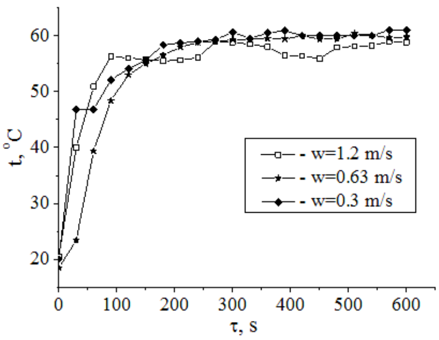

Fig. 6. Heating of claydite in the working chamber at various air filtering rates w_f

5. 3. Comparative characteristic of intensity of heat exchange in stationary and moving layers

A plot of dependence of coefficients for moving (1) and stationary (2) layers of claydite is shown in Fig. 7. Other things being equal, the coefficient of intercomponent heat exchange in a moving layer was comparable to or higher than in a stationary layer (Fig. 7).

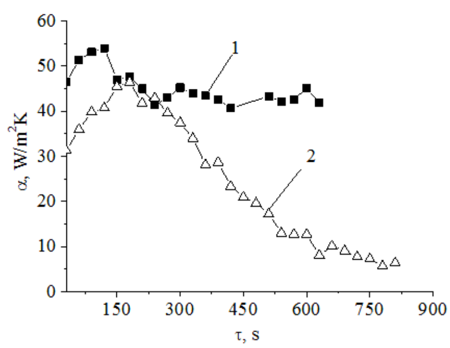

Fig. 7. Change of the average value of the coefficient of intercomponent heat exchange: moving claydite layer (1); stationary claydite layer (2)

The results were obtained for the following conditions: inlet air temperature $t_1' = 80$ °C; average filtering rate $\bar{w} = 1{,}2$ m/s, average layer speed $\bar{w}_k = 4{,}4\cdot10^{-3}$ m/s. Line (1) for the moving layer remained above the line (2) throughout the experiments which indicates a higher intensity of the heat exchange process. On the average, the increase $\bar{\alpha}_{ic}$ in the data of Fig. 7 has grown by 27 %. However, the decrease in the layer velocity to $\bar{w}_k = 0{,}8\cdot10^{-3}$ m/s has led to obtaining of comparable values of $\bar{\alpha}_{ic}$ When designing heat accumulators and evaluating their efficiency as a part of the heat recovery unit, it should be taken into account the fact that arrangement of movement of the layer considerably complicates its design. Therefore, the final choice of conditions of heat exchange between a gas flow and a layer of granular material depends on the immediate practical tasks and conditions of the heat accumulator operation.

6. Discussion of the results obtained in the study of heat exchange between an air flow and a dense layer of a granular material

The study of heat exchange between a gaseous (air) moving medium and a stationary granular layer shows that efficiency of the heat exchange device is determined by the choice of the packing heating period. At a weight of claydite m=2.01 kg and air temperature $t_a' = 80$ °C at the inlet, the temperature curve changed its shape after 450 s: the rate of air cooling, hence the rate of material heating was significantly reduced. With available data on the heat-transfer coefficients which are determined experimentally, it is possible to estimate heating period for the heat accumulator at an arbitrary load weight in accordance with the heat balance equation for the heating period:

$$Q_1 = \bar{\alpha}_{ic}\cdot F_S\cdot\left(\bar{t}_1 - \bar{t}_{m1}\right)\cdot\tau_1 = m\cdot c\cdot\left(t_m^{\tau_1} - t_m^0\right), \qquad (3)$$

where $\bar{t}_{m1}$ are the period-average temperatures of the heating medium (air) and the heated medium (granular material); $\bar{t}_{h1}$ is the average surface temperature of the granular material during the heating period, τ_1 is the heating period, m is the weight of the material, $\left(t_m^{\tau_1} - t_m^0\right)$ is the changes of the material temperature during the heating period. Dependence (3) enables estimation of duration τ_1 of the heating period. In order to calculate final temperatures of the heated material and the heating flow, it is possible, according to the experimental data, to take a temperature 10–15 % lower than the temperature of the inlet gas (for the inlet temperature range of $t_a' = 60 \div 80$ °C). Temperatures of the components (heating and heated media) approach each other asymptotically at the exit from the working section which gives grounds to consider them equal with a high degree of accuracy when making engineering calculations.

Comparison of the data on the coefficients of intercomponent heat transfer obtained for the moving and stationary layers shows that the heat exchange rate for a moving layer will be commensurable to or higher than that for a stationary one. In contrast to the classical concepts [17, 18] according to which the heat transfer rate is much lower in the moving layer than in the stationary layer, an opposite result was obtained under the conditions of the given studies. It is explained by the differences in the motion nature of the layers. During intensive movement of the layer, it gets less dense and porosity increases. Conditions for the occurrence of this phenomenon did not arise (velocity did not exceed 0.44 cm/s), so the flow remained rod-like.

Another important result that should be taken into account is a significant change of the heat-transfer coefficient over time. Therefore, it is irrational to represent dependences for definition of $\bar{\alpha}_{ic}$ in the form $Nu = f(\mathrm{Re})$, which is common in data generalization. Taking into account only the Reynolds number does not result in reliable values. It is expedient to use the experimental dependence of $\bar{\alpha}_{ic}$ change, and as it was obtained in the analysis of experimental data, this dependence is described with a high degree of accuracy by a sigmoid.

Practical significance of this study is the rationale for the choice of claydite as an optimal material for the heat accumulators. Claydite can significantly intensify heat transfer and this intensification is more pronounced for the moving layers. As was shown above, the time to onset of a stationary mode for a moving claydite layer is reduced by 2.4 times in comparison with gravel and by 2.2 times for a stationary layer. Moreover, claydite features a relatively low bulk density (ρ=450 kg/m^3) and low cost.

The proposed method for estimating duration of the heating period enables establishing of the operating mode of heat recovery units for enterprises with various production capacities. The experimental data obtained for the coefficient of intercomponent heat exchange are an indispensable part of this procedure.

Compared with similar studies made by other authors, data on the heat exchange of polydisperse particles without their preliminary treatment, such as claydite and gravel, have been obtained. This will make it possible to predict intensity of heat exchange in real heat recovery units with a satisfactory accuracy.

The use of the obtained results is limited by the type of materials: claydite with an equivalent particle diameter $\overline{d}_e = 0.018$ m and gravel with an equivalent particle diameter $\overline{d}_e = 0.021$ m as well as the experimental area: filtering rate of 3.5–0.5 m/s, the material layer velocity of $0.8 \cdot 10^{-3}$–$-4.4 \cdot 10^{-3}$, inlet air temperature of 60–80 ^{o}C.

Disadvantages of this work include the fact that the dependences for calculation of intercomponent heat transfer are not represented in a form of criterion equations. To obtain empirical equations of this kind, additional experiments should be conducted with a wider range of temperature and component velocity changes. Also, it is necessary to test claydite and gravel with another composition of fractions which will enable to draw up a conclusion on the optimal equivalent particle diameter.

To further this study, it is necessary to start tests with full-scale samples. This requires a cooperative work with enterprises. Difficulties of transition in this direction relate to the organization of construction and commissioning works.

7. Conclusions

1. The rational condition for operation of heat accumulators based on devices with a stationary dense bed is to limit duration of the heating period to a final temperature equal to 80 % of the gas temperature at the inlet. Subsequent heating in the apparatus is accompanied by a decrease in the rate of material heating which results in impairing of its efficiency. An increase in the air filtering rate brings about intensification of heat transfer. The influence of air velocity is much less when heating the claydite layer than the gravel layer. An increase in air temperature at the inlet to the device from 60 °C to 80 °C results in a 1.8-fold increase in the rate of claydite heating in the stabilization zone.

2. Intensity of heat exchange in a moving layer is comparable or somewhat higher than in a stationary layer. Both in a moving and a stationary layer, claydite is heated more intensively than gravel which relates to different physical properties. For the moving claydite layer, the time to the onset of the stationary mode is on the average 2.4 times shorter than for gravel layer (air speed range: 0.5–3.5 m/s, average material velocity: $0.9 \cdot 10^{-3}$ m/s) and 2,2 times shorter for the stationary layer.

3. The coefficient of intercomponent heat exchange between the air flow and a dense layer of granular material increases with increase in velocity of the gas flow. When the dense stationary layer of material is heated by a gas (air) medium, the coefficient of intercomponent heat transfer decreases monotonically and the shape of the curve is described by a sigma function.

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