Thermal conditions of systems for solar thermal regeneration of adsorbents

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Abstract. Energy supply of fruit and vegetable storages, especially in those remote from the centralized energy supply using solar energy, is relevant. The authors of the article propose a system of thermal regeneration of adsorbents based on the use of solar energy. The paper presents studies of heat transfer and thermal regime of the developed system of solar-thermal regeneration of the adsorbent (activated carbon) in non-stationary mode. The results of the study of heat transfer and thermal regime of systems for solar-thermal regeneration of adsorbents (activated carbon) under unsteady conditions are presented. A mathematical model of the temperature field of the adsorbent layer during solar heating using a solar air collector is proposed. The proposed mathematical model of the thermal regime of the solar adsorption installation allows you to qualitatively control the technological process of thermal regeneration of adsorbents and significantly reduce the cost of traditional energy resources.

1. Introduction
The leadership of our country has set tasks to reduce the energy intensity and resource intensity of the economy, the widespread introduction of energy-saving technologies into production, and the expansion of the use of renewable energy sources [1]. The implementation of these provisions, including the improvement of the efficiency of using solar energy in the heat-technological processes of fruit and vegetable storage facilities, is considered one of the most important tasks.

On the basis of our research, we have developed a solar air heating system for thermal regeneration of adsorbents (TPA) and active ventilation (AV) of fruit and vegetable chambers [2,3,4]. The studies carried out show that the thermal regime of TPA depends on the intensity of convective heat transfer between the surface of the adsorbent and the hot washing air. The main thermotechnical parameters of convective heat transfer is the heat transfer coefficient, which depends on many factors [5,6,7,8,9,10].

The purpose of this work is to investigate the heat transfer and thermal regime of the developed system of solar thermal regeneration of the adsorbent (STRA) in a nonstationary regime. Convective heat transfer during forced air movement through a fixed bed of adsorbent in the solar regeneration mode has a pronounced unsteady character, i.e. air temperatures and adsorbent temperatures vary both in time and in space. To calculate the cycle of adsorption plants, determine the duration of the solar regeneration regime, select the optimal thermal engineering parameters for their implementation, it is necessary to calculate the temperature field and calculate the change in the adsorbent temperature along the length of the adsorbed at the moment of time under study.
2. Method
A system of thermal regeneration of adsorbents based on an air solar collector has been developed and studied [4 – 6], which is shown in Fig.1.

![Figure 1. Schematic diagram of TPA systems in a refrigerating chamber using a solar air collector.](image)

1. solar air collector; 2. sun rays; 3. inner air duct; 4, 6, 8, 12. air pipelines; 5, 7. gate type valves; 9. electric fan; 10. cassette for adsorbent (adsorbed); 11. thermoelectric heater.

3. Results and Discussions
The heat transfer coefficient in the granular layer of activated carbon, in the processes of thermal regeneration, was determined by the method of modeling convective heat transfer using criterion equations of similarity [11, 12]. The experimental results were processed using the following similarity criterion equations, i.e. according to the formula of V.N. Timofeeva:

\[
\frac{Nu}{ds} = 0.106 \cdot Re^{0.67}, \quad \text{at } 20 < Re < 200
\]

\[
\frac{Nu}{ds} = 0.61 \cdot Re^{0.67}, \quad \text{for } Re > 200
\]

The results of studies to determine the coefficient of heat transfer from air to the adsorbent are summarized in table. 1.

The process of unsteady heat exchange in the main apparatus of an adsorption plant - an adsorber - allows one to present a physical model of the process as follows. The process is one-dimensional, there is no heat exchange with the environment through the side surface of the adsorber, at any moment of time the temperature of the adsorbent particle can be considered constant throughout its volume, convective heat transfer between the air flow and the adsorbent layer is decisive, heat transfer by thermal conductivity through the air and the layer in the axial direction and heat transfer by radiation are small and can be neglected, the air pressure when moving through the layer remains unchanged, the mass air flow rate is constant, all the thermophysical properties of the air and the layer are considered constant and independent of temperature [13, 14, 15].
Table 1. The results of studies of heat transfer in a granular adsorbent layer during thermal regeneration by atmospheric air.

| №  | W, m/c | Re_s | Nu_s | α, Vt/m².K |
|----|--------|------|------|------------|
| 1  | 0.2    | 141.2| 14.95| 35         |
| 2  | 0.3    | 211.7| 22   | 51.15      |
| 3  | 0.4    | 282.3| 26.7 | 62.1       |
| 4  | 0.5    | 352.9| 31   | 72         |
| 5  | 0.6    | 423.5| 35.1 | 81.6       |
| 6  | 1.0    | 705.9| 49.4 | 114.6      |

When considering non-stationary temperature fields in adsorbers in heat transfer processes, in addition to the above assumptions, it is assumed that the adsorption properties of the layer do not affect the heat transfer process - the specific mass flow rate of air in any cross section remains constant, and the heat effects accompanying the processes of adsorption and desorption are insignificant and they can be neglected.

To derive the basic equations for air and particles enclosed in the elementary volume of the layer, heat balance equations are drawn up. For air: the change in the enthalpy of air during the considered period of time plus the heat introduced by the flow, in total, is equal to the amount of heat transferred to the layer in the process of convective heat transfer. For the particles of the layer: the change in the enthalpy of the particles during the considered time interval is equal to the amount of heat transferred to the layer in the process of convective heat transfer [16,17,18,19,20,21].

The sought functions are the air temperature \( t_v \) and the temperature of the particles of the layer \( t_c \), these functions are functions of two independent variables (Fig. 1).

The temperature of the adsorbent bed is determined by the following data, which \( m_{ad} \) is the mass of the adsorbent, kg; \( c_v \) - specific heat capacity of the adsorbent J / (kg·°C); \( t_0 \) - initial temperature of the adsorbent bed, °C; \( t_c(t) \) - the temperature of the adsorbent at a time \( t(t \geq 0) \).

The amount of accumulated heat in the layer of adsorbent grain at time \( t \) is determined by:

\[
Q = c_v \cdot m_{ad} \cdot t_c(t) = c_v \cdot m_{ad} \cdot t, \quad (2)
\]

and at time \( t = 0 \):

\[
Q_0 = c_v \cdot m_{ad} \cdot t_0. \quad (3)
\]

Within the time \( dt \), the amount of heat received by the adsorbent layer will increase by the value:

\[
dQ = c_v \cdot m_{ad} \cdot dt(t). \quad (4)
\]

This amount of heat is transferred to the adsorbent by air at a constant temperature during convective heat exchange between the air and the adsorbent:

\[
dQ = \alpha \cdot (t_v(t) - t_c(t)) \cdot d\tau, \quad (5)
\]

where \( \alpha \) is the heat transfer coefficient, W / m²·°C; \( t_v \) - air temperature, °C.
Figure 2. The design scheme of unsteady heat transfer during heating of the adsorbent layer

Equating (4) and (5), the following heat balance equation was obtained:

\[ c_c \cdot m_{ad} \cdot \frac{dt}{dt} = \alpha \cdot (t_a - t_c) \cdot d\tau . \]  

(6)

Separating the variables as follows:

\[ \frac{dt}{t_a - t_c} = \frac{\alpha}{c_c \cdot m_{ad}} \cdot d\tau , \]  

(7)

and integrating equation (7):

\[ \int \frac{dt}{t_a - t_c} = \frac{\alpha}{c_c \cdot m_{ad}} \cdot \int d\tau , \]  

(8)

Determined

\[ \int \frac{dt}{t_a - t_c} = \frac{\alpha}{c_c \cdot m_{ad}} \cdot \tau + C_1 , \]  

(9)

where \( C_1 \) is an arbitrary constant of integration.

To calculate the integral in the left-hand side of equation (9), the following substitution is introduced:

\[ t_a - t_c = x , \]  

(10)

we have \( d (tv - tc) = dx \), if we assume that \( tv = \text{const} \),

\[ dt_c = -dx . \]  

(11)

Taking into account expressions (10), (11) and the presence of the constant of integration \( C_1 \) in equation (9), after integration we obtain:

\[ \int \left(-\frac{dx}{x}\right) = -\ln x . \]  

(12)

Replace the left side of equation (9) taking into account (11)

\[ -\ln x = \frac{\alpha}{c_c \cdot m_{ad}} \cdot \tau + \ln C_1 . \]  

(13)

The resulting equation (12) after transformation taking into account (9) has the following form:

\[ t = t_a - \frac{1}{C_1} \cdot e^{\frac{\alpha}{c_c \cdot m_{ad}}} . \]  

(14)

Under the initial condition \( \tau = 0, t(0) = t_0 \), from (14) we obtain:

\[ t_0 = t_a - \frac{1}{C_1} \cdot e^{0} = t_a - \frac{1}{C_1} \cdot 1 = \frac{1}{C_1} = t_a - t_0 . \]  

(15)
Further, for convenience of calculations, we introduce the following notation:

\[ b = \frac{\alpha}{c_c \cdot m_{ad}} \]  

(16)

from (14) taking into account (16) we obtain the final equation:

\[ t = t_e - (t_e - t_0) e^{-bt} \]  

(17)

The resulting equation (17) makes it possible to determine the heating temperature of the adsorbent in a solar air heating unit (SAHU) taking into account the environmental parameters and the thermal characteristics of the adsorbent itself (\( \alpha, c_c, m_{ad} \)).

From the analysis of the obtained dependence, it can be concluded that the heating temperature of the adsorbent in the adsorber is determined by its mass and heat capacity, initial temperature, heat transfer coefficient and heating duration. The resulting equation (17) will allow solving the following problems:

1) By setting the limiting maximum heating temperature of the adsorbent, it is possible to determine the maximum duration of its heat treatment with air through the IHU (duration of TPA).
2) Setting the maximum duration of heat treatment of the adsorbent, we determine the possible temperature of its heating.

The obtained mathematical equation (17) is convenient for practical engineering calculations of TPA systems and does not require a large amount of initial and experimental data.

Let's make a calculation according to the following initial data:

\( W = 0.2 \text{m/s}; \alpha = 35 \text{W/(m}^2 \cdot ^\circ \text{C}); c_c = 0.84 \text{kJ/(kg} \cdot ^\circ \text{C}); m_{ad} = 28.8 \text{kg}; t_e = 60 \ ^\circ \text{C}; t_0 = 18 \ ^\circ \text{C}; \)

\[ b = \frac{\alpha}{c_c \cdot m_{ad}} = \frac{35}{0.84 \cdot 10^3 \cdot 28.8} = 1.44 \cdot 10^{-3}. \]

Based on the calculation results, a graph of the change in the temperature of heating of the adsorbent in the adsorber is plotted (Fig. 3).

Figure 3. The graph of the temperature of the heating of the adsorbent (activated carbon) in the adsorber of a solar air-heating installation.
4. Conclusions
The proposed mathematical model of the temperature field of the adsorbent layer during solar heating makes it possible to determine the change in the temperature of the adsorbent along the length of the absorber and in time, and also takes into account the influence of the thermal characteristics of the adsorbent itself.

At the maximum heating temperature of the adsorbent, it is possible to determine the duration of heat treatment with hot air heated in the IHL.

As seen from fig. 2. with an increase in the heat transfer coefficient (α) from air to the adsorbent, the intensity of heating of the adsorbent layer increases.

Thus, the obtained results of the study of the thermal regime of the STRA and the mathematical model of the temperature field of the adsorbent layer make it possible to qualitatively control the STRA process and select the optimal technological parameters of the systems for regulating the gaseous medium in the fruit and vegetable storage facilities.

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References
[1] "Strategy of actions for the further development of Uzbekistan in 2017-2021". Decree of the President of the Republic of Uzbekistan No.UP-4947 dated February 7, 2017.
[2] A.Sychev, V.Kharchenko, P.Vasant, G.Uzakov. “Application of various computer tools for the optimization of the heat pump heating systems with extraction of low-grade heat from surface watercourses".//International Conference on Intelligent Computing & Optimization. 10.4. (2018) Springer, Cham: 310-319.
[3] Khujakulov S.M., Uzakov G.N., Vardiyashvili A.B. Effectiveness of solar heating systems for the regeneration of adsorbents in recessed fruit and vegetable storages. //Applied Solar Energy. – USA. 2013. – vol.49, № 4. – pp. 257-260. (05.00.00. №4.Scopus CiteScore 2018, IF:0.9)
[4] Khujakulov S.M., Uzakov G.N. Research of thermo moisten mode in underground vegetable storehouses in the conditions of hot –arid climate. //European science review. – Premier publishing s.r.o., Austria, 2017. – №11-12. pp. 164-166. (05.00.00. №3. Global 2018, IF:1.36)
[5] Uzakov G.N., Khuzhakulov S.M. Helio-air heating installation with solar thermal regeneration of adsorbents // Tekhnika. Technology.Engineering. - 2016. - No. 2. - S. 7-10. - URL https://moluch.ru/th/8/archive/40/1339/ (date of access: 06.10.2019).
[6] Uzakov G.N., Khuzhakulov S.M. Investigation of heat exchange processes in systems of solar-thermal regeneration of adsorbents // Tekhnika. Technology.Engineering. - 2016. - No. 2. - S. 10-13. - URL https://moluch.ru/th/8/archive/40/1340/ (date of access: 06.10.2019).
[7] Uzakov G.N., Khuzhakulov S.M. "Investigation of temperature regimes of a helium-air heating unit for systems of thermal regeneration of adsorbents." Solar engineering, 2017.- No. 1.from. 40-43.
[8] Khuzhakulov S.M., Uzakov G.N. "Device for the regeneration of adsorbents." FAP No. 01259.
[9] Abbasov ES, Umurzakova MA, BoltaboevaMP ..“Efficiency of solar air heaters”.Solar technology. 2016. - No. 2. from. 13-16.
[10] Uzakov G.N. Technical and economic calculation of combined heating and cooling systems vegetable store-solar greenhouse// Applied Solar Energy. – Allerton Press, USA, 2012. –vol.48, №1.–PP. 60-61.
[11] Kattakulov, F., Muslimov, T., Khusainov, A., Sharopov, S., Vokhidov, O., Sultanov, S. Water resource saving in irrigation networks through improving the efficiency of reinforced concrete coatings. IOP Conference Series: Materials Science and Engineering. 2020. 883. Pp. 012053. DOI:10.1088/1757-899X/883/1/012053.
[12] Uzakov G.N., Davlonov Kh.A., Holikov K.N., Study of the Influence of the Source Biomass Moisture Content on Pyrolysis Parameters// Applied Solar Energy, Vol. 54, No. 6, pp. 481-484. 2018, (05.00.00; №4. Scopus CiteScore 2018, IF:0.9).

[13] Zhuravlev, P., Marukyan, A., Markova, I., Khidirov, S., Nazarov, B. The rationale for taking into account the organizational features of work in the winter when designing. IOP Conference Series: Materials Science and Engineering. 2020. 883(1). DOI:10.1088/1757-899X/883/1/012212.

[14] Xaritonov B.P. Adsorption in conditioning on refrigerators for fruits and vegetables. M: Food industry, 1978. - 192 e.

[15] Chabane F. “Design, developing and testing of a solar air collector experimental and review the system with longitudinal fins”. International journal of Environmental Engineering Research. Vol. 2. Issue 1. pp. 18-26. 2013.

[16] Henden L., Rekstad J., Meir M. “Thermal performance of combined solar systems with different collector efficiencies”. Solar Energy, 72 (4). 2002.

[17] Kolb A., Winter E.R.F., Viskanta R. “Experimental studies on a solar air collector with metal matrix absorber”. Solar Energy, 65 (2). 1999.

[18] Kurtas I., Turgut E. “Experimental Investigation of solar Air Heater with Free and Fixed Fins: Efficiency and Exergy Loss”. International Journal of Science & Technology, 1(1). 2006.

[19] Garg H.P., Choundghury C., Datta G. “Theoretical analysis of a new finned type solar collector”. Energy, 1991, 16.

[20] Kartashov AL, Safonov EF, Kartashova MA.. “Investigation of schemes, structures, technical solutions of flat solar thermal collectors”. SUSU Bulletin, No. 16. p. 4-10. 2012.

[21] Uzakov G.N., Toshmamatov B.M., Kodirov I.N., Shomuratova S.M. On the efficiency of using solar energy for the thermal processing of municipal solid waste. Journal of critical reviews. ISSN-2394-5125 VOL 7, ISSUE 05, 2020.