Investigation Adsorption Process Energy Capacity Reducing Possibility by Composite Adsorbents Implement

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Abstract. The research results presented in the article are devoted to the compressed air adsorption drying processes energy intensity reducing possibilities study. The investigation concerns the new adsorbent – composite. The material is considered as one of the most perspective at the present time. It’s energy efficiency is proved comparing traditional adsorbents such as silica gel, alumogel, zeolites, etc. The authors consider the bulk density as one of the factors at the adsorption process energy efficiency increase. The formulas given at the articles allow to calculate the different adsorbents bulk and apparent density, the compressor’s energy efficiency by using different adsorbents at pneumatic schemes, etc.

1. Introduction
Energy efficiency of the adsorption method for drying compressed air concerned with the moisture content certain parameters achievement in accordance with the purity classes according to ISO 8571-1-2016 is in doubt, as the most important criteria for choosing a method for compressed air drying is not only the required purity class but the followings as well [1,2]:
- process energy consumption;
- process resource consumption.

Regarding the achievement of numerical values of compressed air purity indicators corresponding to high ISO or GOST [3] classes, it is the adsorption drying technology to allow them to be achieved regardless regulatory document type.

2. The problem
However, the moisture adsorption process from compressed air allowing to reduce the moisture content in compressed air to values of the dew point temperature \( t_{d.p.} = -70°C \) possesses the only significant drawback - high energy consumption, which depends as on the atmospheric air thermophysical parameters and the adsorbent itself physical characteristics, which primarily include its bulk density[4]. It is the bulk density, which is the mass of a unit, the volume of the adsorbent layer and takes into account not only the adsorbent granules volume, but also the air gaps volume between the granules [5].

In previous works [6], the authors carried out studies related to the determination of the dependence of the energy intensity of various types of adsorbents on the parameters of the intake air, the speed of its passage through the adsorbent and the required purity class. The studied adsorbents list included various brands of adsorbents - silica gels, zeolites, molecular sieves - seventeen species in total [7].
However, the adsorbents list did not include the recently appeared and gaining momentum in industry - composite adsorbents, which are multicomponent materials with different chemical properties, contributing to the new material emergence with characteristics differing from the individual components characteristics.

It is the composite adsorbents having a unique structure with a clearly defined matrix and filler.

A composite adsorption materials distinctive feature is also the ability to absorb not only moisture, but also oil particles, which will allow avoiding the installation of oil filters in the compressed air purification technological scheme, thereby reducing hydraulic losses on additional resistances, which are oil filters, which ultimately should help to reduce the adsorption process energy intensity [8,9]. This article gives the calculation and analysis for the composite adsorbent using feasibility in the compressed air drying processes with an analysis of the feasibility of its use from the standpoint of the energy consumption of the processs [10,11].

Based on the experimental data of measuring the substance apparent density, it is calculated the composite adsorbent bulk density made on the expanded perlite basis, glauconite and expanded vermiculite and analyze the feasibility of using this adsorbent in compressed air drying processes.

The adsorbent bulk and apparent density, gr/cm$^3$, are determined by the formulas [1]:

\[
\rho_b = \frac{m}{V_{\text{lay}} + V_{\text{pore}} + V_{\text{sp}}} \quad \text{(1)}
\]

\[
\rho_{\text{app}} = \frac{m}{V_{\text{lay}} + V_{\text{pore}}} \quad \text{(2)}
\]

where $m$ – mass per unit volume of the adsorbent layer, equal 1000 gr;

$V_{\text{lay}}$ – the volume of the adsorbent layer, including pores, cm$^3$;

$V_{\text{pore}}$ – inner pores volume, cm$^3$;

$V_{\text{sp}}$ – volume of free space between granules, cm$^3$.

From formula 2 we find the sum of the layer volume and the volume of the internal pores of the adsorbent:

\[
V_{\text{lay}} + V_{\text{pore}} = \frac{m}{\rho_{\text{app}}} \quad \text{(3)}
\]

\[
V_{\text{lay}} + V_{\text{pore}} = \frac{1000}{0.26} = 3846 \text{ cm}^3.
\]

The volume of voids between the granules $V_{\text{pore}}$ cannot be accurately calculated due to the complex geometric shapes of the granules, so we will calculate it approximately, assuming that the granules have the shape of an ideal ball and a regular quadrangular pyramid can be inscribed between them (Figure 1). In this case, the volume of empty space that does not enter the pyramid is balanced by the volume of granules cut off by the edges of the pyramid. Let us assume the granule diameter is 8 mm and the adsorption tower diameter is 1000 mm.
Then the pyramid volume will be equal to:

\[ V_{pyr} = \frac{1}{3} \cdot a^2 \cdot H, \]  

(4)

where \( a \) – pyramid side, cm; 
\( H \) – pyramid height, cm.

\[ V_{pyr} = \frac{1}{3} \cdot 0.27^2 \cdot 0.22 = 0.005 \text{ cm}^3. \]

Assuming that the adsorbent is filled with even layers in the adsorption tower, we determine the average number of granules in 6 layers of adsorbent:

\[ n = \frac{\pi \cdot R^3}{\pi \cdot r^3} \cdot 6 = \frac{R^3}{r^3} \cdot 6, \]  

(5)

where \( R \) – adsorption tower radius, cm; 
\( r \) – adsorbent granule radius, cm.

\[ n = \frac{50^3}{0.4^3} \cdot 6 = 93750. \]

Then the total empty space volume of between the adsorbent granules per unit mass will be:

\[ V_{pore} = n \cdot V_{pyr}, \]

\[ V_{pore} = 93750 \cdot 0.005 = 501,2 \text{ cm}^3. \]  

(6)

Thus, the bulk density of the composite adsorbent will be:

\[ \rho_b = \frac{1000}{3846 + 501,2} = 0.23 \text{ gr/cm}. \]

Similarly, the bulk densities of silica gel, activated carbon, alumogel, zeolite were calculated, and the calculation data are summarized in Table 1.

From the data presented in Table 1, it is clearly seen that the composite adsorbent has the lowest bulk density among other common adsorbents. Low bulk density indicates the adsorbent denser packing possibility, which makes it possible to minimize the air gap between its granules, which in turn contributes to the provision of a uniform front of adsorption advance, a decrease in hydraulic...
resistance during air passage and, as a consequence, a decrease in the air drying process energy consumption and the adsorbent regeneration process.

Table 1. Bulk density of various types of adsorbents.

| Adsorbent       | Silicagel | Activated carbon | Alumogel     | Zeolit      | Co composite material |
|-----------------|-----------|------------------|--------------|-------------|-----------------------|
| Bulk density, gr/cm³ | 0.4…0.7  | 0.3…0.6          | 0.45…0.55   | 0.6…0.9    | 0.23                  |

To determine the adsorption process energy efficiency or its absence from the composite adsorbent usage based on expanded perlite, glauconite and expanded vermiculite in comparison with other types of adsorbents, we will calculate the energy consumption for the drive of the KT-6 piston compressor and compare the results obtained.

Let us determine the mass of the adsorbent required to implement the drying process, according to the formula 7 [18]:

$$M_a = \frac{G \cdot (d_i - d_f) \cdot \tau}{a_d},$$  \hspace{1cm} (7)

where $G$ – compressed air consumption, m³/sec.

$d_i, d_f$ – initial and final moisture content of compressed air, respectively, gr/kg;

$\tau$ – adsorption cycle time, c. For the calculation, it is taken equal to 3600 sec;

$a_d$ – adsorbent dynamic moisture capacity.

Below we present the dynamic moisture capacity of commonly used adsorbents.

- for composite materials 75 %;
- for silicagels 50 %;
- for activated carbons 30 %;
- for alumogels 30 %;
- for zeolites 26 %.

The moisture content of the compressed air at the inlet to the adsorber can be determined by the formula:

$$d_i = \frac{V_1 \cdot h_{u_{max1}} \cdot \varphi_1}{100 \%} - \frac{V_2 \cdot h_{u_{max2}} \cdot \varphi_2}{100 \%},$$  \hspace{1cm} (8)

where $V_1$ and $V_2$ – air volume before and after compression, respectively, m³/min;

$h_{u_{max1}}, h_{u_{max2}}$ – maximum moisture before and after compression, respectively, gr/m³. Maximum air humidity at 0 °C is 4.87 gr/m³;

$\varphi_1$ and $\varphi_2$ – relative humidity before and after compression, %. In the calculations, we take the range of variation from 50 % up to 100 % respectively.

Final moisture content $d_i$ is taken depending on the compressed air purity class GOST R or ISO 8573-1-2016. For the 1st class of purity, the moisture content is 0.001 gr/m³ (dew point -70 °C), 2-nd – 0.01 gr/m³ (dew point - 40 °C) and 3-nd class – 0.09 gr/m³ (dew point -20 °C). Then the amount of moisture to be removed is defined as:

The volume of the adsorbent is calculated by the formula:

$$V_a = \frac{M_a}{\rho_H};$$  \hspace{1cm} (9)

The diameter of the adsorption column is determined by the following ratio:

$$D = \sqrt{\frac{4.64 \cdot G}{\pi \cdot \rho_t \cdot w}},$$  \hspace{1cm} (10)

where $w$ – compressed air velocity, m/sec. Accepted for initial calculation: 0.3 m/sec;
ρ_g – air density at operating conditions, kg/m^3. Defined as:

\[ ρ_g = ρ_0^0 \cdot \frac{P \cdot T_0}{P_0 \cdot T}, \]  

(11)

where ρ_0^0 – air density under normal conditions is 0,367 kg/m^3 [20];

P, P_0 – pressure at the inlet to the adsorber and pressure under normal conditions, MPa. P = 0,7 MPa, P_0 = 0,1 MPa;

T, T_0 – temperature at the inlet and at normal, K. T = 303 K, T_0 = 273 K.

The adsorbent layer thickness or height is calculated by the formula:

\[ H = \frac{4 \cdot V_a}{π \cdot D^2}; \]  

(12)

The adsorbent layer aerodynamic drag Δp, taking into account the influence of the intergranular space, is determined by the formula:

\[ Δp = 9,81 \cdot w^2 \cdot H \cdot ε, \]  

(13)

where ε – the porosity of the adsorbent bed, determined by the formula:

\[ ε = 1 - \frac{ρ_{app}}{ρ_g}, \]  

(14)

where ρ_{app} – apparent density of the adsorbent, gr/cm^3.

Then the losses will be:

The porosity value presence in the formula 13 makes it possible to take into account the effect of the voids between the granules included in the adsorbent bulk density value on the loss of the compressed air velocity.

Thus, the energy consumption for the compressor drive is calculated as:

\[ ΔN = \frac{k_3 \cdot G \cdot 2,3 \cdot 10^3 \cdot p_1 \cdot \left[ \log \left( \frac{P_2 + Δp}{P_1} \right) - \log \left( \frac{P_2}{p_1} \right) \right]}{102 \cdot h_k \cdot h_a} \cdot 10^7, \]  

(15)

where p_1 – atmosphere pressure, bar;

p_2 – air pressure at the outlet of the compressor, bar. Compressor performance from table 4 is 7 bar; k_3 – safety factor equal to 1.15.

**Table 2.** The results of calculating the energy consumption for the compressor drive when using various types of adsorbents.

| Characteristics | Silica gel | Activated carbon | Alumogel | Zeolit | Composite material |
|-----------------|-----------|------------------|----------|--------|-------------------|
| d_0, g/kg       | 0,19      |                  |          |        |                   |
| d_1, g/kg       | 0,09      |                  |          |        |                   |
| M, kg           | 64,8      | 108              | 108      | 125    | 43,2              |
| V_a, m^3        | 0,09      | 0,21             | 0,22     | 0,17   | 0,19              |
| ρ_g, kg/m^3     | 2,3       |                  |          |        |                   |
| D, m            | 0,44      |                  |          |        |                   |
| H, m            | 0,61      | 1,40             | 1,43     | 1,10   | 1,24              |
| ε               | 0,312     | 0,40             | 0,333    | 0,423  | 0,115             |
| Δp, bar         | 0,167     | 0,494            | 0,416    | 0,407  | 0,126             |
| ΔN, W           | 387       | 530              | 496      | 492    | 341               |
Compressor and drive efficiency values are also shown in Table 2.

The given above calculations characteristics results at a flow rate of 0.3 m/s for silica gel, activated carbon, alumina gel, molecular sieve and composite material are summarized in Table 2.

We realize similar calculations for changing the dried air movement speed in the range (from 0.2 to 0.5), cleanliness classes (from 1st to 3rd) and relative humidity (from 50% to 100%) and build dependency diagrams energy consumption to drive the compressor from them. The calculation results according to the method described above are presented in Table 3.

**Table 3.** The results of calculating the energy consumption for the compressor drive for various adsorbents.

| Cleanliness class and speed | Relative humidity, % | Composite material | Alumogel | Silica gel | Carbon | Zeolit |
|----------------------------|----------------------|--------------------|----------|-----------|--------|--------|
| 3; 0.2 m/sec               | 2                    | 4                  | 325      | 335       | 358    | 333    |
|                            | 50                   | 292                | 333      | 325       | 358    | 333    |
|                            | 60                   | 325                | 358      | 335       | 375    | 359    |
|                            | 70                   | 330                | 375      | 340       | 387    | 375    |
|                            | 80                   | 333                | 392      | 350       | 404    | 392    |
|                            | 90                   | 339                | 406      | 358       | 425    | 405    |
|                            | 100                  | 346                | 425      | 365       | 446    | 421    |
|                            | 50                   | 341                | 496      | 375       | 496    | 466    |
|                            | 60                   | 363                | 510      | 387       | 530    | 492    |
| 3; 0.3 m/sec               | 70                   | 375                | 521      | 396       | 558    | 517    |
|                            | 80                   | 392                | 571      | 421       | 617    | 567    |
|                            | 90                   | 408                | 621      | 442       | 675    | 617    |
|                            | 100                  | 429                | 667      | 463       | 729    | 658    |
|                            | 50                   | 387                | 542      | 408       | 654    | 542    |
|                            | 60                   | 417                | 663      | 458       | 813    | 654    |
| 3; 0.4 m/sec               | 70                   | 458                | 750      | 500       | 833    | 750    |
|                            | 80                   | 496                | 875      | 558       | 958    | 863    |
|                            | 90                   | 518                | 958      | 608       | 1084   | 958    |
|                            | 100                  | 571                | 1063     | 650       | 1175   | 1050   |
|                            | 50                   | 454                | 750      | 500       | 917    | 742    |
|                            | 60                   | 500                | 946      | 583       | 1188   | 917    |
| 3; 0.5 m/sec               | 70                   | 583                | 1125     | 667       | 1417   | 1084   |
|                            | 80                   | 667                | 1284     | 767       | 1485   | 1271   |
|                            | 90                   | 729                | 1434     | 833       | 1584   | 1334   |
|                            | 100                  | 792                | 1571     | 917       | 1612   | 1417   |
|                            | 50                   | 329                | 367      | 333       | 379    | 367    |
|                            | 60                   | 333                | 383      | 342       | 396    | 383    |
| 2; 0.2 m/sec               | 70                   | 337                | 400      | 346       | 417    | 396    |
|                            | 80                   | 342                | 417      | 354       | 433    | 413    |
|                            | 90                   | 350                | 433      | 362       | 454    | 429    |
|                            | 100                  | 354                | 450      | 367       | 471    | 446    |
|                            | 50                   | 375                | 496      | 387       | 529    | 492    |
|                            | 60                   | 383                | 546      | 408       | 588    | 542    |
| 2; 0.3 m/sec               | 70                   | 404                | 596      | 433       | 646    | 589    |
|                            | 80                   | 417                | 642      | 450       | 700    | 637    |
|                            | 90                   | 438                | 692      | 475       | 754    | 683    |
|                            | 100                  | 450                | 738      | 496       | 808    | 729    |
We present the calculation results visualization in the histograms form in Figures 2-3, displaying the obtained dependencies for the first, highest purity class that meets the ISO 8573-1-2016 requirements.

**Figure 2.** Dependence of power losses on the compressor drive on adsorbent material and relative humidity of atmospheric air (Red for composite material, purple for alumogel, green for silicagel, sand for carbon and blue zeolite respectively).
Figure 3. Power losses on the compressor drive on the adsorbent material and bulk density dependence. (Red for composite material, purple for alumogel, green for silicagel, sand for carbon and blue zeolite respectively).

3. Resume
From the analysis of the obtained histograms (Fig. 2, 3) and the calculation data presented in the tables, there is a clear tendency to a decrease in energy consumption for the compressor drive with an increase in the flow rate, relative humidity and the required air purification class (Fig. 2), however, this increase has minimal values at the composite adsorbent. This tendency is due to lower values of the bulk density of the composite (Fig. 3), which makes it possible to reduce the hydraulic resistance, and therefore the pressure loss when compressed air passes through the adsorbent layer, and, as a consequence, the energy costs for carrying out the adsorption processes.

4. References
[1] Ripol-Saragosi T, Ripol-Saragosi L. System Approach Realization Under Compressed Air Quality Increase Strategy Choice Based on Resource Saving Proceedings of the 4th International Conference on Industrial Engineering ICIE 2018 Springer, Charm pp 2255-2262
[2] Ripol-Saragosi T, Ripol-Saragosi L. Adsorption Equipment Energy Efficiency Increase, Proceedings of 2020 International Multi-Conference on Industrial Engineering and Modern Technologies (FarEastCon) DOI: 10.1109/FarEastCon50210.2020.9271276 https://ieeexplore.ieee.org/document/9271276
[3] GOST 32202-2013 Compressed air of railway rolling stock pneumatic systems Requirements for quality p 7
[4] Salazar Duarte G, Schürer B, Voss C, Bathen D 2017 Adsorptive separation of CO from flue gas by temperature swing adsorption processes ChemBioEng Rev. 4 277–288
[5] Ripol-Saragosi T, Ripol-Saragosi L. 2019 Compressed Air Drying Process Energy Consumption Decrease by Intellectual Management Systems Implement Proceedings of International Multi-Conference on Industrial Engineering and Modern Technologies (FarEastCon) (Vladivostok)
[6] Hristov J, Boyadjiev Chr. and Pantofchieva L 2000 Sulphur Dioxide Adsorption in a Magnetically Stabilized Bed of a Synthetic Anionite Theoretical Foundations of Chemical Engineering 34 439-443 https://doi.org/10.1007/BF02827387
[7] Jinsheng Xiao, Ruipu Li, Pierre Benard, Richard Chahine 2015 Heat and Mass Transfer Model of Multicomponent Adsorption System for Hydrogen Purification International Journal of Hydrogen Energy Vol. 30 p 1
[8] Sarah Abaza Adsorption compression in surface layers June 2012 Molecular Physics 110(11-12) 1-10 DOI:10.1080/00268976.2011.648963
[9] Dąbrowski A 2001 Adsorption—from theory to practice Adv. Colloid Interface Sci. 93 135–224
[10] Yang R T 2013 Gas Separation by Adsorption Processes. Imperial College Press (London) https://doi.org/10.1142/p037
[11] Grande C A 2012 Advances in pressure swing adsorption for gas separation *ISRN Chem. Eng.* 1–13