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# Hydraulic Regularities of Fluidized Bed During Encapsulation of Organo-mineral Fertilizers

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Abstract: The advantages of using encapsulated organo-mineral fertilizers are presented. It is proposed to use a fluidized bed apparatus for coating carbamide granules with an organic shell. Importance of the fluidized bed hydraulic characteristics and their influence on the energy costs of the process are emphasized. Experimental study results prove that irrigation density of granular layer with the suspension has significant influence on the hydraulic resistance of a fluidized bed. It is proposed an analytical dependence for determining the hydraulic resistance of a fluidized bed, which takes into account influence of the organic suspension flow rate.

Keywords: organo-mineral fertilizers, granulator, fluidized bed; hydraulic resistance of the suspension

## 1. Introduction

Present time agriculture is impossible without the use of granular mineral fertilizers. At the same time, with increasing environmental problems, the use of granular fertilizers, which combine mineral and organic substances, is actively promoted. This approach is implemented by encapsulating of mineral granules with an organic shell.

The process of applying protective organic shells onto mineral fertilizer granules can be called both encapsulation and granulation, since a significant increase of the initial granule size is observed. Therefore, standard equipment designed for granulation of fertilizers can be used to implement such a process [1-3]. However, it should be considered that, unlike mineral substances, organic substance has its own characteristics, which include burning ability, decomposition at high temperatures, increased ability to stick together and lump.

Among all the types of granulation equipment, the most significant role in modern technology is played by the fluidized bed [4, 5]. Encapsulation of dispersed materials in the fluidized state is a common physical method of applying polymer shells, which is used in chemical and related industries. Fluidization technique has become widely used due to high intensity of heat and mass exchange processes.

To maintain the granular layer in suspended state, it is required the continuous exchange of energy between it and the fluidizing agent. Energy released by the fluidizing agent is spent both on overcoming the friction of particles against each other and the gas flow on their surface, and on the expansion of the layer. It predetermines the existence of a certain pressure drop, i.e. hydraulic resistance of the fluidized bed. This parameter needs to be taken into account when choosing fan machines for supplying the fluidizing agent to a fluidized bed apparatus. Therefore, calculation of this parameter makes it possible to select rational energy costs for implementation of the encapsulation process in a fluidized bed apparatus.

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## 2. Problem Statement

Hydraulic resistance is one of the most important characteristics of the fluidized bed apparatuses. Classical ideas about the dependence of hydraulic resistance of a fluidized bed on the velocity of gas or liquid flows are as follows. Up to reaching the first critical velocity (fluidization process initial velocity) resistance increases and when this velocity is reached, the resistance remains constant value [6, 7]. At the same time, it is proposed [8-10] to determine the hydraulic resistance value of the layer using the common dependence

$$\Delta P = (\rho_S - \rho_L) g (1 - \varepsilon) H, \tag{1}$$

where $\Delta P$ – hydraulic resistance of the layer, Pa; $H$ – fluidized bed height m; $g$ – free fall acceleration of solid particles, m/s$^2$; $\rho_L$, $\rho_S$ –flow and solid particles density, respectively, kg/m$^3$; $\varepsilon$ – layer porosity.

Particle size has significant effect on the hydraulic resistance of a fluidized bed. With the particle size increase, the hydraulic resistance of the layer increases [11]. Neglecting pressure losses due to friction, the authors of [11] propose an equation for determining the hydraulic resistance of a fluidized bed as following

$$\Delta P / H = g\,(\rho_L \varepsilon_L + \rho_S \varepsilon_S), \tag{2}$$

where $\varepsilon_L$, $\varepsilon_S$ – volume content of the flow and solid particles in the layer, respectively.

The more accurate Ergun formula takes into account the fluidized particle size and flow velocity [12]

$$\Delta P = f \frac{H w^2 \rho_L (1 - \varepsilon)}{d_S \varepsilon^3}, \tag{3}$$

where $f$ – flow resistance coefficient; $w$ – flow rate, m/s; $d_S$ – particle diameter, m.

The authors in [13] obtained an empirical dependence for determining the flow resistance coefficient in the equation (3) as a function of the Reynolds criterion. A similar approach was applied by the authors in [14]: the formula for determining the flow resistance coefficient was defined by introducing the layer porosity into the equation.

In [15], the authors analysed the most well-known dependences for determining the hydraulic resistance of a fluidized bed. The results are presented for the fluidization mode with and without the thermomechanical effect. The effect of the fluidized bed height and fluidizing agent velocity on the pressure drop across the fluidized bed was determined. A regular increase in the pressure drop with an increase in the layer height and gas flow rate was revealed. The authors proposed an experimental correlation to determine the maximum hydraulic resistance of the layer in the form of a dependence

$$\frac{\Delta P}{\rho_S w^2} = 1{,}069 \left( \frac{H}{D} \right)^{0{,}65} \left( \frac{2gH(\rho_S - \rho_L)}{\rho_L} \right)^{0{,}3575}, \tag{4}$$

where $D$ – layer diameter, m.

In [16], authors analysed the pressure drop during the movement of the gas flow through the holes of a gas distribution grid and free space for unloading particles from the layer. Dependences have been obtained for estimating the velocity profile of a gas flow as it passes through perforation holes of an inclined gas distribution grid.

In [17], the authors studied the dependence of the hydraulic resistance of a circulating fluidized bed on different heights of the bed. In [18], the authors studied influence of the apparatus diameter ratio to the diameter of the granular material particle on the hydraulic resistance of the layer.

In [19], the authors studied the influence of factors such as inlet air temperature, gas flow rate, moisture content, mixing rate, and binding agent properties on the fluidized bed agglomeration process.

The authors in [20] prove the crucial influence of such factors as the height of the fluidized bed and the solid particles circulation on the granule coating process. It is shown that regulation of these parameters leads to a change of the particle coating thickness. However, influence of the flow rate of the suspension, sprayed onto the fluidized bed, on the value of the hydraulic resistance of the fluidized bed has not been studied.

In [21], a new conceptual model for the simultaneous control of a particle size and porosity in the fluidized bed granulation process was proposed, which ensured stable operation of the process, automatic adjustment of the desired properties of the finished product, and prevention of unforeseen violations of the technological mode. However, regulation of the particle size was carried out by auxiliary processes - grinding and sieving of the finished granules. The influence of mode and technological parameters on the granulation process, including the hydraulic resistance of the layer, has not been studied.

In [22] there was studied influence on the granulation process in a fluidized bed of such parameters as the granule growth rate and density of the granule surface spraying. Though density of spraying influence on the granule growth rate was studied, but there was no research of its effect on hydrodynamic characteristics of the fluidized bed.

The analysis of the conducted studies of the fluidized bed processes showed insufficient knowledge of the hydraulic characteristics. Density of spraying influence on the layer hydraulic resistance in a fluidized bed granulator remains insufficiently studied.

## 3. Experimental Materials and Methods

Studies of encapsulation of mineral fertilizer granules with an organic shell were carried out in a laboratory unit (Fig. 1, a). Urea was used as a core mineral fertilizer.

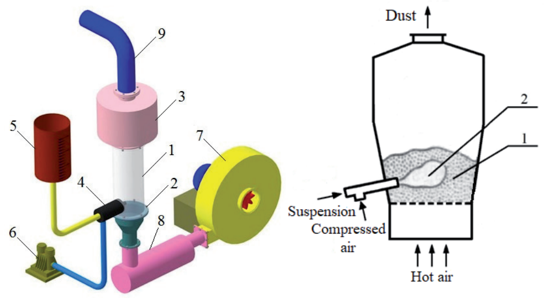


Figure 1: Scheme of the laboratory unit (a) and apparatus (b) for encapsulation of granular fertilizers: 1 – working chamber; 2 – air distributor; 3 – separation chamber; 4 – pneumatic nozzle; 5 – measuring tank; 6 – compressor; 7 – blower; 8 – heater; 9 – air corrugation; 10 – pellet drying zone; 11 – irrigation zone.

The laboratory unit (Fig. 1, a) includes the working chamber 1, made of organic glass, which enables visualization of the research process. Encapsulation takes place directly in the fluidized bed. For this, a suspended layer of 150-200 mm height is prepared on the surface of the gas distribution grid 2. On the side of the device, approximately in the middle part of the layer, a pneumatic nozzle 4 is installed, to which compressed air and liquid organics, which is a suspension (a mixture of liquid and small (10-20 μm) organic particles), are supplied from the compressor 6. The organic suspension from measuring tank 5 is captured by compressed air and sprayed onto the layer of granules, forming a cavity in it. Thus, the fluidized bed is divided into two zones: the main zone 10, where the granules are dried, and the spraying zone 11, where the granules are covered with the layer of suspension (Fig. 1, b). The drying agent is supplied into the device by the gas blower 7 and heated in the heater 8 to a temperature of 80°C. Spent drying agent is removed from the device through the separation chamber 3.

First, the initial sample of urea granules was weighed on a Momert-6000 electronic balance with an accuracy of 0.1 g and loaded into the product chamber 1. The gas blower 7 was turned on and four different air flows were set through the layer of granules under study with the help of a control valve. Semiconductor hot-wire anemometer with an accuracy of 0.001 m/s measured the gas flow rate in the free space under the gas distribution grid. The apparatus pressure drop was measured with an alcohol U-shaped manometer, one tube of which was connected to a point in the apparatus body at a distance of 2 mm above the gas distribution grid, and the second tube was connected to the gas outlet opening positioned past the fluidized bed section. The measurement error when reading two levels (on each tube) was ±2 mm at an ambient temperature of 20 ± 5°C.

Liquid air flow rate was changed according to the values of 2.8; 3.5; 4.8; 5.6 m/s. The study was conducted at four constant (for each case) suspension flows: 10; 13.5; 20; 25 ml/min. The obtained experimental results of the fluidized bed hydraulic resistance were compared with the hydraulic resistance values of the dry gas distribution grid. To determine the latter, impulse tubes of the U-shaped manometer were placed under the gas distribution grid and above it, respectively. In this case, the research was carried out without feeding the suspension and without charging the granular material.

## 4. Results

To generalize the results, hydraulic resistance values of the dry gas distribution grid (Fig. 2) and the suspended layer of urea granules (Fig. 3) were determined at different liquid air flow rates, respectively.

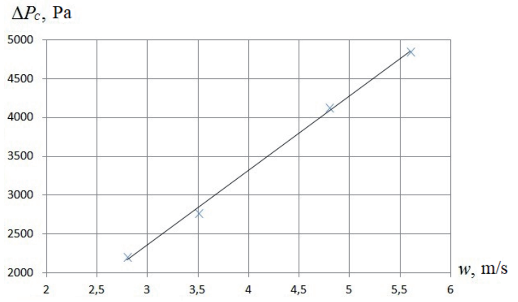


Figure 2: Dependence of the dry gas distribution grid resistance $\Delta P_C$ on the liquid air flow rate w

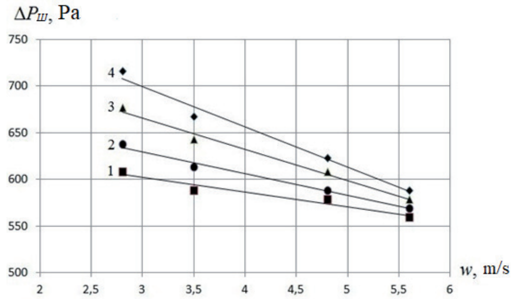


Figure 3: Dependence of the urea granule layer resistance $\Delta P_L$ in the fluidized form on the liquid air flow rate w with the corresponding consumption of the chicken manure suspension $G_C$ ($l_{CONS}$): *1 – 10 ml/min (0,00657 kg/(s·m²)); 2 – 13,5 ml/min (0,00887 kg/(s·m²)); 3 – 20 ml/min (0,0131 kg/(s·m²)); 4 – 25 ml/min (0,0164 kg/(s·m²)).*

The hydraulic resistance dependence of the dry gas distribution grid on the gas flow rate differs from the one for the fluidized bed. In the first case, the hydraulic resistance monotonically increases, and in the second one, on the contrary, it decreases with the gas flow rate growth.

## 5. Discussion

According to the classical concepts [4], in the mode of active fluidization, fluidized bed hydraulic resistance does not change with an increase in the gas flow velocity in the range from the first to the second critical velocity. As it is shown by the analysis of dependences (Fig. 3), encapsulation process is characterized by the hydraulic resistance change of a different nature: its value increases with the gas flow rate growth. It is explained by the presence of a film-making substance on the granule surface. The liquid film changes the rheological properties of the granular layer by increasing the adhesion forces between the particles. As it can be seen from Fig.3, as gas flow rate increases and suspension flow rate decreases it reduces the difference between the resistance values. It is explained by a decrease of the particle surface area on which the film-forming solution is spared.

The obtained experimental results are presented as a dependence of dimensionless values:

$$\frac{\Delta P_\Sigma}{\Delta P_C} = f\left(\frac{l_{CONS}}{g_{CONS}}\right), \qquad (5)$$

where $\Delta P_C$ – resistance of the dry gas distribution grid, Pa; $\Delta P_\Sigma$ – total resistance of the granular layer sprayed with the suspension and the gas distribution grid, Pa; $l_{CONS} = \frac{G_C}{S}$ – specific consumption of organic suspension, kg/(s·m²); $g_{CONS} = \frac{G_{II}}{S}$ – $g_{CONS}$ specific consumption of liquid air, kg/(s·m²); $S$ – cross-sectional area of the apparatus, m²; $G_S$, $G_A$ – respectively, mass consumption of organic suspension and liquid air, kg/s.

According to equation (1), experimental data can be represented by the dependences shown in Fig. 4.

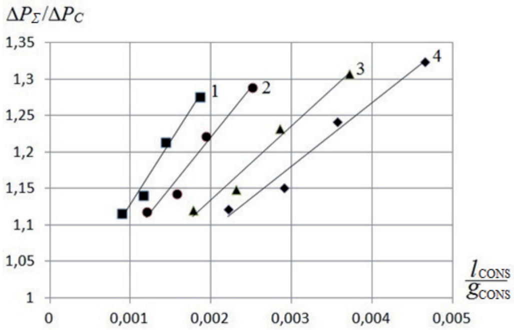


Figure 4: Graphic dependence $\frac{\Delta P_\Sigma}{\Delta P_C} = f\left(\frac{l_{CONS}}{g_{CONS}}\right)$, with the corresponding specific consumption of chicken manure suspension $l_{CONS}$ : 1 – 0,00657 kg/(s·m²); 2 – 0,00887 kg/(s·m²); 3 – 0,0131 kg/(s·m²); 4 – 0,0164 kg/(s·m²).

Dependence $\frac{\Delta P_\Sigma}{\Delta P_C} = f\left(\frac{l_{CONS}}{g_{CONS}}\right)$, we consider linear, i.e.:

$$\frac{\Delta P_\Sigma}{\Delta P_C} = A \cdot \left(\frac{l_{CONS}}{g_{CONS}}\right) + B, \qquad (6)$$

where A, B – empirical constants.

Values of the constants A and B are found by approximating the experimental data (Table 1).

Table 1: Numerical values of constants A and B.

| $l_{CONS}$, kg/(s·m²) | A | B |
|---|---|---|
| 0,00657 | 173,4 | 0,9547 |
| 0,00887 | 137,5 | 0,9511 |
| 0,0131 | 101,2 | 0,9495 |
| 0,0164 | 87,0 | 0,9489 |

As it can be seen from the Table 1, values of the constant B at different feed of organic suspension are approximately the same and equal to B=0,95.

To generalize values of the constant A, one makes its graphic dependence on the specific consumption of the suspension $l_{CONS}$ (Fig. 5), which is best approximated by the following exponential function

$$A = 3{,}8 \cdot l_{CONS}^{-0{,}76}. \tag{7}$$

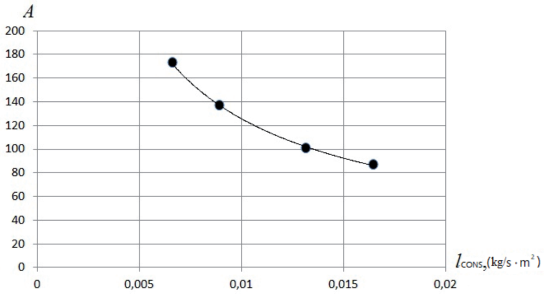


Figure 5: Dependence of constant A on the specific consumption of the suspension $l_{CONS}$.

Substituting (3) into equation (2) and taking into account value of the constant B, one obtains the equation for predicting the hydraulic resistance change of the material in the fluidized bed during its spraying, depending on the specific consumption of organic suspension and liquid air:

$$\frac{\Delta P_{\Sigma}}{\Delta P_{\tilde{N}}} = 3{,}8 \cdot l_{CONS}^{-0{,}76} \cdot \left(\frac{l_{CONS}}{g_{CONS}}\right) + 0{,}95. \tag{8}$$

The root-mean-square deviation of the experimental and theoretical values according to equation (4) fluctuates within the limits 5 – 10%.

## 6. Conclusions

An equation for calculating the hydraulic resistance of a fluidized bed of granular material is obtained, taking into account the spraying intensity of the film-forming substance on the urea granule.


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## References


1. Yukhimenko, N., Vakal, S. (2016). The exergy analysis of energy efficiency of the technology of granulated phosphorus-potassium fertilizers. Eastern-European Journal of Enterprise Technologies, 5(6), 4–10. doi:10.15587/1729-4061.2016.77182
2. Moure Abelenda, A., Amaechi, C.V. (2022). Manufacturing of a granular fertilizer based on organic slurry and hardening agent. Inventions, 7, 26. https://doi.org/10.3390/inventions7010026
3. Nadhem, A.-K. M., Skydanenko, M., Ostroha, R., Neshta, A., Yukhymenko, M., Yakhnenko, S., Zabitsky, D., Yesypchuk, S., & Moskalchuk, O. (2022). Research of plate granulator operation modes in the production of coarse carbamide granules. Technology Audit and Production Reserves, 1(3(63), 12–15. https://doi.org/10.15587/2706-5448.2022.252367.
4. Ravi Maharjan, Seong HoonJeong. (2022). Application of different models to evaluate the key factors of fluidized bed layering granulation and their influence on granule characteristics. Powder Technology, Volume 408, August 2022, 117737. https://doi.org/10.1016/j.powtec.117737
5. Ostroha, R., Yukhymenko, M., Bocko, J., Artyukhov, A., & Krmela, J. (2021). Determining the main regularities in the process of mineral fertilizer granule encapsulation in the fluidized bed apparatus. Eastern-European Journal of Enterprise Technologies, 4(6(112), 23–32. https://doi.org/10.15587/1729-4061.2021.239122
6. Kaza, S.R.V.N. (2008). Effect of the shape of the baffles on the hydrodynamics of a fluidized bed. Int. J. Chem. React. Eng., 6, 1–14.
7. Sippola, P., Kolehmainen, J., Ozel, A., Liu, X., Saarenrinne, P., Sundaresan, S. (2018). Experimental and numerical study of wall layer development in a tribocharged fluidized bed. J. Fluid Mech., 849, 860–884.
8. Richardson, J.F., Zaki, W.N. (1997). Sedimentation and fluidization: Part i. Chem. Eng. Res. Des., 75, S82–S100.
9. Chen, X.Z., Shi, D.P., Gao, X., Luo, Z.H. (2011). A fundamental cfd study of the gas-solid flow field in fluidized bed polymerization reactors. Powder Technol., 205, 276–288.
10. Islam, M.T., Nguyen, A.V. (2021). Effect of particle size and shape on liquid-solid fluidization in a hydrofloat cell. Powder Technol.,

379, 560–575.

11. Abdulrahman, A.A., Mahdy, O.S., Sabri, L.S., Sultan, A.J., Al-Naseri, H., Hasan, Z.W., Majdi, H.S., Ali, J.M. (2022). Experimental investigation and computational fluid dynamic simulation of hydrodynamics of liquid–solid fluidized beds. Chem. Engineering, 6, 37. https://doi.org/ 10.3390/ chemengineering6030037
12. Ergun, S. (1952). Fluid flow through packed column. Chem. Eng. Prog., 48, 89–94.
13. Peng, J., Sun, W., Xie, L., Han, H., Xiao, Y. (2022). An experimental study of pressure drop characteristics and flow resistance coefficient in a fluidized bed for coal particle fluidization. Minerals, 12, 289. https://doi.org/ 10.3390/min12030289
14. Geller, Y.A., Shatskikh, Y.V., Antanenkova, I.S. (2020). Research of air-fluidized bed in the drying process of granulated hydrophobic polymers. Journal of Physics: Conference Series, 1565, 012033. doi:10.1088/1742-6596/1565/1/012033
15. Monazam, E.R., Breault, R.W., Weber, J. (2017). Analysis of maximum pressure drop for a flat-base spouted fluid bed. Chemical Engineering Research and Design, Volume 122, Pages 43-51. https://doi.org/10.1016/j.cherd.2017.03.032
16. Yukhymenko, M., Artyukhov, A., Ostroha, R., Artyukhova, N., Krmela, J., Bocko, J. (2021). Multistage shelf devices with fluidized bed for heat-mass transfer processes: experimental studies and practical implementation. Appl. Sci., 11, 1159. https://doi.org/ 10.3390/app11031159
17. Teplitskii, Y.S., Kovenskii, V.I. (2001). Resistance of a circulating fluidized bed. Journal of Engineering Physics and Thermophysics 74, 86–93. https://doi.org/10.1023/A:1016630121519
18. Bakhronov, K.S., Khudoiberdieva, N.S. (2007). Hydraulic resistance of a granular bed in a rising liquid flow. Chem Petrol Eng 43, 716–719. https://doi.org/10.1007/s10556-007-0129-2
19. Yuksel, H., Nur Dirim, S. (2018). Agglomeration process in the fluidized bed, the effecting parameters and some applications. Croatian Journal of Food Technology, Biotechnology and Nutrition 13 (3-4), 159-163. https://doi.org/10.31895/ hcptbn.13.3-4.10
20. Seyedin, S.H., Ardjmand, M., Safekordi, A.A., Raygan, S. (2017). Experimental investigation and CFD simulation of top spray fluidized bed coating system. Periodica Polytechnica Chemical Engineering, 61(2), 117-127. doi.org/10.3311/PPch.8611.
21. Neugebauer, C., Bück, A., Kienle, A. (2020). Control of particle size and porosity in continuous fluidized-bed layering granulation processes. Chem. Eng. Technol, 43, No. 5, 813–818. doi: 10.1002/ ceat.201900435.
22. Dosta, M., Antonyuk, S., Heinrich, S. (2013). Detailed macroscopic flowsheet simulation of fluidized bed granulation process based on microscale models. In "The 14th International Conference on Fluidization – From Fundamentals to Products", J.A.M. Kuipers, Eindhoven University of Technology R.F. Mudde, Delft University of Technology J.R. van Ommen, Delft University of Technology N.G. Deen, Eindhoven University of Technology Eds, ECI Symposium Series. http://dc.engconfintl. org/ fluidization_xiv/49.