Simulation of the particle motion in devices with vertical sectioning of workspace

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Abstract

Introduction. The relevance of the topic is determined by the wide using of suspended bed apparatus during the heat treatment of dispersed materials.

Materials and methods. Analytical studies were carried out using the classical provisions of gas and fluid mechanics and technical fluid mechanics. Physical experiment was done on the development of industrial design multistage shelf device.

Results and discussion. The mathematical model to calculate the residence time of a particle in shelving unit is developed, its adequacy confirmed by experimental studies. The model can be applied for the drying, cooling, granulation processes calculation. The residence time of a single particle on a shelf in operating mode from 2 to 20 seconds, depending on the constructive execution shelf and the gas flow rate. The mutual influence of particles during their stay on the shelf increased by an average of 40 times. For the regime of particle motion in fluidized bed (constricted movement) the maximum time can be up to 20 minutes. Changing the angle of the shelf and its length has little influence as compared with a change in the hydrodynamic regime of gas flow. Design of shelf significantly affect the residence time of the particles in the apparatus only in compressed motion regime. This work theoretically and experimentally proved the existence of different regimes shelf apparatus.

Conclusions. The influence mechanism of design shelf and hydrodynamic regime of the gas flow on particle residence time in multistage gravity shelf apparatus is established. The research results are the basis of engineering calculation of equipment with a vertical sectioning of the workspace.

Introduction

The most widely in the chemical and food technology convective method of heat treatment is widespread [1-3]. It involves the transfer of heat from the coolant (air, inert gases and smoke) to the surface of the material during heating.

One of the methods of convective heat treatment is material contact with the coolant in suspended or semi suspended state [4-8]. It can take place in drum apparatus, the fluidized bed apparatus, pneumatic tubes-dryers [9-13].

Each of mentioned types of equipment is characterized by certain disadvantages. Drum machines and the fluidized bed apparatus have large sizes and significant power consumption. Pneumatic tubes drying do not provide the required contact time of wet material with coolant and characterized by a large height.

In recent years carried out a search for new highly efficient methods of convective heat treatment of granular materials. Gravity machines with vertical sectioning of interior space (shelving units) are one of the most perspective designs. It occupies an intermediate position between fluidized bed and pneumatic tubes devices. Specific air flow in such devices smaller than in the case of fluidized bed (0,5-0,6 kg/m^3 against 1,4-2,8 kg/m^3), unit load by the product for the same types of equipment – 0,1-0,5, and 15-20 kg/(m^2·s) respectively [14].

These types of devices are used in industry as air classifiers, coolers, dryers. The use of multistage contact between gas and grains on cooling section of vortex pellet is proposed [A method for producing granules in suspended layer and device for its implementation, application No.a201403429, 03.04.2014]. At the residence time of the material in these devices exert major influence organizing gas flow movement and design shelf contacts.

Objective - to develop mathematical instrument to calculate the residence time of the dispersed phase in the multistage shelf devices, experimental verification of the adequacy of mathematical models.

Materials and methods

In this work the analytical and experimental methods are used.

Mathematical modeling of hydrodynamic flows was carried out on the basis of classical mechanics provisions of liquid, gas and technical hydromechanics. Solving equations of the mathematical model was conducted by using the computer algebra system Maple 12.

Experimental studies carried out on research and industrial models multistage shelf devices. The experimental setup is presented in fig. 1.

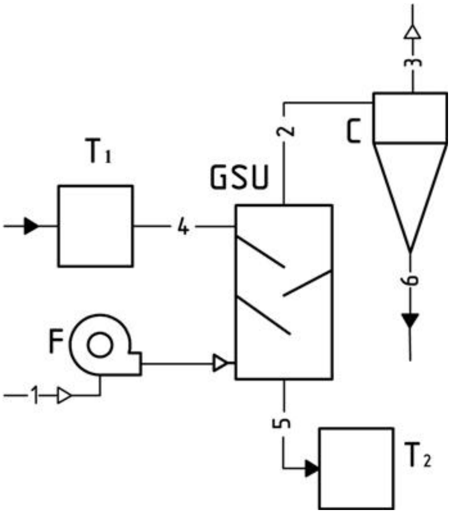


Fig. 1. Schematic diagram of the experimental setup for the study of hydrodynamics shelf devices:
F – fan; GSU – gravitational shelf unit;
C – cyclone; T_1 – container (tank) for source material;
T_2 – container (tank) for waste material.
1 – the air; 2 – exhaust air; 3 – cleaned exhaust air; 4 – the initial material; 5 – waste material; 6 – fine material

Air flow consumption is controlled by diaphragm chamber as the primary instrument, measuring differential pressure transducer and an analog device. Changing the air flow was conducted by using sliding latch that is located after the fan.

Consumption of particulate material is controlled by flow meter of bulk materials. Changing the particulate material consumption carried out by dosing device that is located on the pipeline granular material.

The distribution of the gas flow velocity in the workspace shelf device was investigated, using 5-channel spherical aerodynamic probe. Aerodynamic probe pulse pipelines connected to the micromanometer that was registered data measurements. Calibration of the probe is executed by Prandtl (Pitot) tube in an aerodynamic tube with strong orientation in space.

The residence time of the particles in the volume of the device controlled with a stopwatch. For compressed motion of particles on the shelf, the method "tracer" particles are used. As a model material polypropylene granules with a size of 2-3 mm are used. For granules first calculated (early fluidization velocity) W_{g1} and then (initial speed of particles) W_{g2} critical velocity gas flow [15].

Reliability of the experimental results caused by the use of exhaust practice methods.

Results and discussion

Consider the motion of a particle between shelf spaces (fig. 2).

If the working gas velocity in the holes is $W>W_{g1}$ it will be kept in suspension until achieving value $W=W_{g2}$, which causes it passing. If air velocity is $W<W_{g2}$, then this $\Delta W = W_{g2} - W$ difference will result in movement of the particle velocity down. If $W<W_{g1}$ particle will move in a gravitational mode falling layer with a sharp decrease in the residence time on the shelf. Time τ movement along the shelf at an angle $\gamma = 90\,°$ and length L is equal to

$$\tau = \frac{L}{\Delta W}. \qquad (1)$$

In the case when shelf set at a slight angle (in practice within the 10-35°), the speed ΔW that characterizes the motion of a particle from top to bottom have a rolling component $F_r = f(\Delta W \cdot \sin\gamma)$, because the normal pressure force particles on the shelf are $F_n = f(\Delta W \cdot \cos\gamma)$ and therefore, the normal components of acceleration and speed will be compensated normal reaction of shelf N (fig. 2).

Thus, the movement of particles along the shelf by the equation

$$\tau = \frac{L}{\Delta W \sin\gamma}, \qquad (2)$$

at $\gamma = 90^{\circ}$ in the previous expression simplifies to (1).

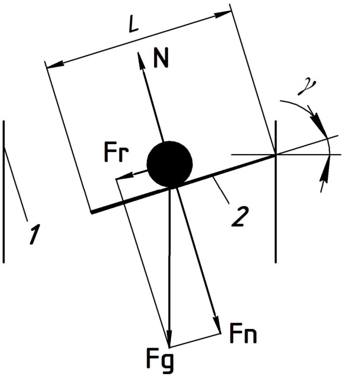


Fig. 2. Power Analysis of particulate material on an inclined shelf contact:

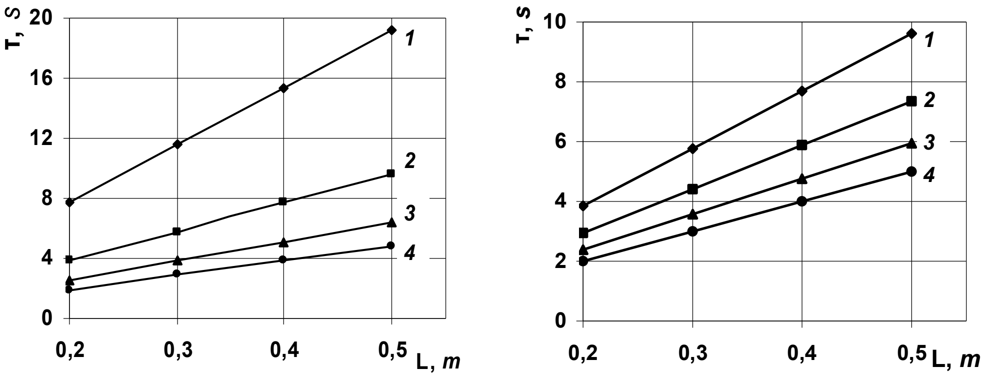
F_g – gravity, N;
F_r – rolling force, N;
F_n – normal pressure force particles on the shelf, N;
N - shelf reaction, N;
γ – shelf angle to the horizontal, deg;
1 – the body of apparatus;
2 – perforated sloping shelf

The ratio of particle time along the shelf inversely proportional to the sine of the angle of inclination of the shelf:

$$\frac{\tau_1}{\tau_2}=\frac{\sin\gamma_2}{\sin\gamma_1} \tag{3}$$

From these considerations we can determine a constructive influence on particle residence time between shelf spaces. For example, reducing the angle of the shelf, achieved an increase in the residence time of the dispersed particles at this stage.

Calculation results of the residence time of single particles on the shelf under different conditions are presented in fig. 3.



ΔW, m/s:
1 – 0.1; 2 – 0.2; 3 – 0.3, 4 – 0.4.

γ:
1 = 15°; 2 = 20°; 3 = 25°; 4 = 30°.

Fig. 3. The residence time of particles on the shelf (single particle motion)

Equation (2) to determine the particle residence time on the shelf that moves independently of the other particles is considered its free movement. This free movement is observed only at low volume content of the dispersed phase in the two-phase system (δ<0,01 m^3/m^3), where the distance between the particles is such that there is not any collisions or mutual influence of particles. At $\delta \geq 0{,}01$ m^3/m^3 (compressed motion of a particle) system behavior changes: the distance between the surfaces of particles or dimensions aisle between particle become smaller of their diameter. The particle cannot freely slip between two other [16-18]. It is necessary to consider the effect of collisions of particles with each other. In addition, the collision of particles in two-phase system may also occur in the case where the dispersed phase consists of poly disperse particles or particles with different density.

Consideration of phenomenon of compressed particle motion and power of interfacial interaction is possible with the introduction coefficient of particle stringency χ.

For coefficient of stringency, particles based on different schemes of arrangement obtained different formulas [19,20]. Specifically, the scheme with the free falling calculated by the formula

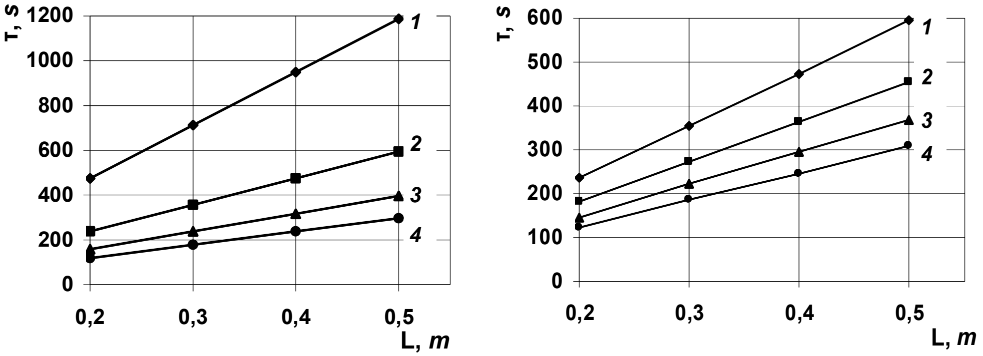
$$\chi=(1-\delta)^{-m}, \tag{4}$$

where δ = 0,6 (free backfill of random nature [19]); m = 3-5 [15].

Therefore, the expression (4) takes the form

$$\tau = \frac{L \cdot \chi}{\Delta W \sin \gamma}. \tag{5}$$

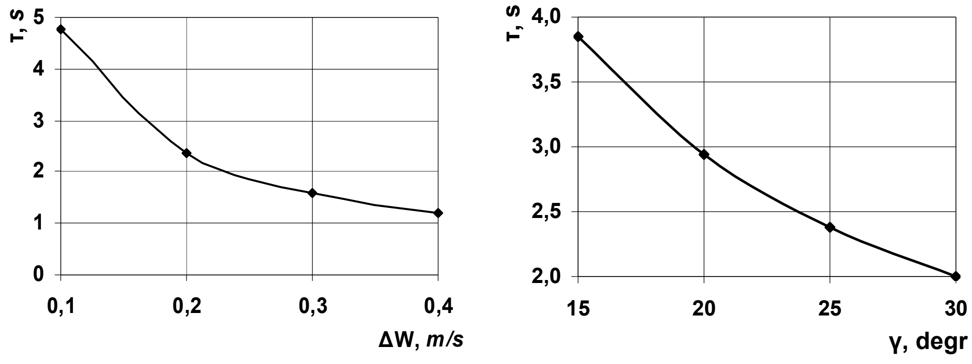
Calculation results of particle residence time on the shelf in compressed regime motion for different initial conditions are presented in fig. 4.



ΔW, m/s:
1 – 0.1; 2 – 0.2; 3 – 0.3, 4 – 0.4.

γ:
1 = 15°; 2 = 20°; 3 = 25°; 4 = 30°.

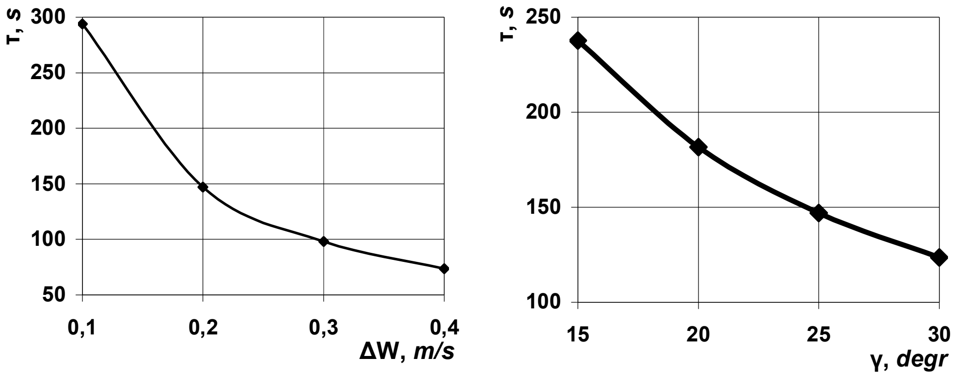
Fig. 4. The residence time of particles on the shelf (stringency particles motion)



a *b*

Fig. 5. The particle residence time on the shelf with length L = 0, 2 m (single particle motion):
a – γ = 25°; *b* – ΔW = 0,2 m/s

In figs. 5,6 the experimental results of determining the particle residence time on the shelf in its single mode and compressed motion depending on the angle of the shelf and the difference of velocities according to formulas (2) and (5). The obtained results allow us to determine the total particle residence time in the working space of the machine depending on the number stages contact with the gas flow and shelf design.

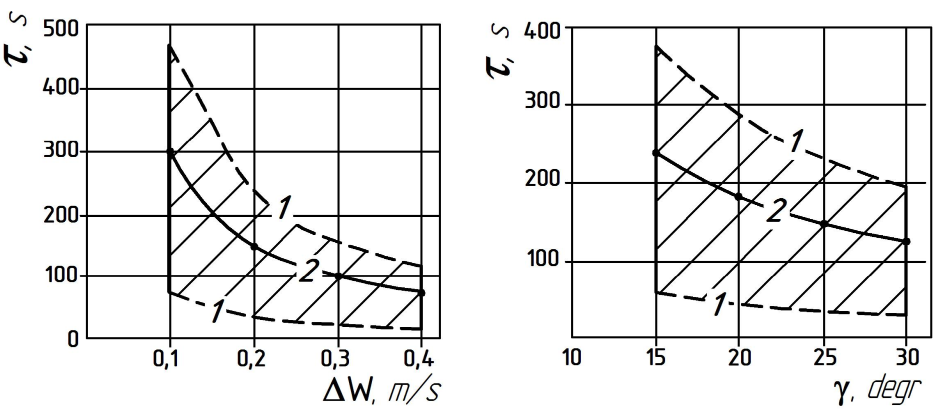


a *b*

Fig. 6. The particle residence time on the shelf with length L = 0, 2 m (stringency particles motion):

a – $\gamma = 25^{\circ}$; *b* – ΔW = 0,2 m/s

Comparison of theoretical calculations of the particle residence time on the shelf in the range *m* from 3 to 5 in formula (4), and experimental determination of this parameter (in the case of compressed motion of dispersed particles) gives satisfactory results (fig. 7).



a b

Fig. 7. The particle residence time on the shelf with length L = 0,2 m (compressed motion of particles):

a – $\gamma = 25^{\circ}$; *b* – ΔW = 0,2 m/s;

1 – theoretical calculation range; 2 – experimental data

In fig. 8 shows the data of experimental research of dispersed particles residence time on a shelf in compressed motion mode with regard to operating mode of shelf apparatus. Research results indicate a sharp increase in dispersed particle, residence time on the shelf at weighted layer (zone III) and closer to zero particle residence time on the shelf when you reach a second critical gas flow rate (removal of particles from the weighted layer zone V).

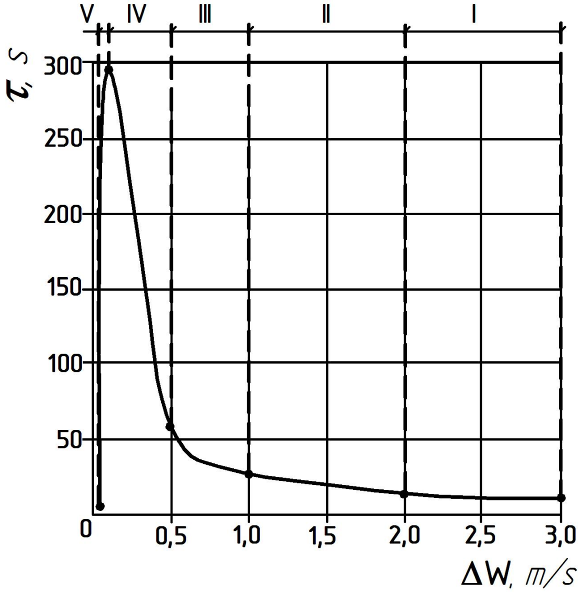


Fig. 8. Experimental study of particles residence time on the shelf in compressed motion regime (L = 0,2 m, γ = 25º):

regimes (according to [21]):
I – falling gravitational layer regime;
II – first transitional regime;
III – weighted layer regime;
IV – second transitional regime;
V – entering particulate material regime

Conclusions

1. A theoretical model for calculating the particle residence time on a shelf in a multistage apparatus.
2. The features of the calculation of particles residence time of it single and compressed movement on the shelf.
3. The influence of shelf design and hydrodynamic motion of the gas flow on particle motion duration on the shelf.
4. It is proved that the design of the shelf significantly affect particles residence time in the apparatus only in its compressed motion regime.
5. According to the calculation of residence time particles on the shelf proved the existence of different hydrodynamic regimes of operation.
6. The results of the analytical solution of the equations of the mathematical model are confirmed experimentally.

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