# Method for determination of minimum fluidization velocity of polydisperse mixtures in running unit with fluidized bed.

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***Abstract* -** The aim of this article is to develop an experimental method for determining the minimum fluidization velocity for multi-solid beds, which are a mixture of two polydisperse beds in a case where particles constituting each bed differ greatly in shape and size from the particles of the other bed. It is shown that the known methods for determining the minimum fluidization velocity by the change of pressure drop in a bed at increasing (or decreasing) the velocity of gas blown through a bed are not applicable to multi-solid beds.

It is suggested determining the minimum fluidization velocity for multi-solid beds using the curves of changes of root-mean-square deviation of pressure fluctuations in a bed at increasing or decreasing the velocity of gas blown through a bed. The proposed method allows determining the minimum fluidization velocity in the running unit without bed deposition that is very important for the control of technological processes, which are accompanied by a change in granulometric composition of a bed (sintering, particles crushing, etc.).

***Keywords* -** Multi-solid bed, pressure fluctuation, straw pellets, turbulent fluidization.

## I. INTRODUCTION

THE technique of fluidization is widely used in chemical engineering, metallurgy, oil refining and other industries due to its main advantages. In the last 20-30 years, the scope of its application has spread to a number of new areas, including, above all, power engineering. These include mainly high-efficiency processes of combustion and gasification of coal and brown coal, biomass, and the processing of coal into liquid fuel. These processes allow overcoming a number of technical difficulties, and in particular, solving the urgent problem of a significant reduction in emissions of nitrogen and sulfur oxides [1]-[3].

Placing of significantly larger particles in a bed that consists of a certain amount of fine particles leads to the formation of a multi-solid fluidized bed.

A multi-solid fluidized bed is one of the forms of the implementation of "constrained fluidization", i.e. the fluidization of fine particles between fixed or moving coarse particles [4]-[10]. It is known that in such beds the degree of conversion of, for example, butane to butadiene is 15-20% higher than in the classical adiabatic reactor with a fixed bed [11]. Initially it was believed that coarse particles remained immobile in a bed and represented a kind of a frame, where fine particles were circulating [12]. But then it was found that coarse particles did not remain immobile, but at the certain velocity of gas blown through a bed and at the certain velocity of fine particles circulation they began to move in the bed volume [13].

Such a multi-solid fluidized bed is considered as an alternative to a conventional circulating bed, since coarse particles, remaining in the bottom of the reactor, stabilize the processes occurring in a bed and increase the residence time of fine particles in the reaction zone [13].

The fractional composition of a bed, especially the proportion of coarse fraction, significantly affects the hydrodynamics of this bed.

In the study of the fluidization of mixture of quartz sand (the average particle sizes are 0.36, 0.50 and 0.85 mm) and stalked biomass pieces (the average diameter is 5 mm, the average length is 25 mm, the apparent density is 385.3 kg/m$^3$, the bulk density is 147.6 kg/m$^3$), we found that when the proportion of biomass in the mixture is 4.36% the transition into the turbulent fluidization regime occurs at air flow rate equal to 1.38 m/s, when the proportion of biomass is 8.36% – at air flow rate equal to 1.04 m/s, and when the proportion of biomass is 31.33 % – at air flow rate equal to 0.67 m/s (Figure 1). Further development of a multi-solid fluidized bed technique requires obtaining new

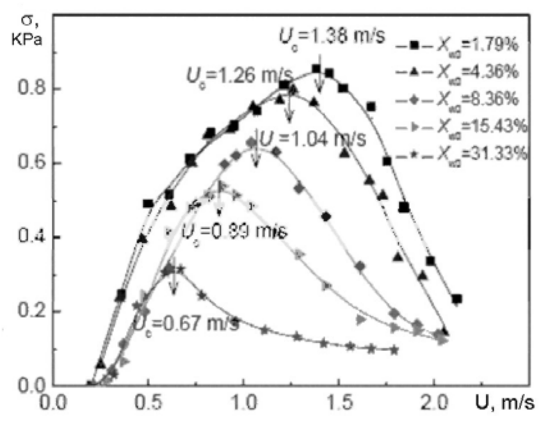



Fig 1. Standard deviation of pressure drop in a bed vs. airflow rate blown through a bed of sand and biomass pieces

knowledge about the hydrodynamics of such systems, even more so the results of studies of hydrodynamics of a monodisperse fluidized bed are inapplicable to the hydrodynamics of multi-solid fluidized systems, since fine and coarse particles, as mentioned above, mutually influence each other's behaviour and the transition of a bed into a fluidized state in general [13].

Early studies of the fluidization process of multi-solid systems revealed that in such a bed the simultaneous presence of several states of dispersion medium is possible: fixed bed, fluidized bed and pneumatic transport (entrainment). This complicates the study of transient processes in multi-solid beds (i.e., the transition of a bed into a fluidized state) and, in particular, the determination by means of the known methods of such an important parameter as the minimum fluidization velocity.

## II. Study of processes of transition into fluidized state of multi-solid beds of particles

Usually, during the study of transient processes in the systems gas – solid particles the diagram of dependence of pressure drop in a bed on the velocity of gas filtered through a bed is made. Before the beginning of fluidization, a monotonic increase of the resistance of a bed is observed with the increase of gas velocity. Graphically this is expressed by a line inclined to the axis of abscissae. Upon reaching a fluidized state, the pressure drop in a bed ceases or nearly ceases to change with the increase of the velocity of gas filtered through a bed. Graphically this is expressed by a line parallel to the axis of abscissae. The gas velocity, corresponding to the transition point of an inclined line into a horizontal one, is considered as the minimum fluidization velocity of a bed of these particles. However, this is a simple method for the determination of the minimum fluidization velocity for a monodisperse bed of spherical particles [14]. As Kondukov N. [15]-[16] has shown and other researchers [17]-26] have subsequently confirmed, the process of fluidization of a polydisperse bed of spherical or near-spherical particles is characterized by not one, but two velocities: one velocity is the initial velocity of fluidization transition zone – corresponds to the beginning of fluidization of the finest particles in the mixture, the second corresponds to the complete fluidization of a bed. Graphically this is approximately expressed in Figure 2.

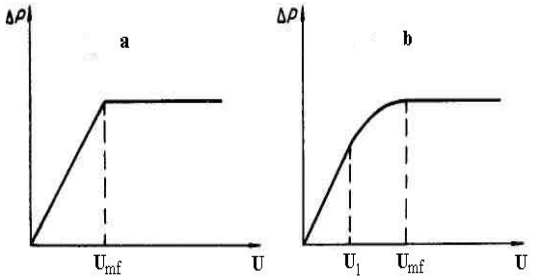



Fig 2. Curves of fluidization of beds: (a) monodisperse and (b) polydisperse

We identify the velocity, indicated in Figure 2 as $U_1$, as the initial velocity of transition of a bed into a fluidized state, $U_{mf}$ – as the minimum fluidization velocity, which corresponds to the generally accepted terminology in the world literature [22] - [24].

It is more difficult to show graphically the transition process determined by the interval of velocities ($U_1$-$U_{mf}$) for a bed, consisting of fine and coarse irregularly shaped particles, i.e. for a multi-solid bed. Figure 1.3 shows the diagrams obtained in the study of the process of fluidization of sawdust (the equivalent diameter is 0.766 mm), rice husk (the equivalent diameter is 1.5 mm) and nut shells (the equivalent diameter is 0.613 mm) [27].

The authors, apparently basing on their visual observations over the process of transition of beds into a fluidized state, assert that the fluidization of a bed of sawdust occurs at airflow rate of 0.23 m/s, rice husk – at airflow rate of 0.38 m/s, and nut shells – at air flow rate of 0.28 m/s. However, if you follow just only a graphical representation of the experimental data, then from the standpoint of the above arguments it turns out that the minimum fluidization velocity for a bed of sawdust can be equal to 0.55 m/s, and for rice husk – 0.57 m/s.

It is not possible to determine at which airflow rate the

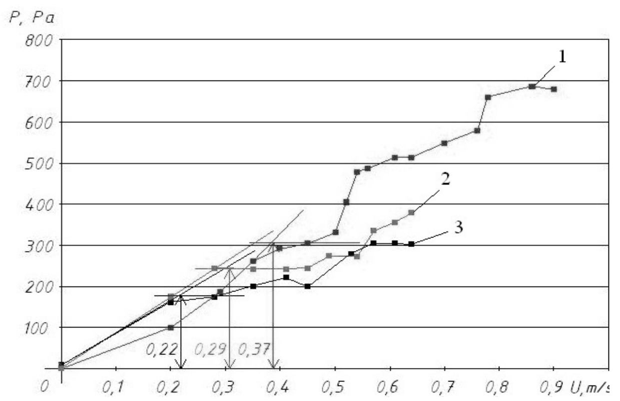



Fig 3. Curves obtained in the study of fluidization process of sawdust (1), rice husks (2) and nut shells (3).

process of fluidization begins for a bed consisting of nut shells particles at air flow range from 0 to 0.7 m/s as shown in Figure 3 (curve 3).

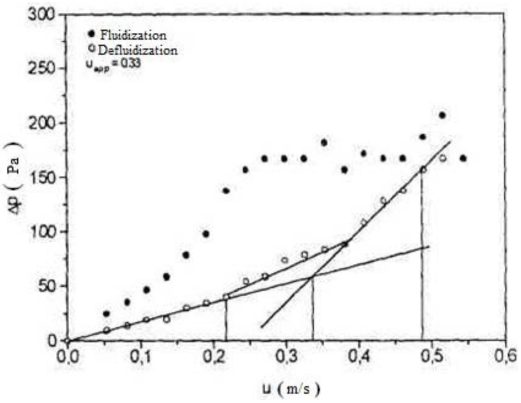
Even more complicated curves of fluidization are obtained at the fluidization of beds of particles consisting of wood waste produced during the crushing of furniture fittings and wooden structures (fig. 4) [28] for a bed where a): the fraction of particles ranging in size from 1.20 to 2 mm is 24%, from 0 71 mm to 1.20 – 56%, from 0.32 mm to 0.71 – 18%, from 0.18 mm to 0.32 – 2%; for a bed b): 24%, 59%, 14% and 3%.

Random nature and geometry of particles, creating the instable hydrodynamic resistance, right up to its sudden drops, make it difficult to determine the minimum fluidization velocity.

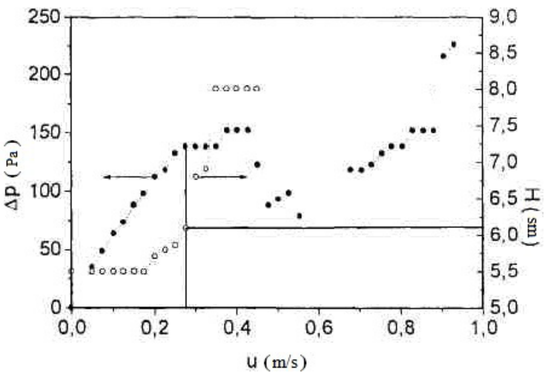
It follows that for the study of the process of the transition of multi-solid beds of particles with complex shapes and sizes in a fluidized state we cannot use only graphical representation of the pressure drop dependence in a bed on the velocity of gas filtered through a bed.

The paper [29] suggests evaluating the value of the minimum fluidization velocity using the dependence of root-mean-square deviation of pressure fluctuations in a bed on the velocity of gas filtered through a bed.

The authors of this work have experimentally proved that for the beds consisting of corundum particles (the equivalent diameters are 0.175 and 0.715 mm) or calcium




a)




b)

Fig 4. Curves for fluidization of a bed consisting of particles obtained by: (a) crushing of furniture fittings, (b) crushing of wooden structures

carbide (the equivalent diameters are 0.565 mm, 0.715 mm, 0.900 mm and 1.125 mm) or calcium oxide (the equivalent diameter is 0, 9 mm) or lignite ash (the equivalent diameter is 0.9 mm), the dependence of root-mean-square deviation of pressure fluctuations in a bed σ on the gas velocity U can be presented as follows:

$$\sigma = A + B \cdot U \qquad (1)$$

The authors have proved that the value of root-mean-square deviation in a state of minimum fluidization is equal to or close to zero. In this case:

$$U_{mf} = -A / B \qquad (2)$$

where: $U_{mf}$ – minimum fluidization velocity, m/s.

Thus, having obtained at least two experimental values of σ, we can graphically depict the dependence σ = f (U), determine the values of A and B and the value of the minimum fluidization velocity. The authors of this work report that the proposed method makes it possible to determine very precisely the minimum fluidization velocity at both room and elevated temperatures (the maximum temperature of fluidizing gas in experiments attains 800 °C).

Subsequently, the suitability of this method for evaluating the value of the minimum fluidization velocity of a bed is confirmed in experiments with aluminum oxide particles ($Al_2O_3$, the particle equivalent diameter is 0.290 mm) and silicon dioxide particles ($SiO_2$, the particle equivalent diameter is from 0.290 to 0.423 mm)

at both room and elevated temperatures (70 °C, 170 °C and 270 °C) [31].

Moreover, the proposed method can be used to evaluate the minimum fluidization velocity of a bed in the running unit. In order to do this it is necessary to receive two values σ at two values of the velocity of gas blown through a bed, the first one – at the current gas velocity, and the second one – at higher or lower gas velocities. Still, the deposition of a bed, i.e. the termination of the unit operation, is not required.

However, the applicability of this method for evaluating the minimum fluidization velocity of multi-solids beds of particles has not been proved. Furthermore, there are experimental data obtained for beds consisting of a mixture of spherical silica particles (the equivalent diameters are 1.5 mm and 3.09 mm), and almost spherical particles of soybean (the equivalent diameter is 7.68 mm), which suggest that dependence σ = f (U) is shown by a straight line not in the whole range of changes of gas velocity [31].

I.e. the experimental verification of the applicability of the proposed [30] method for evaluating the minimum fluidization velocity for a multi-solid bed of particles is required. It includes the beds, which are a mixture of two, polydisperse ones: a polydisperse bed of fine coal particles and a polydisperse bed of cylindrical biogranules.

The study of the process of fluidization of such a bed is relevant in terms of the development of coal and biomass co-combustion. The technology of coal and biomass co-combustion in a fluidized bed is increasingly frequently applied for the achievement of a better control over a combustion process with a simultaneous decrease in greenhouse gases, ash and sulfur oxides emissions into the atmosphere. Straw can be considered as one of the largest, annually renewed sources of fuel among all other types of biomass. Low bulk density of straw in the initial condition and necessity for its long distance transportation stimulate to process straw into pellets.

## III. EXPERIMENTAL UNIT

Coal particle and straw pellet beds were exposed to the analysis. The fractional compositions of coal were the following: a mass fraction of particles in the size of: up to 1.0 mm – 20.87%; from 1.0 to 1.2 mm – 61.79%; from 1.2 to 1.5 mm – 5.66%; from 1.5 to 1.7 mm – 2.7%; from 1.7 to 2.0 mm – 1.81%; from 2.0 to 2.5 mm – 1.14%; from 2.5 to 3.0 mm – 0.47%; from 3.0 to 4.0 mm – 4.07%; more than 4.0 – 1.49%. The moisture content of coal particles was 5.35% on the average; the density of coal particles was 1200 kg/m³. Straw pellets had the following characteristics: the granule diameter was 6 mm, the

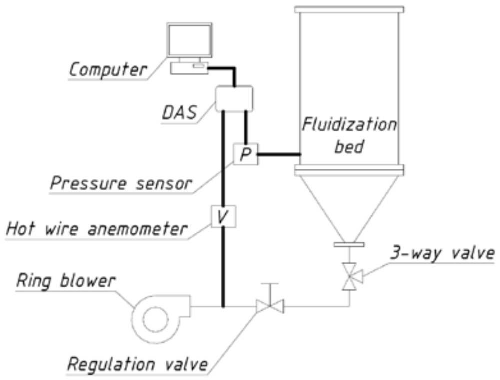



Fig 5. Schematic diagram of the experimental unit.

granule average length to diameter ratio was 0.59; the pellet density was 1190 kg/m³, the heating value of straw granules – 15.5 MJ/kg. The analyses were conducted by means of an apparatus (fig.5) with the rectangular cross-section of 194x485 mm and height of 1500 mm which was rested upon an air distribution grill with 5% of an open area. The airflow rate was measured by a thermo-anemometer Delta-OHM HD 2103-1after the air left the apparatus. Not less than 100 measurements of the airflow rate were taken in each experiment. The pressure drop in a bed was measured by means of a differential micromanometer Testo-525 which allowed taking 1200 measurements of pressure drop within 60 seconds. A digital signal from a micromanometer Testo-525 was transmitted to a personal computer for the subsequent processing.

In the course of the pilot experiments, it was established that if the content of coal particles in a bed was higher than 40%, the complete segregation of particles by size was evidenced, in this case pellets remained motionless and rested on the air distribution grill. For this reason, the pressure fluctuations were measured in beds containing 100%, 95%, 90%, 85%, 80%, 70%, 65 and 60% of pellets and corresponding amount of coal ash. The obtained range of random values of the pressure drop in a bed was exposed to a statistical analysis. In addition, we determined the mean value of the pressure drop in a bed during the observation period:

$$\Delta Pm = \Sigma \Delta Pi/N \quad (3)$$

and the root-mean-square deviation of the pressure fluctuation:

$$\sigma = [\Sigma\, (\Delta Pi - \Delta Pm)^2/(N-1)]1/2 \quad (4)$$

Changes of bed behaviour were recorded by a video camera Panasonic DVC 30. Then each second of the video recording was broken into 50 video shots that allowed receiving consecutive images of bed behaviour in every 0.04 second.

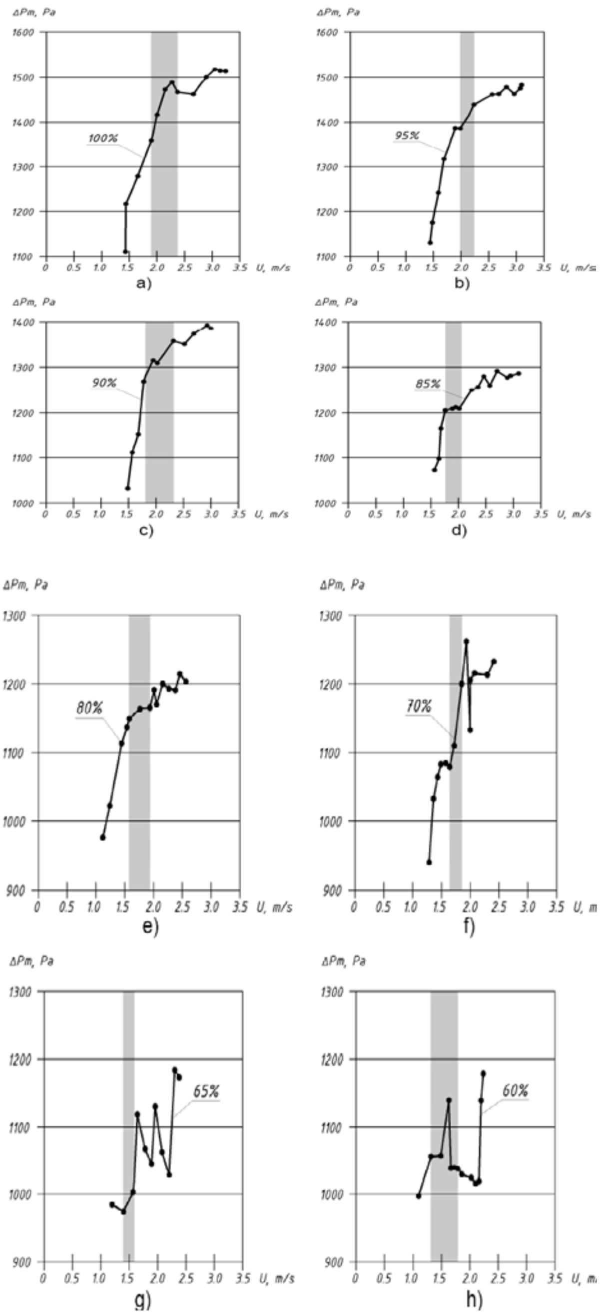



Fig 6 (a-h). Average pressure drop in a bed *vs.* airflow rate for different mixtures. Diagrams show the content of straw pellets in a bed.

As we knew the image scale we could obtain the values of the maximum height of a bed in every 0.04 second and, considering the change of a bed height as a random process, we could also obtain the mean value of the maximum height of a bed during the observation period, the mean value of the relative height of a bed $H_m/H_0$ in the given experiment and the root-mean-square deviation of the relative height of a bed from the dependences which were similar to the dependences introduced above.

## IV. Results and Discussion

Fig. 6 shows the dependences of the pressure drop on the airflow rate in the bed, for different bed mixtures. A dark line on the diagrams indicates the range of the airflow rate values at which the process of bed fluidization $U_{mfi}$ begins and the bed becomes completely fluidized $U_{mf}$. The value of the minimum fluidization velocity decreases with the increase of a coal particle fraction in a mixture: the minimum fluidization velocity is 2.4 m/s for a 100% pellet bed; 2.1 m/s – for a bed with 15% of coal particles and 1.75 m/s – for a bed with 45% of coal particles.

Fig. 7 shows the dependences σ = f (U). For mixtures with 80-100% of pellet content the dependence diagram σ = f (U) can be divided into three portions: the portion where σ ≈ 0, the portion where a weak increase of σ is observed with the increase of U, and the portion where a fast increase of σ is observed with the increase of U. For mixtures with granule content lower than 80%, the first portion is practically absent on the diagram, but the 2-nd and 3-d are shown distinctly. The comparison of figure 3 with the results of the visual observation allows us to draw the conclusion that the value of the air flow rate corresponding to the transition of the dependence σ = f (U) from the first portion on the curve to the second is the velocity when the fluidization just begins. The airflow rate corresponding to the transition of the dependence σ = f (U) from the second portion on the curve to the third one is the velocity when a bed becomes completely fluidized. Hence, the dependence diagram σ = f (U) can be applied for the experimental evaluation of $U_{mf}$.

As fig. 8 shows, the reduction of a bed relative height is observed with the increase of a pellet fraction from 55 to 80%: the bed with 80% of pellets practically doesn't expand, while the maximum height of a fluidized bed of the bed with 55% of pellets twice exceeds the height of a fixed bed. The relative height of a bed starts to increase again with the increase of a pellet fraction in a mixture: the maximum height of a fluidized bed of pellets 1.5 times exceeds the height of a fixed bed.

Fig. 9 shows the dependence of the root-mean-square deviation of the bed relative height value on the average value of σH, which is evidently proportional to the frequency of formation and eruption of air bubbles, which

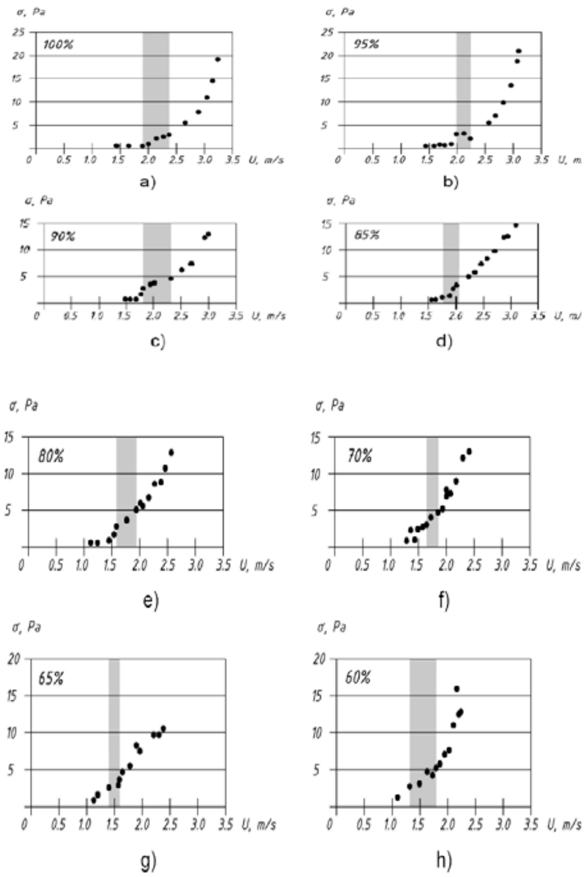


Fig 7 (a-h). Root-mean-square deviation of pressure fluctuations *vs.* airflow rate for different mixtures. Diagrams show the content of straw pellets in a bed.

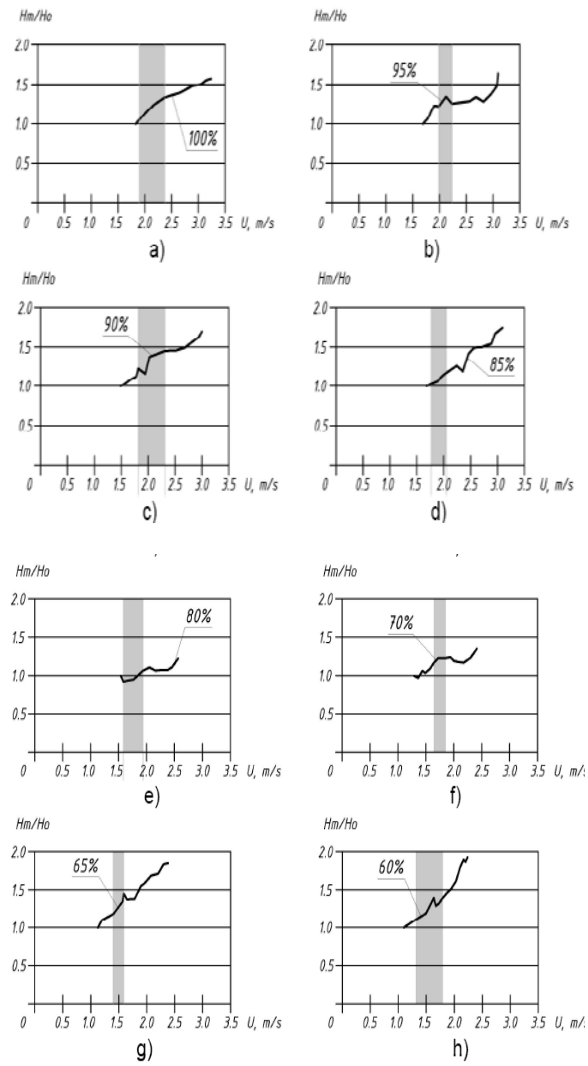


Fig 8 (a-h). Relative height of a bed *vs.* airflow rate for different mixtures. Diagrams show the content of straw pellets in a bed.

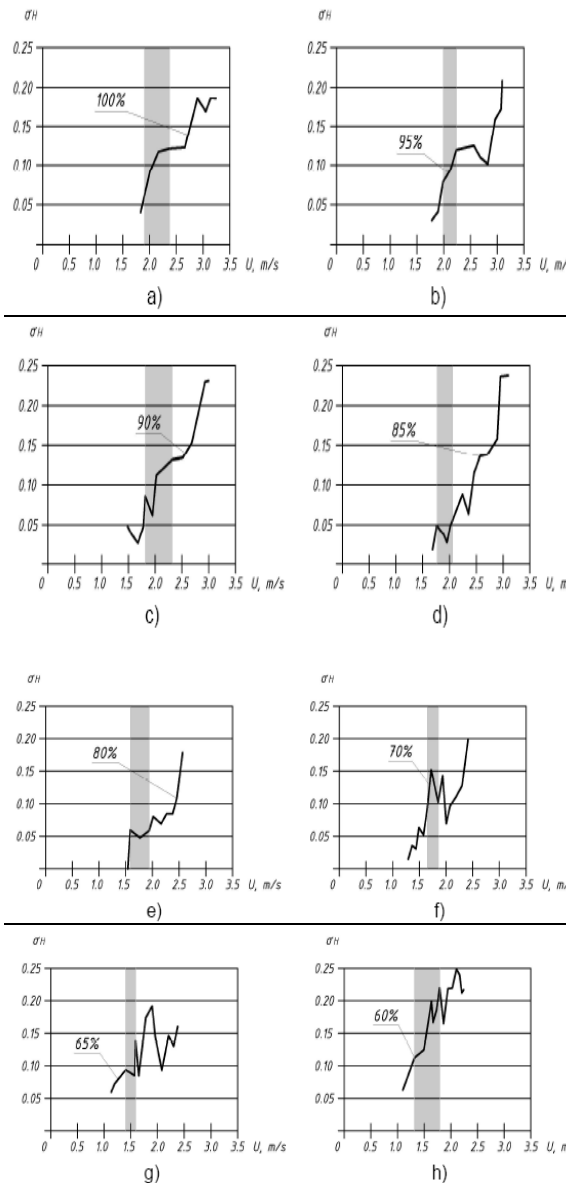



Fig 9 (a-h). Root-mean-square deviation of a bed relative height value *vs.* average value of airflow rate for different mixtures. Diagrams show the content of straw pellets in a bed.

form in a bed and erupt with the approach to its surface. With the increase of a pellet portion from 55 to 80%, we can observe the decrease of σH, i.e. the frequency of formation and sizes of air bubbles decrease with the increase of a biogranules portion. With a further increase of a pellet portion in a bed, larger air bubbles start to form (1), and their eruption results in more violent fluctuations of the upper limit of a bed that cause the increase of σH.

The reduction of the relative height of a bed with the increase of a pellet portion results in the increase of the separation space height in a furnace and lets the furnace and boiler dimensions remain the same that should lead to the reduction of fuel loss with entrainment.

## V. Conclusion

From the results of this study, the following conclusions can be drawn:

- Hydrodynamic features of the transition into a fluidized condition of the bed compounded of fine particles of coal and biogranules have been studied.
- It has been shown that the increase of a biogranules fraction in a mixture leads on the whole to the reduction of a bed relative height and to the decrease of frequency of the formation and sizes of air bubbles that should diminish a fuel loss from mechanical and chemical incompleteness of combustion.
- We have suggested the method for the evaluation of the minimum fluidization velocity in a bed compounded of a mixture of coal and biogranules particles from the root-mean-square deviation of pressure fluctuation versus airflow rate curve.

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## Notation

$\Delta P_m$ – average value of pressure drop in a bed, Pa;
$\Delta P_i$ – value of pressure drop in a bed, Pa;
σ – root-mean-square deviation of pressure fluctuations, Pa;
σH – root-mean-square deviation of the bed relative height value on the average value;
$H_m$ – maximum height of a bed during the observation period, mm;
$H_0$ – height of a fixed bed, mm;
N – number of measurements in the experiment;
U – gas velocity referring to the cross-sectional area of an empty apparatus, m/s;
$U_{mfi}$ –initial velocity of fluidization, m/s;
$U_{mf}$ –minimum fluidization velocity, m/s;

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