APPLICATION OF STEREOLOGY FOR TWO-PHASE FLOW STRUCTURE VALIDATION IN FLUIDIZED BED REACTORS

by

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Paper describes a novel method for two-phase gas-solid flow structure validation in fluidized bed reactors. Investigation is based on application of stereology techniques. This is an innovative approach in the field of fluidization phenomena research. Study is focused on the analysis of flow structure images, obtained with high-speed visualization of the fluidization process. Fluidization is conducted in transparent narrow channel, where plastic balls are fluidized by air. Applied stereological analysis is grounded on the linear method and on the method of random and directed secants. This enables 2-dimensional image measurement and 3-dimensional stereological extrapolation. The major result is that for each two-phase gas-solid flow structure a set of stereological parameters exists. This enables quantification of the process. It has been found that the observation of interrelation of all stereological parameters, during the changing of the flow structure, can be used for system control. The basic conclusion is that knowledge about the character of the changes may be used for constant process adjustment for various two phase systems such as gas-solid or gas-liquid.

Key words: *stereology, two-phase flow pattern, image measurement, gas-solid fluidization, fluidized bed reactor*

Introduction

Fluidized bed processes are widely used in industry. One of the common applications of fluidization process include fluidized bed combustion of fuels [1], waste gas purifying [2], gas sorption [3], gas capturing [4], regeneration of bed fillings [5], material drying [6], food processing [7], pharmaceutical industry [8], *etc*. Fluidization process is studied by many authors for many years. In 1963 there were settled particle fluidization basics by Harrison and Davidson [9]. Than in 1974 industrial fluidization processes were described in detail again by Harrison and Davidson [10]. Finally the comprehensive overview on the available measuring techniques for fluidized beds was given in 1999 [11]. Despite the strong interest, it is still not known at the extent allowing full automation and trouble-free operation of fluidized bed reactors. The paper presents research on classic fluidization of monodisperse deposits. The essence of the process lies in the gas blowing through the particulate material layer. At a certain flow rate of gas – so called the critical speed, the layer of particulate material enters the fluidized state (is suspended), and assumes the properties of a liquid. In this state, the distance between the individual particles is increased (interfacial surface increases) so that for their displacement less energy consumption is required, than if the layer has not been suspended in

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the gas stream. Fluidized phase is similar to the liquid when the fluidization is homogeneous, *i. e.* when, fluidized bed material is homogeneous and the gas flows at a uniform velocity across the reactor. Then no formation of bubbles and channels is observed. On the other hand gas bubbles and other turbulences in the bed increase the mixing effects and temperature distribution.

However, when there is fluidization of two types of particulate solids and they differ significantly in size or density, segregation appears. The smaller particles collect in the upper layers and larger particles agglomerate in the lower bed layers. The maximum flow rate of the gas at a uniform fluidization depends on the properties of solids and reactor design.

Hydrodynamics of gas-solid two-phase processes, was and still is, the subject of interest of many researchers. Problems of heat and mass transfer are studied in a wide range for different fluidized-bed systems, either by computational methods or by experimental techniques. Often both methods are used simultaneously in order to verify the empiric results or test mathematical models. Like X-ray measurements in the mass transfer [12], laser sheet visualization of flow structures [13], dynamic image analysis and recognition of two-phase flow patterns [14] or computational fluid dynamics (CFD) [15]. The authors, who extended the development of fluidization science are Hewitt [16] and Molerus [17]. The effect of their work on the particulate flows were empirical equations, describing the behavior of gas-solid mixtures. This provides the foundations for the modern approach to fluidized bed science.

Currently, the gas-solid mixture structure of the fluidized bed reactors research is mainly based on the analysis of data from pressure drop measurements at different heights of the bed. This information makes it possible to determine the overall flow regime, but does not inform about such aspects as the interfacial surface or volume fraction. Sometimes complicated calculations enable such evaluations, but they are very rough. With pressure drop analysis, it is impossible to determine the forms of structure and spatial distribution of the phases or phase concentration, not to mention the size of the individual objects.

Image analysis gives more options. Tests are performed for the whole volume of the apparatus, and not only at the wall. A new method of image analysis in the fluidization study is stereology. It allows a 3-D reconstruction of the structure, based on 2-D. Acquiring an image for analysis is performed by non-invasive techniques which increases the accuracy of the measurements.

Problem definition

The structure of the two phase flow has a significant effect on the parameters of the fluidization process. It is difficult to embrace it mathematical due to the high level of dynamics (resulting from a large number of particles) and vulnerability to disorder. The knowledge about the dynamics of the fluidized bed enables the design and control of the reactors. Its purpose is to maintain the stability of the process and maximization the effects of heat and mass transfer, combustion, the intensity of coating, reducing energy consumption, material savings or device miniaturization. The main problem is thus evaluation of the flow structure inside fluidized-bed reactor. The structure of the two-phase fluidization process determines in particular the interfacial surface, the volume fraction, the porosity of the bed and the presence of *dead zones*. Due to the two phase structure importance, authors made research on the evaluation by using stereological image analysis techniques. This is pioneer use of such method in the fluidization process assessment.

Measurement set-up and method

Two phase mixture structure assessment is primarily based on digital analysis of the images obtained using a high speed video camera. The process of fluidization was conducted in 2-dimensional model of fluidized bed reactor with clear walls. Figure 1 describes the reactor and the idea of the image acquisition process. Internal dimensions of the channel for classic fluidization are:

– width $W = 0.3$ m,
– thickness $t = 0.03$ m, and
– height $H = 1.2$ m.

The bed rested on the grate which is attached between the conical and the rectangular chambers. As the disperse phase, solid monodisperse polypropylene spherical particles were used. Particles have constant diameter of d = 6.0 mm and density of ρ = 1,050 kg/m^3. Gas velocity was in the range of u_{G0} = 0.0-5.9 m/s. Designed fluidized bed column was filled with solid particles up to $h = 0.25$ H. This means that the height of the test bed was $h = W = 0.3$ m and is on the border between the shallow beds ($h < W$) and deep beds ($h > W$).

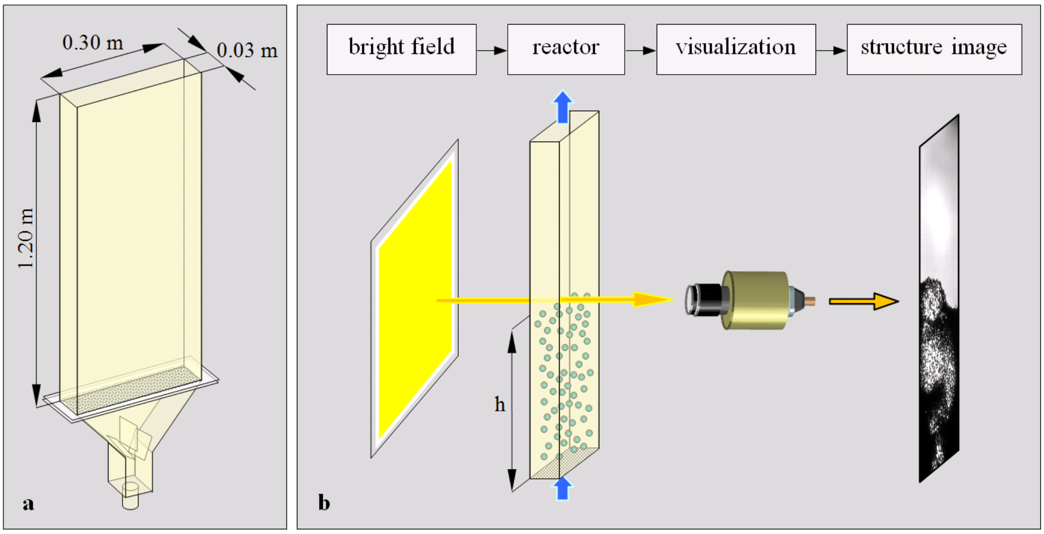

Figure 1. Measurement set-up for two-phase flow structure visualization; (a) schematic view of the fluidization reactor; (b) the idea of bright field visualization technique

The data acquisition was conducted with the use of *bright field* technique. The resulting image sequences are projections of two phase flow structures. Stereological analysis was performed on images whose gray level index (GLI) was closest to the average GLI value obtained for the entire sequence of images. This picture was considered to be representative of the entire sequence. This method is shown in fig. 2.

Image analysis have been applied to the selected projections of the flow structure. This analysis consisted of stereological techniques. These techniques are based on the so called *Linear Methods* and *Secant Methods* [18]. In this case the technique of *random secants* and the technique of *targeted secants* were used and the analysis was digitally enhanced [19].

Based on the analysis of collected data, the 5 specific stereological parameters were determined. These parameters are:

– the volume fraction V_V,
– the interfacial surface S_V,
– the number of objects N_V,
– the mean chord l'_m, and
– the free distance λ.

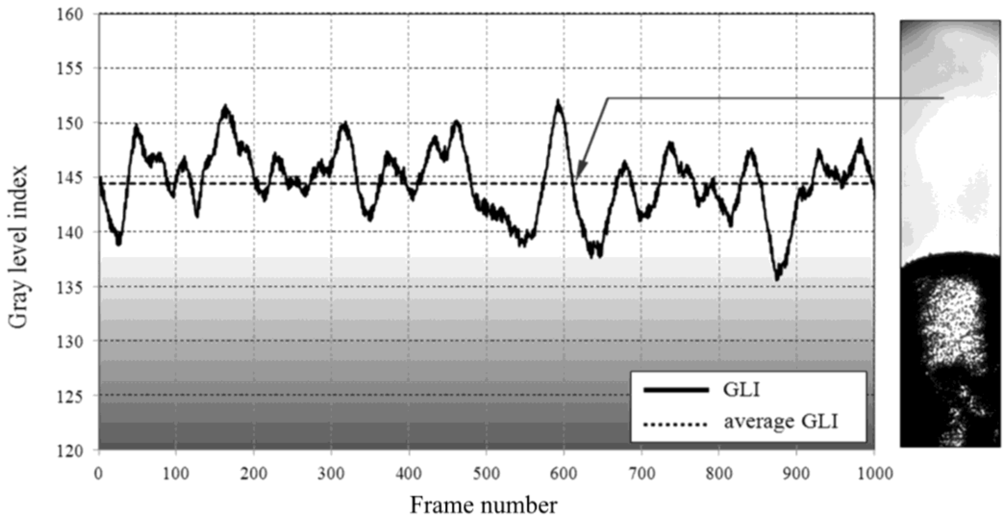

Figure 2. An example of the GLI changes during bubble-plug fluidization where gas velocity is u_{G0} = 3.4 m/s, with marked representative image

Selected parameters are the structural coefficients of two-phase gas-solid mixture flow. These parameters were used for analysis and evaluation of the two-phase flow structure and were calculated with the use of eqs. (1-5).

Relative volume of convex shapes from the projection equation:

$$V_V = \frac{A'_A l_m}{t} \tag{1}$$

Relative interfacial area of closed body from the projection equation:

$$S_V = \frac{4A'_A}{t} \tag{2}$$

Number of closed bodies in the volume from the projection equation:

$$N_V = \frac{N'_A}{t} \tag{3}$$

Average length of chords for projected objects equation:

$$l'_m = \frac{L'_L}{N'_L} \tag{4}$$

Average free distance for convex shapes from the projection equation:

$$\lambda = \frac{t\text{-}A'_A l_m}{N'_L l'_m} \tag{5}$$

More detailed description of applied methods and additional explanation of stereological parameters have been presented in earlier works [20]. These parameters allow quantitative and qualitative assessment of the two-phase gas-solid particles flow structure.

Results

The results of visualization stage are images of the two-phase flow pattern evolution. Recorded images are projections of gas-solid structures inside the fluidized bed reactor (fig. 3).

The obtained fluidization flow patterns have been classified in accordance to generally accepted nomenclature (tab. 1) [21].

For the image analysis stage two areas of examination have been designated. The first measurement area (A) covers the entire apparatus, the second region (B) is a segment in the lower part, as shown in fig. 4.

Stereological parameters calculated on the basis of area A characterize solid phase. The results are shown in tab. 2.

To determine the interesting features from the gas phase point of view, there is need to narrow the measurement area to eliminate the empty space above the bed. It is a difficult task because the higher the speed of the gas phase, the bed undergoes greater expansion. To get comparable results for all the observed structures narrow region must always comprise a fragment of the reactor in which the expansive bed consists. The most reliable placement of such area is in the lower part. The size should correspond to the space occupied by the fixed bed. In this way the measurement area B have been defined (fig. 4). Stereological parameters calculated on the basis of region B shows tab. 3.

Finally, for each flow structure, five parameters characterizing solid phase and five parameters characterizing gas phase have been obtained. Analysis of changes in these parameters enables the assessment of the two-phase gas-solid mixture structure.

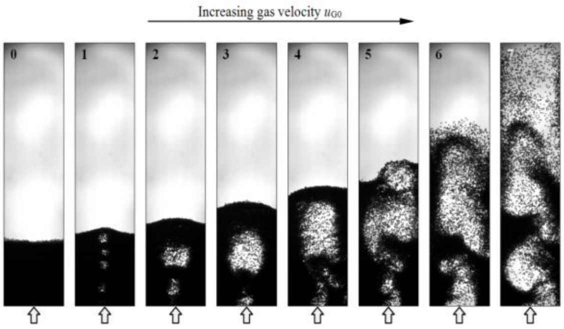

Figure 3. Representative images of the various classical fluidization structures (gas velocity u_{G0} = 0.0-5.9 m/s)

Table 1. The classification of obtained two-phase flow structures

Image number	u_{G0} [ms^{-1}]	Two phase flow structure
0	0.0-0.50	Fixed bed
1	2.16	Bubbling
2	2.78	Bubbling
3	3.40	Bubbling-Slugging
4	4.01	Slugging
5	4.63	Slugging
6	5.25	Slugging-Turbulent
7	5.86	Turbulent

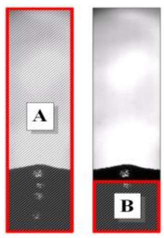

Figure 4. Presentation of measurement areas

Table 2. Example of calculated stereological parameters for the selected structures in measurement area A

Parameter	Unit	Image number							
		0	1	2	3	4	5	6	7
l'_m	mm	297.7	160.1	78.2	76.7	46.4	27.5	21.0	16.7
N_V	pcsdm^{-3}	0.001	0.002	0.004	0.005	0.008	0.016	0.019	0.024
S_V	mm^{2}mm^{-3}	0.02	0.03	0.04	0.04	0.05	0.08	0.09	0.11
V_V	%	25.21	27.97	29.57	30.83	32.93	38.35	33.40	32.92
λ	mm	89.0	77.1	70.8	66.8	60.0	46.1	56.1	55.9

Table 3. Example of calculated stereological parameters for the selected structures in measurement area B

Parameter	Unit	Image number							
		0	1	2	3	4	5	6	7
l'_m	mm	2.46	5.10	9.73	31.01	10.22	6.64	17.40	24.94
N_V	pcsdm^{-3}	0.00002	0.00242	0.013	0.009	0.017	0.013	0.019	0.022
S_V	mm^{2}mm^{-3}	0.00006	0.00945	0.052	0.05	0.072	0.053	0.088	0.113
V_V	%	0.00	0.05	7.92	24.65	12.44	2.48	27.19	47.22
λ	mm	60,098.7	699.24	51.57	8.60	68.02	68.63	3.80	1.85

Discussion

Gas-solid mixture flow change detection in the fluidized bed reactor was conducted with the application of stereological methods. Particular set of stereological parameters was used for image analysis on the A and B measurement areas. Courses of parameter changes, depending on the increasing gas velocity in the fluidized bed have been obtained. On the basis of the relationship between the stereological parameters, flow structure assessment was possible.

Analysis of image in area A gives information about the solid phase. In particular about the number of separated solid objects, their size and the distance between them. There can be seen some instabilities of the volume fraction V_V. The volume fraction of the solid phase (V_V) should be constant throughout the range of the flow structures. The observed excess of V_V for increasing gas velocity, relative to the fixed bed, is a result of the obscuring effect shown in fig. 5. This difference increases along with: increasing of the gas bubble sizes; increasing of the gas bubble number and with decreasing of the particles diameter. The knowledge of this effect is important to determine the actual volume fraction.

In contrast to the measurement area A, parameters determined in the area B represent the gas phase. With the increase of the gas phase velocity, increases the average chord l'_m and the volume fraction V_V, while reducing the free distance λ. The analysis results in a form of numbers (tab. 2 and tab. 3). Those numbers indicate that the total amount of bubbles N_V and their sizes l'_m increase, but at the same time distance λ between them decreases. This is consistent with the observations.

Flow structure image analysis in area A and B enables evaluation from the quantitative and qualitative point of view.

In order to make the quantitative assessment of the process, first of all serve such properties as: the volume fraction of selected phase mixture V_V, or the size of the interfacial surface S_V. These parameters provide for example the information on the quantity of gas present in the bed and the development of the interfacial surface.

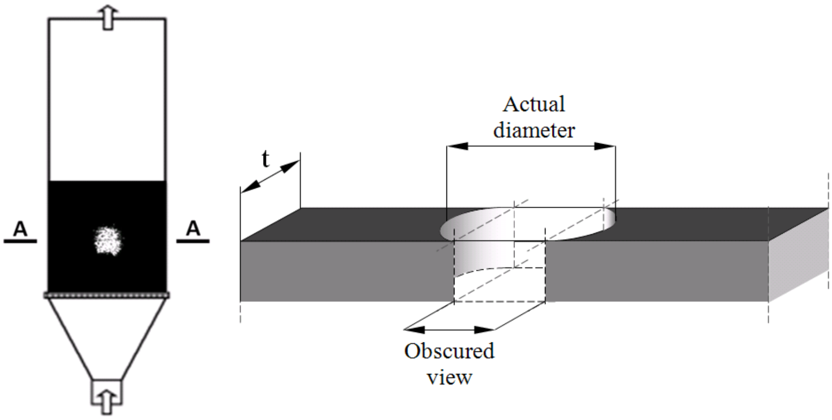

Figure 5. The obscuring effect

The entire set of stereological parameters contains sufficient information that allows qualifying the structure to the generally accepted characteristics of classical fluidization structures. On this basis the size of the objects (whether gas bubbles or solid particles), and their mutual arrangement in an expanding fluidized bed can be determined. Investigation of these changes must be based on the analysis of the interaction of all parameters. Trend analysis of single parameter is usually ambiguous.

Figure 6 and fig. 7 show the relationship between the values obtained for the individual stereological parameters. These values were determined from images of structures shown in fig. 3.

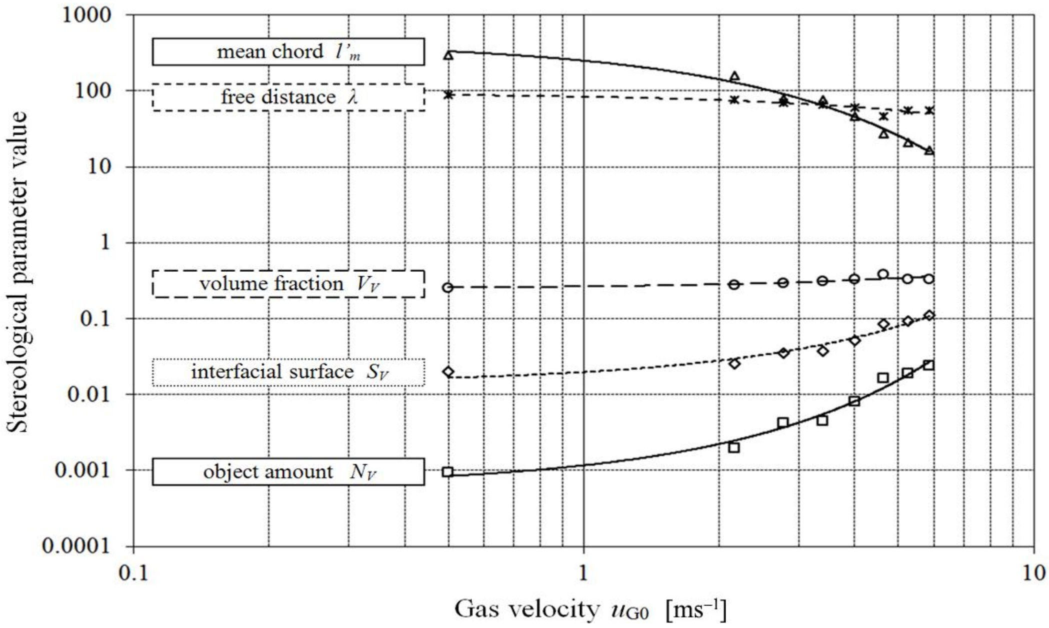

Figure 6. The graph of stereological parameters determined on the basis of the area A, and the increasing gas velocity u_{G0}

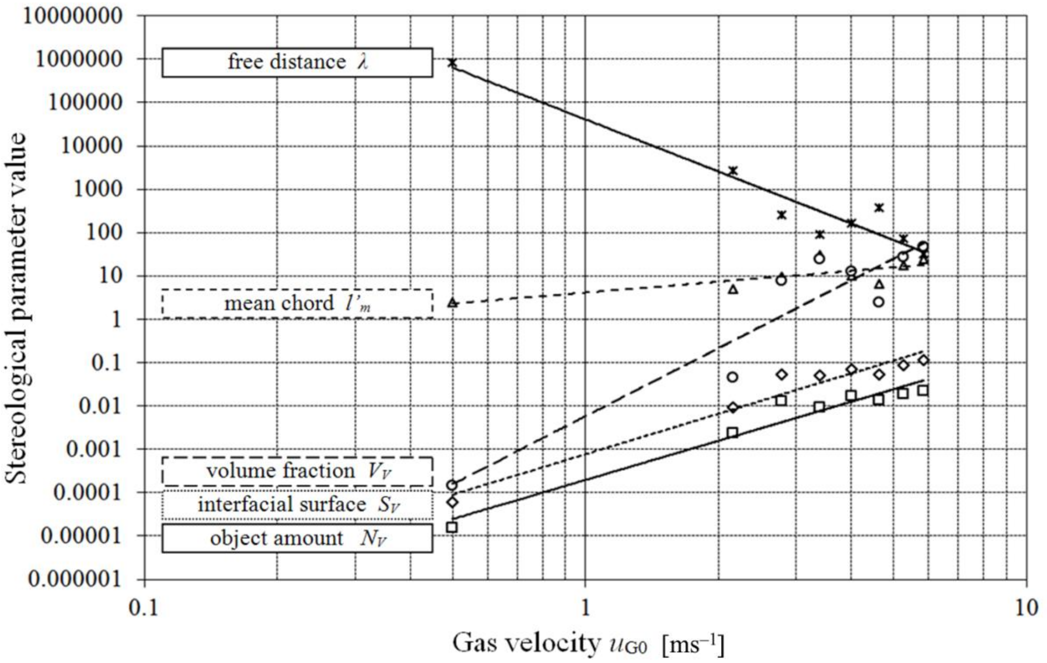

Figure 7. The graph of stereological parameters determined on the basis of the area B, and the increasing gas velocity u_{G0}

In fig. 6 the average free distance λ (A) between the objects of dispersed phase, defined by the analysis of measurement area A, decreases throughout the rising gas velocity u_{G0}. This means that the fragmentation of the bed is increasing. This is clear because the amount of material in the bed is fixed. Decrease of λ is small because the distributed objects are close together.

In fig. 7, stereological parameter λ (B), defined by the analysis of measurement area B, also decreases throughout the rising gas velocity u_{G0}. Despite this, in contrast to area A, the bed can be in three different states. First – the increasing amount of gas bubbles of the same diameter. Second – the amount of bubbles is constant but their diameter is growing. Third – both, the amount of gas bubbles increases and their size increases too. To clarify the evaluation of the structure, other parameters should be checked how they behave. In this case, increasing the number of objects N_v and the increasing average chord l'_m clearly shows the bed is in the third state *i. e.* increasing size and a larger amount of gas bubbles. This coincides with increasing volume fraction V_V of the gas phase and developing interfacial surface.

Stereological parameters exhibit different changes during analysis of the image, according to the change of gas velocity and, depending on the measurement area (A and B). Their detailed assessment can detect subtle effects in the fluidized bed.

Conclusions

The studies found wide possibilities of application of stereological methods for the analysis of fluidization process. With the adaptation of stereological techniques to study the structure of the two-phase gas-solid flows, five stereological parameters characterizing a two-phase fluidized-bed structure have been derived. The volume fraction V_V, interfacial surface

S_V, number of objects N_V, mean chord l'_m and the free distance λ. These stereological parameters are used to interpret and assess the fluidization process.

Stereological analysis performed for the two measurement areas allowed the evaluation of the structure from the point of view of both phases. Analysis of the relationship between each stereological parameters, when changing the flow regime, in fluidized bed reactor allows surveillance of the process. Monitoring of the selected parameters changes can be used to control the process through the automatic feedback.

An additional advantage of this method is that regardless of the image source of the flow structure (tomography, ultrasonography, *etc*.) provides the same evaluation capabilities.

Nomenclature

A'_A – total field of flat projections on the individual β-phase per unit area, [m^2m^{-2}]
d – particle diameter, [m]
H – total reactor height, [m]
h – fixed bed height, [m]
L'_L – total length of the β-phase chords per unit length of secant on the projection, [mm^{-1}]
l_m – average chord length of the cross-sectional image, [mm]
l'_m – average chord length, [m]
N'_A – number of cross-sections of objects per unit surface projection, [$pcsm^{-2}$]
N'_L – number of objects' chord per unit length of the secant on the projection, [$pcsm^{-1}$]
N_V – number of bodies in the volume, [$pcsdm^{-3}$]
S_V – relative interfacial surface area, [mm^2mm^{-3}]
t – thickness of the reactor, [m]
V_V – total volume of the objects per unit volume of the mixture, [%]
W – total reactor width, [m]
u_{G0} – superficial gas-phase velocity, [ms^{-1}]

Greek symbols

λ – average free distance, [mm]
ρ – particle density, [kgm^{-3}]

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