MEASUREMENT OF PARTICLE SIZE DISTRIBUTION BY ACOUSTIC EMISSION METHOD

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Abstract: Continuous measurement of size distribution of particles is the necessary parameter regarding the control of some specific production processes. A possible solution is the use of the acoustic emission method which is based on the measurement and analysis of pressure pulses generated by an impact of solid particles against a solid obstacle. Our paper focuses on the practical verification of the method in laboratory conditions. Two sets of experiments were conducted with air-borne particles. Based on the completed experiments it can be concluded that it is possible to establish the proportion of solid particle fractions using the acoustic emission method.

Keywords: acoustic emission, solid particle flow, particle size distribution, Hertz theory of impact, power spectrum analysis.

1. INTRODUCTION

Measurements of particle size distribution, i.e. establishment of the proportion of fractions in a mixture, are undertaken quite frequently in the industry. They are required e.g. in the pharmaceutical and chemical industries, where sizes of the final product granules have to be checked during the technological process. It is required for many processes that prespecified particle size distributions are obtained, or the production of only one fraction of particles requested. Swift and mainly continuous measurements of particle size distribution may significantly help in optimizing the whole production process with regard to energy consumption.

The measurement of particle size distribution is typically carried out through analyzing of a mixture sample. A sample of the measured material is divided with sieves into different fractions based on granularity of particles and the individual fractions are weighed. Based on their masses, volume or mass proportions or possibly numerosity of particles can be determined. The method is known as sieve analysis; it allows for direct determination of the proportion of individual fractions through sampling and brings highly accurate results, however, its considerable disadvantage consists in the sample analysis being time-consuming and costly. Because of that the sieve analysis method is only suitable for technologies that do not involve a very rapid change in the proportion of individual components of the mixture. On the other hand, it is not appropriate where we need to measure the particle size distribution on a continuous basis, e.g. in order to control or optimize the technological process.

As for on-line measurement, the continuous measurement of particle size distribution in a two-phase medium is only practicable by means of several essentially different methods. Frequently used is the optical method, based on the Optical Doppler Effect [1] principle. Through this method a high accuracy of measurement can be achieved. Its drawback is the requirement for a clear opening into the flow channel. Other limiting factors include great demands on the processing of the measured optical signal and a very high cost of instrumentation. Another method described in the literature is the measurement using acoustic spectroscopy or measurement of attenuation of the propagating ultrasonic signal [2].

In our paper, we focus on the method of solid particle flow measurement by means of acoustic emission (AE). The method has been known and applied over some period of time [3],[4]. It is based on creating an artificial or natural obstacle in the flow channel (e.g. a flow channel bend), which the flowing solid particles whose parameters we want to establish run against. The situation is shown in Figure 1. The solid particles hitting against the obstacle generate pulse acoustic emission and the resulting mechanical waves (acoustic emission signal) propagate through the obstacle in the same way as through the auditory canal. We record the signal with a piezoelectric acoustic emission sensor. The acoustic emission method offers advantageous characteristics which include swift and continuous assessment of the measured signal, a very small effect on the flow channel and finally very simple and relatively inexpensive instrumentation.

The generation of acoustic emission during the impact of solid particles against an obstacle can be described using the Hertz theory of impact. The Hertz theory defines the relations for a period of impact T (1) and a maximum force during the impact F_{max} (2). Approximation relations in the shape suitable for an impact of a sphere against a flat board following from the Hertz theory are described by Benes and Zehnula [5]. Approximate relations determine the dependence on the radius of the hitting particles. In summary, it can be concluded that the acoustic emission

method can be used for the measurement of particle size distribution.

$$T \approx (\alpha_1 + \alpha_2)^{0,4} \rho^{0,4} v^{-0,2} r \qquad (1)$$

$$F_{MAX} \approx (\alpha_1 + \alpha_2)^{-0,4} \rho^{0,6} v^{1,2} r^2 \qquad (2)$$

where:

T is duration of impact,

F_{max} is magnitude of force during impact,

ρ is density of spherical body material,

v is impacting velocity and

r is radius of impacting particle.

$$\alpha_1 = \frac{1 - \mu_1}{G_1} \qquad (3)$$

$$\alpha_2 = \frac{1 - \mu_2}{G_2} \qquad (4)$$

where:

μ_1 and μ_2 are the Poisson`s constants of particle material and impact plate material,

G_1 a G_2 are modulus of elasticity of particle material and impact plate material (indices are similar like for Poisson`s constants).
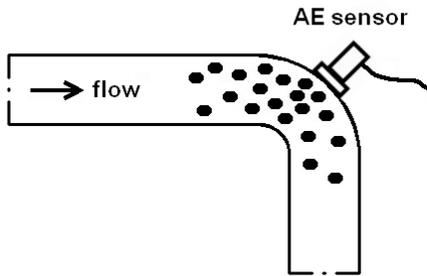

Fig. 1.: Example of arrangement for measuring by the use of acoustic emission method (natural barrier).

Most authors, however, who have investigated the use of AE method in the particle distribution measurement, have only focused on the measurement of the mean value of particle sizes. Cao et al. analyzed AE signal using a wavelet transform and apart from the mean size of particles also investigated the energy of AE signal in his study [6]. Hou et al. discusses in his work the measurement of the mean size of particles in the fluid layer, and, among other things, also researches into the prediction of undesirable clusters [7]. Measurements of the mean value of particle diameters are broadly applied within granulation processes, indispensable e.g. in the pharmaceutical industry. The practical application of the acoustic emission method is described in the literature for the case of ´end-point detection´ in the granulation process. At that point the greatest quantity of granules is generated of the required size with the defined amount of active substance. Matero et al. focuses in his work on the analysis of the average size of granules and the predicted

moisture content in the examined granules [8]. Tsujimoto et al. studies the effect of change of several parameters on the magnitude of AE signal amplitude, where the size of particles is again one of the studied parameters [9]. Briens et al. deals with the granulation end-point detection in close relation to particle sizes and studies the effect of AE sensor location [10].

Nonetheless, the problems relating to continuous measurement of particle size distribution have so far not been given adequate attention in the available literature. Therefore, the aim of experiments was to verify a possibility of using the acoustic emission method in measurements of particle size distribution in a mixture of granules of the same material. It follows from the aforementioned approximation relations that a period of impact T and a maximum force during the impact F_{max} affect the magnitude of an amplitude of spectral lines. Therefore it should apply that smaller particles reach lower amplitudes of spectral lines in the low-frequency range, while in the high-frequency range their spectral lines should reach higher amplitudes. On the other hand, it should apply to larger granules that higher amplitudes of spectral lines are in the low-frequency range, while in the high-frequency range their spectral lines should reach lower amplitudes. Based on the above mentioned presumptions it can be establish the proportion of solid particle fractions using the acoustic emission method.

2. EXPERIMENTAL

Experiments were carried out using a measuring apparatus schematically represented in Figure 2. The apparatus consisted of a container mounted over a capture receptacle. Discharging of material was controlled by a valve. The measured data was obtained through measurements for ceramsite granules (Figure 3) regarding which very similar material constants were assumed, the tested mixtures only differed in the distribution of particle sizes. Between the outlet of the container and the receptacle was inserted a dural square which served as an obstacle and at the same time a waveguide to guide ultrasonic waves of acoustic emission to the sensor. A piezoelectric sensor AURA SV 416 was used as an acoustic emission sensor. The signal from the sensor was sampled by 24-bit resolution National Instruments PXI 5922 high speed digitizer. The signal was further processed using NI LabVIEW 2009. A suitable measuring application was set up for data processing, which enabled direct calculation of the performance spectrum using the measured data. At the same time the application recorded the calculated spectrum to the computer hard disk. Based on the record of the spectrum there were average values of the spectral lines calculated for subsequent analysis. The average was acquired from a file of 1000 sequential spectra. AE signal was measured by the measuring card at the selected range of 10 V. To calculate each short-time power spectrum for statistic analysis, 1024 samples were used with the selected Hanning window function. The recording speed of the measuring card was set to 256 kS/s.
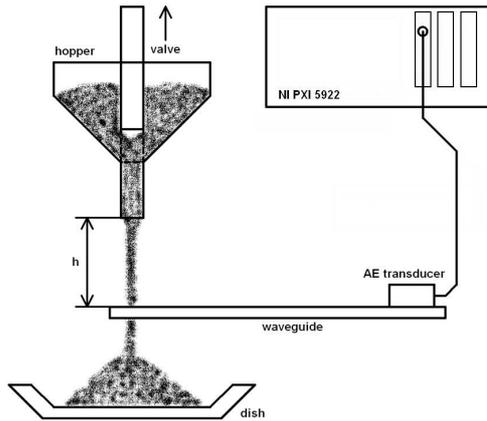
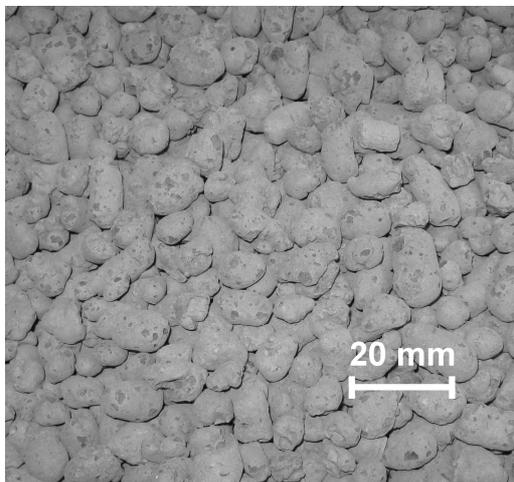Fig. 2.: Scheme of stand for mass ratio measurement using of acoustic emission method.

Fig. 3.: Expanded clay aggregates (ceramsite, LECA) used for performed measurements.

The first part of the completed measurements involved experimental verification of the effect of particle sizes on the AE signal generated spectrum. The following experiment was undertaken to verify the validity of our assumptions. Two fractions of ceramsite granules were available, with 4-8mm and 8-16mm sizes of particles. Using a measuring jig, both fractions were poured from a height of 15 cm and the performance spectra of the AE signal thus generated were measured. In the next step, five different mass mixtures of the fractions were created. The mixtures were prepared in the ratio of a small granule to the total mass of a mixture as the proportions of 2/8, 3/8, 4/8, 5/8 and 6/8. Performance spectra were also measured for the aforementioned mixtures under the same conditions.

The second part of the measurements completed experimental verification of the dependence of a spectrum shape on the velocity of particles hitting the obstacle. The velocity of particles is one of the essential parameters affecting the AE measured signal, and it is useful to learn

about its effects. Therefore a single fraction of ceramsite granules, 4-5 mm particle size, was selected for the experiment. The change of velocity of the falling particles was effected in this measurement through the change of the height from which particles fell onto the obstacle. Heights were changed during the experiment through a constant step of 5 cm.

3. RESULTS AND DISCUSSION

To effect the basic statistical processing of the signal based on the completed experiments and comparison of the obtained spectra between themselves, the measured amplitudes were processed in frequency bands with the same step. The step of individual frequency intervals equalled 8 kHz, the average values of amplitudes of the spectra were calculated in these frequency bands and plotted in the diagram presented in Figure 4 and Figure 5.
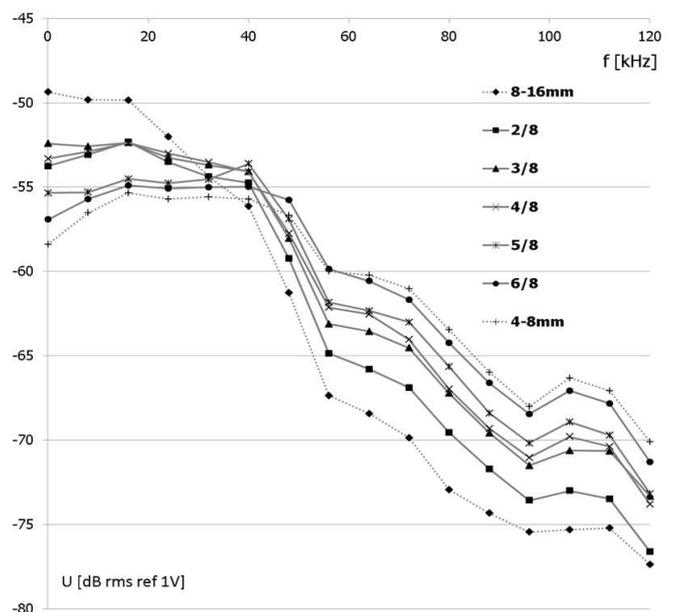

Fig. 4.: Dependency of average spectral lines on the mass ratio of small particles in a mixture.

The diagram in Figure 4 shows that the analyzed spectra obtained for both fractions of granules (marked as limit curves with a broken line) and their mass mixtures are highly consistent with the theoretical assumptions. Particle mixtures with a higher content of smaller particles have greater amplitudes in higher frequencies while mixtures with prevalence of larger particles have their amplitude maxima of spectral lines in lower frequencies consistent with a longer period of impact.

The signal recording and processing in the experiments to determine the effect of velocity of particles did not differ from the measurements to determine the effect of sizes of particles, the calculation of spectra used the same parameters and the subsequent analysis performed through

averaging of amplitudes of the spectra in the selected frequency steps was also conducted in the same manner. The analyzed data obtained is shown in the diagram in Figure 5.
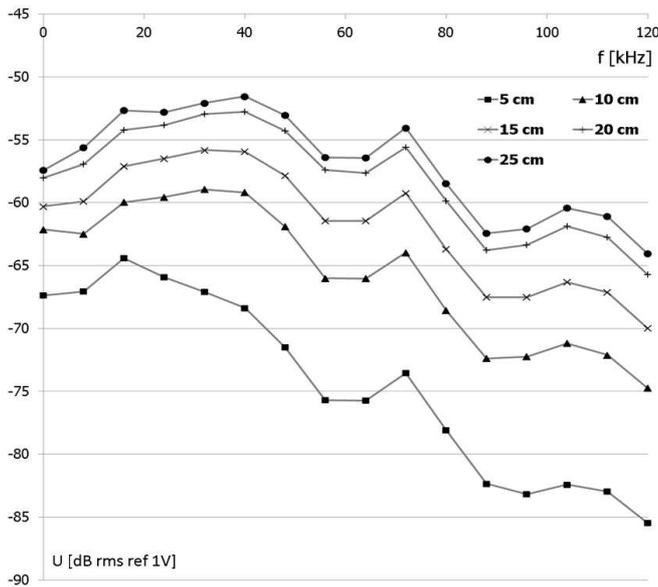

Fig. 5.: Dependency of average spectral lines on the height from which were particles falling.

It follows from the diagram in Figure 5 above that the change of particle velocity affects the whole curve of the spectrum within the analyzed frequency range. The changed parameter of velocity therefore does not cause any changes to the spectral line amplitudes which would take place differently in specific frequency bands, as it was observed for the parameter of particle sizes, or any intersection of individual spectra. The increasing velocity of particles only causes shifting of the whole spectrum toward higher amplitudes of spectral lines. The origin of the aforementioned facts relates to the theoretical dependence of the parameters of the measured acoustic emission signal on the input parameters that are changing. If we go back to the relations (1) and (2), we can see that the change of a maximum force F_{max} during an impact changes in relation to velocity with a power of $v^{1,2}$, whereas the period of impact changes with the change of velocity to a much smaller degree and, moreover, in the opposite direction, with a power of $v^{-0,2}$. The shift of the spectral line amplitudes is therefore hardly noticeable on the frequency axis in the aforementioned analysis, as opposed to the significant change in the spectral line amplitude. On the other hand, the spectra obtained for mixtures of different size particles clearly demonstrate a major effect of the weights r^1 for the period of impact, and r^2 on the magnitude of a force amplitude during the impact.

The presented values validate the theoretical assumptions regarding the shape of spectral characteristics. Small differences can only be observed in a mixture of 6/8 (for small granules) at lower frequencies. The remaining

dependences obtained from the measurement provide a very good possibility of distinguishing between different mixtures of particles by means of spectral analysis of AE signal.

There was accomplished confirmation if it is possible to use a mathematical model based on the Hertz theory of impact for measuring of the particle size distribution The theoretical model was created from the aforementioned mathematical relationship (1), (2).

The major part of the confirmation was completed through the calculation of theoretical dependence of the force F_{max} on the average particle diameter in a mathematical model. This characteristic was scaled by the highest value corresponding to the highest value of the force (in this case for an average particle diameter of *12 mm*). Further, the voltage values were calculated from the spectral lines of the measured power spectrum; the voltage corresponds to the force F_{max}. This voltage was then also scaled by the highest value. Both curves, established theoretically and experimentally, were plotted in charts together, the selected example shown in Figure 6 was obtained for the spectral lines interval *0 – 8 kHz*. The chart shows that the experimentally obtained increase in the voltage amplitude largely corresponds with the theoretical premises, with a small deviation from the theoretical dependence concerning the aforementioned *6/8* mixture. The remaining spectral intervals demonstrate an exact inversion trend due to the effect of duration of impact *T*.
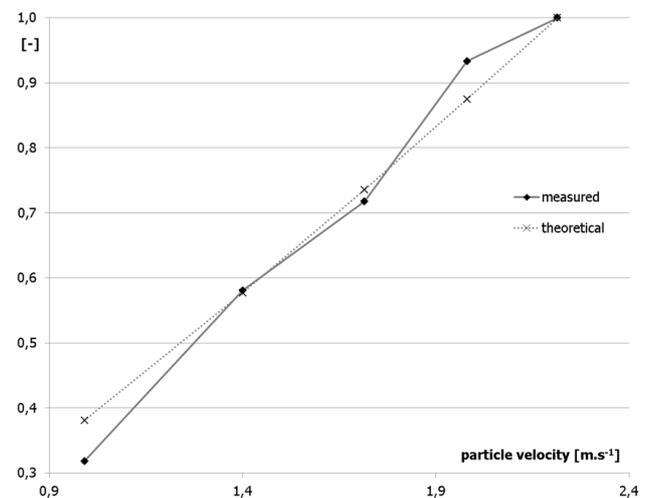

Fig. 6.: Comparison of theoretical model and practical mesurement: parameter is particle velocity (0 – 8 kHz).

The second part of the confirmation was completed through the calculation of theoretical dependence of the force F_{max} on the average particle velocity. This dependence was also obtained from a mathematical model. The particle velocities were calculated based on the impacting heights. The calculated dependences were scaled similarly as in the first step. Next, the voltage values were expressed using the spectral lines. This voltage was also scaled by the highest

value for easy comparison. The theoretical and the measured curves were plotted in charts together. Figure 7 shows an example of spectral lines in the interval *0 – 8 kHz* and in the interval *120 – 128 kHz*. The experimentally obtained shape of increase in the voltage amplitude has again been proved largely consistent with the theoretical presumptions. The other comparisons concerning the remaining intervals are very similar.
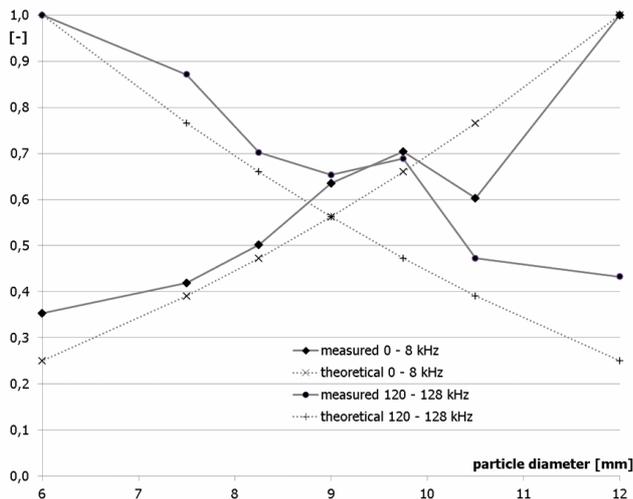

Fig. 7.: Comparison of theoretical model and practical mesurement: parameter is particle diameter (0 – 8 kHz, 120-128 kHz)..

4. CONCLUSION

The paper summarizes the completed experiments and the following analysis of the acoustic emission signal during the measurement of solid particle flow. The anticipated dependence on the size of particles and velocity of particles was observed in the experimentally acquired data. Based on the analysis of the measurements completed in the frequency area it has been verified that it is possible to successfully measure particle size distribution in mixtures employing the acoustic emission method. As expected, velocity of particles only affects the general energy of a signal, without any relevant effect on the shape of a frequency spectrum. The main problem regarding the granulometry of particles using acoustic emission is the great dispersion of the measured parameters, as it is practically impossible to interpret the measurement correctly without statistical processing. The great dispersion of values has to do with the fact that the proposed model of an impact of a particle against an obstacle is very simplified. A real particle is hardly ever spherical in shape and also the impact cannot be considered as entirely flexible, as required by theoretical assumptions. Despite that we believe that the undertaken experiments successfully illustrate the potential of the method. In our further work we wish to focus on creating an appropriate set of parameters for a signal regarding both time and frequency factors, that will provide satisfactory information about the parameters for a two-phase medium flow and establishment of their mutual relations.

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