# Investigations into the Sensing Mechanism of Acoustic Emission Sensors for Particle Size Measurement in a Particular Case: Normal Incidence

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## Abstract

In situ continuous particle size measurement is desirable in a variety of industries. Acoustic emission (AE) is a well suitable technique to achieve on-line continuous sizing of particles in pneumatic conveying pipelines, which utilizes the AE signals due to the impact of particles with a waveguide protruding into the particle flow. Although early attempts have been made to reveal the relationship between the AE parameters and the particle size, the fundamental sensing mechanism of the AE-based technique for particle size measurement is still not established. For instance, the effect of particle size distribution on several AE parameters remains to be examined. This paper aims to gain an in-depth understanding of the AE sensing mechanism for on-line particle sizing by quantifying the parameters of the AE signal, including peak amplitude, count, rise time, duration, energy and root mean square (RMS) value. A theoretical model considering the energy dissipation during plastic impact is also developed to determine the particle size from the AE signal. The proposed method is verified through experimental tests with glass beads on a single-particle test rig. Experimental results obtained indicate that the proposed method is feasible to infer particle size information from the energy of an impact event. The particle size can be measured with a relative error mostly within $\pm 10\%$ over the range from 0.4 mm to 1.2 mm.

**Keywords:** Particle size, Acoustic emission, Single particle, AE parameters, Energy dissipation

## 1. Introduction

On-line continuous particle sizing of pulverized coal is highly desirable in coal-fired power plants to achieve improved combustion efficiency and reduced pollutant emissions [1]. At present, the measurement of particle size in power plants is usually realized using an isokinetic sampling and sieving method, which is cumbersome and time-consuming [2]. Therefore, it is essential to develop a simple and reliable method for on-line continuous particle size measurement.

In recent years acoustic emission (AE) detection has been proposed as a promising method to measure the size of particles in pneumatic conveying pipelines [3-5]. This method has the advantages of high sensitivity, minimum invasiveness, easy maintenance and on-line continuous measurement. In principle, the collision between a solid particle and a plate leads to sudden changes in stress at the vicinity of the impact point, which generates transient elastic stress waves carrying useful information about the collision. These waves are then transformed into electrical signals using an AE sensor [6]. The characteristic parameters of the resulting AE signals are greatly dependent on the physical process of the collision. For this reason, it is possible to determine the particle size through parametric analysis of the AE signal.

Some early efforts have been made to relate certain characteristic parameters of the AE signal to the particle size [7-10]. Most studies have used AE parameters in the time domain such as peak amplitude, energy, rise time and duration to deduce the size information. Hu *et al* [7] demonstrated that the particle size information could be inferred from the peak AE amplitude, which was verified on a laboratory-scale test rig. Droubi *et al* [8] investigated the energy dissipation during impact under different experimental conditions and validated that the AE energy is proportional to the cubic of the diameter. Buttle *et al* [9] proposed a technique to measure particle size by extracting the rise time from the resulting AE signal. However, this method requires a complicated measuring system, which makes it impractical to be applied in power plants. Coghill [10] achieved size measurement of particles in a pneumatic pipeline using the duration of the AE signal, however, the low temporal resolution of this technique limits the measurement accuracy for on-line particle sizing.

Although good progress has been made on verifying the validity of the aforementioned AE parameters for particle size measurement, more work needs to be undertaken in order to improve the measurement accuracy of this method. Different AE parameters can be used to infer particle size, but the measurement accuracy for particle sizing differs between them. Especially, in consideration of the harsh industrial environment where the measurement system will be installed, some parameters are probably inappropriate for practical on-line sizing. Meanwhile, in current studies the collisions between particles and a plate are usually assumed to be elastic. However, the collisions in practice are always inelastic [11], which makes elastic impact models invalid for on-line continuous particle size measurement. The plastic deformation and energy dissipation during an impact have strong effects on the parameters of the AE signal, leading to increased measurement error in particle size measurement. Besides, there exist simultaneous collisions when the AE sensor is installed on a pneumatic conveying pipeline, which brings difficulties to identify the single impact events from the overlapped signals. In order to achieve an in-depth understanding of the AE-based sensing mechanism for on-line particle sizing, it is necessary to analyze the AE signal due to an individual collision. For this purpose, AE signals from single particle impacts need to be collected under well-controlled conditions.

Previous research usually obtained the individual AE signal using free-fall particles impinging onto a plate. Muller *et al* [12] evaluated the impact behavior of spherical particles colliding onto a thin plate based on the resulting AE signals. Schnabel *et al* [13] carried out single-particle-impact experiments by dropping particles onto a metallic plate and studied the elastic waves generated from the impacts in the frequency domain. Hayashi *et al* [14] investigated the AE signals generated by individual impact events and found that two peaks at specific frequencies were contained in the signals, whose amplitude ratio was dependent on the particle size. However, the particle velocities are much less than those in industrial situations due to the limitation of the falling height in these studies. For instance, the velocity of pneumatically conveyed coal particles in power stations is usually more than 20 m/s, which is difficult to achieve in free-fall experiments [15]. Therefore, a single-particle test rig was designed and built in this study. Particle velocities higher than 20 m/s are available on this rig. As the full waveform of an impact event is collected throughout the collision of a single particle, it is possible to reveal the sensing mechanism and hence optimize the design of the particle sizing system. Single particle experiments under controllable conditions also allow elimination of simultaneous collisions and environmental noise that complicate the AE signal and the extraction of AE parameters.

This paper aims to gain insights into the fundamental sensing mechanism of the AE-based technique for particle size measurement. Some preliminary work has been reported in [16], in which the impact dynamics during plastic collision process was investigated and an improved model based on AE peak amplitude was proposed to realize on-line particle sizing. However, the relationship between the AE peak amplitude and the particle size is not explicitly established due to the complexity of the impact dynamics. In comparison with previous work, the characteristics of the AE signal generated by an individual collision is quantified through analytical modelling and practical experimentation in this paper. The parametric analysis is applied to extract and quantify the parameters of the AE signals, including peak amplitude, count, rise time, duration, energy and root mean square (RMS) value. In this way, the effects of particle size on the parameters of the AE signal are quantitatively established. The potential of different AE parameters for on-line particle sizing is also assessed. Meanwhile, the influence of plastic deformation occurring in practical impact events on the energy dissipated as elastic waves is investigated, which has never been considered in previous studies. A theoretical model taking into account the energy dissipation during plastic impact is also proposed for the first time to establish the relationship between the particle size and the AE energy. The effectiveness of the proposed model for on-line particle sizing is assessed through experimentation with single particles.

## 2. Methodology

### 2.1. Parametric analysis

Parametric analysis is a classical method for AE signal analysis. In this study, the AE signal is generated from the collision between an individual particle and a waveguide. The parameters of the resulting AE signal are associated with the contact force during the impact, which is affected by the particle size. Therefore, it is possible to estimate the particle size from certain AE parameters. A typical AE signal and the parameters commonly used for analysis are illustrated in Fig. 1. The definitions of these parameters are respectively explained below [17,18].

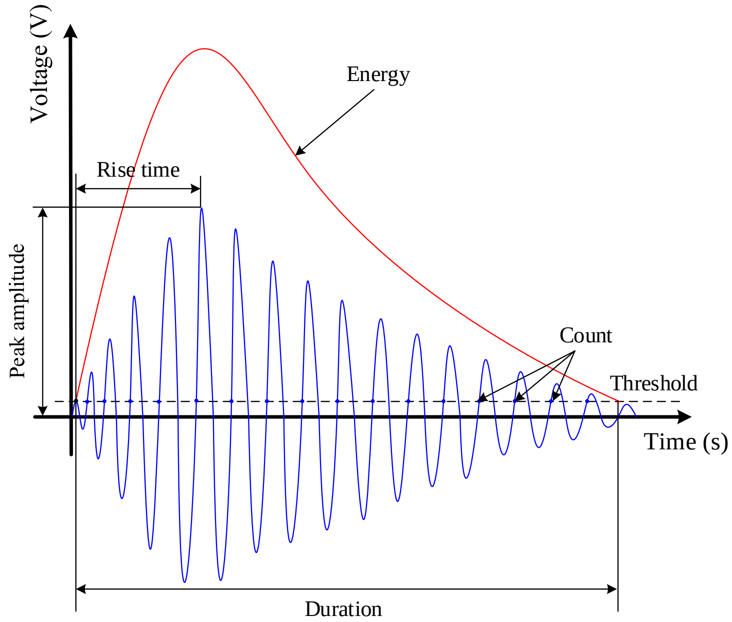


**Fig. 1.** Typical AE parameters.

In an AE event, threshold is a voltage level which is set to distinguish the AE signal from the background noise. Peak amplitude is the highest amplitude attained by the signal. The count refers to the number of times the signal amplitude exceeds the preset threshold. Rise time is the time taken by the signal to reach the peak amplitude from the point it firstly crosses the threshold. Duration defines the time interval between the start and the end of the AE signal with reference to the threshold. The energy of an AE waveform, $E$, means the area under the envelope of the squared signal, which can be expressed as

$$E = \frac{1}{F_s} \sum_{i=1}^{n} \left| v_i \right|^2 \tag{1}$$

where $v_i$ is the signal amplitude and $n$ is the number of samples in the discrete-time AE signal. $F_s$ is the sampling frequency.

In addition, another common parameter $RMS$, which is usually regarded as the effective amplitude of an AE event, is calculated from [19]

$$RMS = \left( \frac{1}{n} \sum_{i=1}^{n} \left| v_i \right|^2 \right)^{\frac{1}{2}} \tag{2}$$

### 2.2. Energy absorbed by elastic waves

When a particle collides normally with a plate, the kinetic energy of the impinging particle is converted into a combination of kinetic energy in the rebounding particle, plastic strain energy causing permanent deformation in the contacting surface and energy dissipated as elastic waves propagating away from the point of collision [20]. Among them, the portion of the energy dissipated as elastic waves is relatively small and can be detected using an AE sensor. In the case of a purely elastic impact between a particle and a plate, the fraction of energy contained in the elastic waves is given by [21,22]

$$\lambda_e = K_e v_0^{\frac{3}{5}} \tag{3}$$

where $K_e$ is a constant of proportionality and $v_0$ is the impact velocity of the particle.

However, plastic deformation is inevitable in practical collision events. The critical velocity at which the plastic impact occurs can be very low [23]. As the impact velocity in the current research is more than 20 m/s, equation (3) is not applicable to describe the energy dissipation due to elastic waves.

Assuming that the compression process during the collision is plastic while the recovery process still elastic, the fraction of energy absorbed in the elastic waves can be estimated from [24]

$$\lambda_p = K_p \frac{\alpha}{1+e} \tag{4}$$

where $K_p$ is also a constant of proportionality and $e$ is the coefficient of restitution. $\alpha$ is a dimensionless function of $e$, which is defined by

$$\alpha = \frac{4(1+e)}{F_0^2 \omega_p} \int_0^{\infty} \omega^2 \left| F(\omega) \right|^2 d\omega \tag{5}$$

where $F(\omega)$ is the Fourier component of the contact force. $\omega_p$ and $F_0$ can be respectively calculated from

$$\begin{cases} \omega_p = \left( \dfrac{3\sigma_Y}{2\rho R^2} \right)^{\frac{1}{2}} \\ F_0 = \dfrac{4\pi\rho R^3 v_0 \omega_p}{3} \end{cases} \tag{6}$$

where $\rho$, $R$ and $\sigma_Y$ are the mass density, radius and yield stress of the particle, respectively.

The coefficient of restitution $e$ can be approximated by [25]

$$e = 3.8\left(\frac{\sigma_Y}{G}\right)^{\frac{1}{2}} \left( \frac{2\pi\rho v_0^2}{3\sigma_Y} \right)^{-\frac{1}{8}} \tag{7}$$

where $G$ is a constant, which is given as

$$G = \frac{1-\mu_1^2}{E_1} + \frac{1-\mu_2^2}{E_2} \tag{8}$$

where $E_i$ and $\mu_i$ are Young's modulus and Poisson's ratio, respectively. Subscript 1 here refers to the impinging particle while subscript 2 represents the plate.

In order to investigate the energy dissipated as elastic waves during a collision, the variation of $\alpha$ with $1+e$ is numerically calculated, as shown in Fig. 2. It can be clearly seen that the value of $\alpha$

keeps a downward trend with $e$. When $e$>0.6, the rate of change in $\alpha$ becomes slow. The coefficient of restitution, $e$, indicates the kinetic energy of the particle dissipated during the collision process, which ranges from 0 to 1. For a perfectly elastic collision, $e$ has a value of 1 while for a perfectly plastic collision, $e$ becomes 0. According to equation (4), the fraction of energy absorbed by elastic waves during an elastic-plastic impact depends on the strength of the collision, which means severer plastic deformation leads to increased energy dissipation in elastic waves.

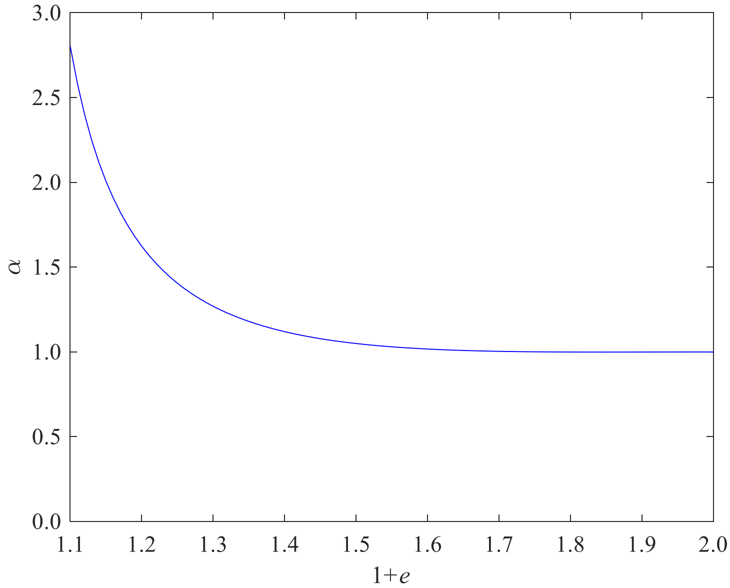


**Fig. 2.** Variation of $\alpha$ with 1+$e$.

### 2.3. Particle size measurement

For an AE-based system, it is generally agreed that the energy of the AE signal is proportional to the energy dissipation due to elastic waves [26]. Therefore, the AE energy can be expressed as

$$E = K\lambda_p E_k \tag{9}$$

where $K$ is a proportionality constant and $E_k$ is the kinematic energy of the impinging particle, which is calculated from

$$E_k = \frac{2}{3}\pi\rho R^3 v_0^2 \tag{10}$$

By substituting equations (4) and (10) into equation (9), the relationship between the AE energy, impact velocity and radius of the particle can be described as

$$E = K_{sys}\frac{\alpha}{1+e}R^3 v_0^2 \tag{11}$$

where $K_{sys}$ is a constant to be obtained through calibration.

## 3. Experimental method

### 3.1. Experimental test rig

In order to carry out the required experimental work, a laboratory-scale test rig was designed and constructed for individual particle impacts on a waveguide. Fig. 3 illustrates schematically the single-particle test rig. In order to achieve similar particle velocities as those at coal fired power stations, the particles are driven by an airstream from the air compressor to move in the horizontal direction to collide normally with the waveguide. In this way, it is convenient to introduce the particles into the launching tube from the open breech, which also ensures that all the particles are positioned at the same location with an initial velocity of zero. Although normal impacts could be achieved by making the particles collide onto the waveguide in the vertical direction, the gravity effect would affect the velocity of particles in an either upward or downward direction (i.e. acceleration or deceleration). Meanwhile, it is impractical to keep all the particles in the same initial condition before being launched. Moreover, it is not straightforward to install the hardware parts and components in the vertical direction.

The length of the launching tube used is 110 mm. The open breech has a diameter of 1.5 mm whilst the inner diameter of the launching tube is 2 mm. In the presence of the air flow from the air compressor, the particle is accelerated along the tube towards the waveguide. The elastic stress waves generated from the particle impact are detected by an AE sensor coupled to the other end of the waveguide (details are given in Section 3.2), which is in a very similar way to install the AE sensor in practical applications. The particle velocity is measured using an electrostatic velocimeter through cross correlation [27], which can realise velocity measurement of a moving particle with a relative error within ±2% [28]. The AE signal is pre-amplified with a voltage gain of 20 dB and filtered through a band-pass filter with a frequency range of 10 kHz - 1 MHz. A signal analyser (DS-4A, Softland) is employed for waveform acquisition at a sampling rate of 3 MHz. The AE parameters are extracted by processing the signals generated from each individual impact event.

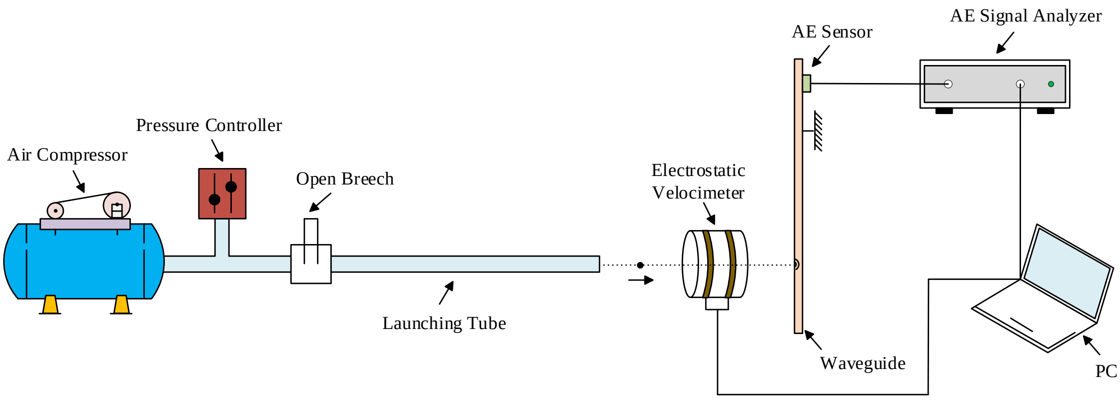


**Fig. 3.** Schematic of the experimental test rig.

As the particle velocity is more than 20 m/s in this study, the gravity effect on the trajectory of the moving particle is negligible. The distance between the outlet of the launching tube and the waveguide is 120 mm. Suppose a particle collides with the waveguide at a velocity of 20 m/s, the vertical offset of the particle is approximately 0.18 mm and the angle between the particle velocity vector and the plane of the waveguide at the impact point is 89.9°. These facts mean the impact between the particle and the waveguide can be regarded as a normal collision. Meanwhile, it is estimated that the vertical offsets of the particles with different velocities in the experiments vary from 0.05 mm to 0.15 mm, which means the eventual impact locations are very close. As the waveguide is not very long, the characteristics of an AE signal are mainly dependent on the particle impact dynamics and are insensitive to the exact location of the impact. As a result, slight variations (especially small particles) in the impact point on the waveguide during the experimental tests have little influence on the resulting AE signals.

### 3.2. AE Sensor and its installation

Fig. 4 shows a photo of the experimental setup. The 187-mm long waveguide is made of stainless steel, which has a 500 mm$^2$ flat plane facing the direction of the particle movement. In this way, the particle can normally collide with the waveguide. The AE sensor used is Nano30 supplied by Physical Acoustics Corporation (PAC), which is attached to the end section of the waveguide. The main technical specifications of the sensor are summarized in Table 1. Vacuum grease is employed to guarantee good coupling between the AE sensor and the surface of the waveguide. The AE senor is also sealed with rubber bushing to isolate the structure vibration. The aperture effect is negligible due to the small diameter of the AE sensor. The installation of the waveguide and the AE sensor is shown in Fig. 5.

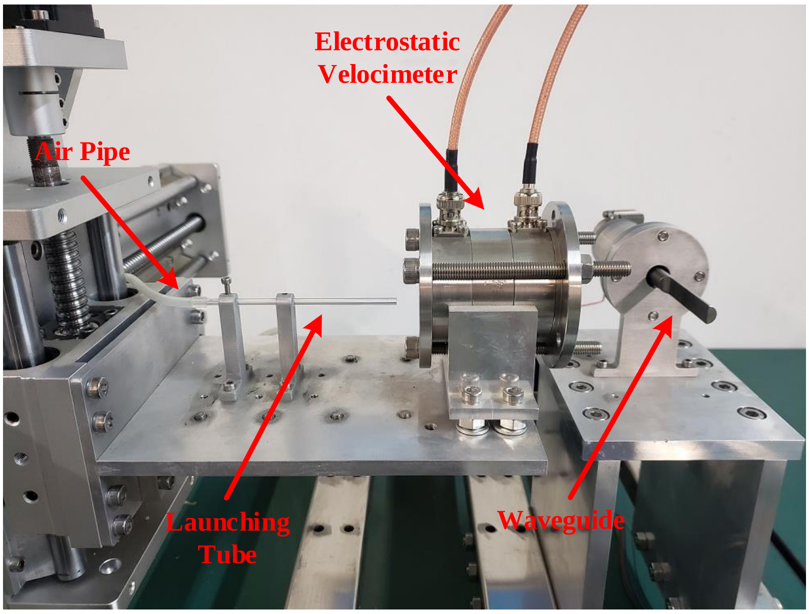


**Fig. 4.** Experimental setup.

Table 1. Technical specifications of the AE sensor

| Specification | Detail |
|---|---|
| Material | Piezoelectric ceramic |
| Outer diameter | 8 mm |
| Height | 8 mm |
| Weight | 2 g |
| Operating frequency range | 125 kHz to 750 kHz |
| Temperature range | -65 to 177℃ |

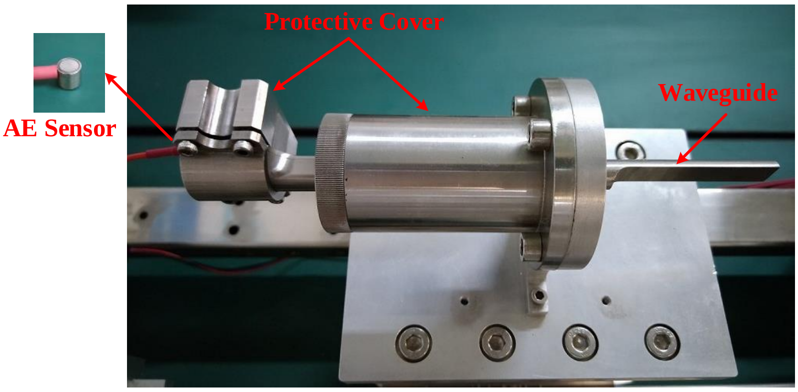


**Fig. 5.** Experimental Installation of the waveguide and the AE sensor.

### 3.3. Experimental conditions

Glass beads were selected as test particles for single-particle impact experiments. In this study, five groups of glass beads with various mean diameters ranging from 0.4 mm to 1.2 mm were utilized as test particles. The single-particle-impact experiments were conducted under well-controlled conditions, which can ensure the acquisition of faithful AE signals. Before the particle launching, the reference particle size of each glass bead was obtained from a micrometer (0.0001 mm resolution). With the changing of the driving pressure from the air compressor, three average velocities, which are 22, 32 and 37 m/s, were achieved by regulating the driving pressure from the air compressor. Ten repeated tests were carried out under each experimental condition. The normalised standard deviations of the particle size and the impact velocities for different tests are all within 3%, which indicates that the tests were well repeated under different conditions.

Pencil lead breaking tests were performed on the impact plane of the waveguide to verify the acoustic coupling between the AE sensor and the surface of the waveguide. The waveguide was also exposed to the airstream from the air compressor to confirm the effect of the air flow on the AE signal. The amplitude of the signal observed was less than 6 mV, which is far below that of the signal generated due to an impact event. In addition, the signal due to the air flow usually has a low frequency component, which is far beyond the operating frequency range of the AE sensor (Table 1). Therefore, the effect of the air flow on the detected AE signal is negligible in this study.

In order to determine $K_{sys}$ for inverting the particle size, another five groups of glass beads were used for calibration at different velocities. Ten particles were tested in each set. According to equation (11), different values of $K_{sys}$ for different sized particles at various velocities are obtained. as shown in Fig. 6. It is evident that the value of $K_{sys}$ is insensitive to the particle size but depends significantly on the particle velocity. The value of $K_{sys}$ increases linearly with the particle velocity.  In order to determine the relationship between $K_{sys}$ and the particle size, the average value of $K_{sys}$ for each particle velocity is calculated respectively. A straight line equation is then obtained through the use of the least square fitting method, as shown in Fig. 7, with a coefficient of determination of 0.9985.

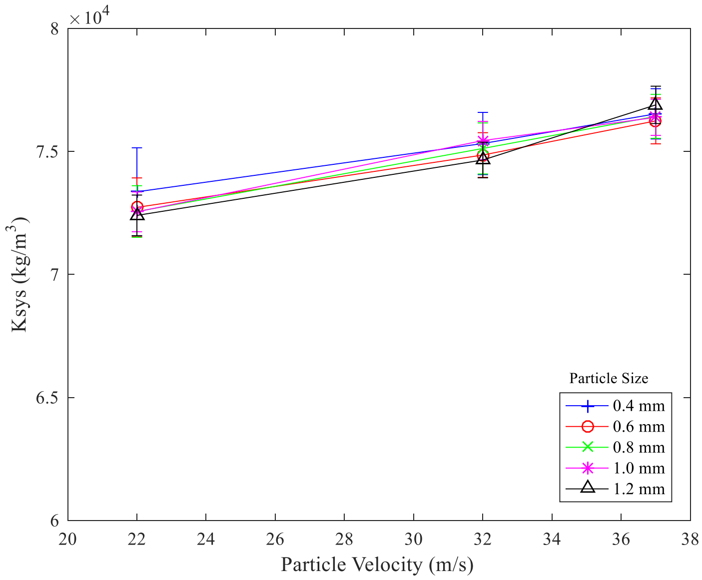


**Fig. 6.** $K_{sys}$ for different sized particles at various particle velocities.

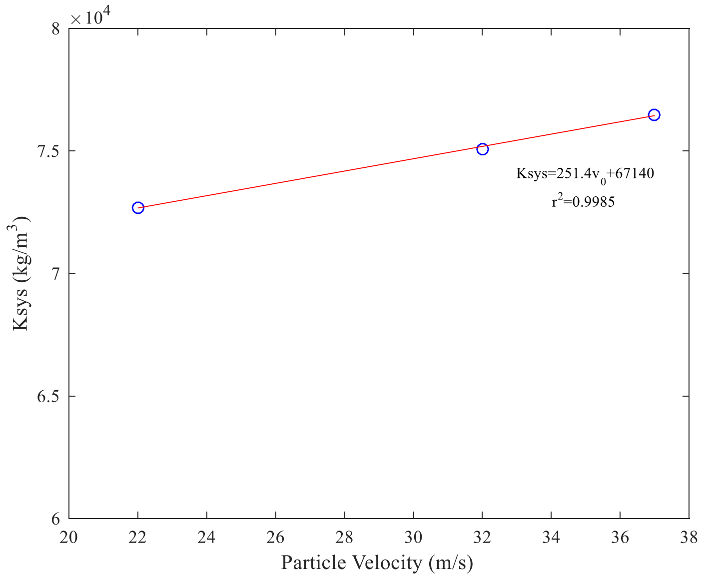


**Fig. 7.** Relationship between the $K_{sys}$ and the particle velocity.

## 4. Results and discussion

### 4.1. Analysis of AE parameters

Fig. 8 illustrates a typical AE signal from an individual collision. It can be seen that the signal waveform quickly reaches the peak amplitude followed by a damped oscillation. Although the contact time between the glass bead and the waveguide is short (microsecond level) during the collision, the damped oscillation can last for several milliseconds. This is mainly due to the reflection of the elastic stress waves within the waveguide and the resonant vibration of the piezoelectric plate inside the AE sensor. The long duration of the AE signal brings challenges to separating overlapping impact signals when the concentration of particles in a pneumatic conveying pipeline is high.

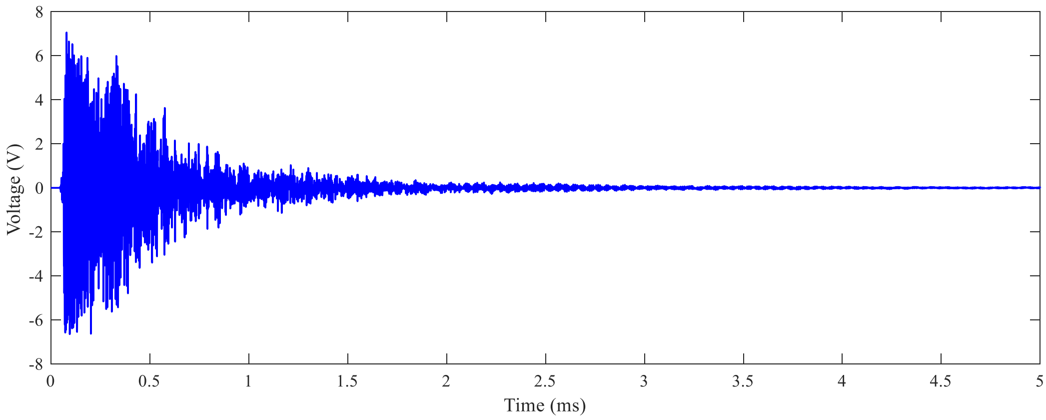


**Fig. 8.** Typical AE signal from an individual collision (particle diameter 0.8 mm and impact velocity 32 m/s).

The parameters of the AE signal under different experimental conditions were extracted. As depicted in Fig. 9, all the parameters generally show an increasing trend with the impact velocity and the size of the glass bead except for the rise time. When a larger particle or a particle with a faster moving speed impacts onto the surface of a waveguide, a greater striking force is produced, resulting in a higher peak amplitude. The kinetic energy of a moving particle also follows an increasing trend with the impact velocity and the size of the particle. As a result, the energy of the resulting AE signal tends to rise, as more kinetic energy is converted into elastic waves. Besides, the increasing particle size or impact velocity during the collision also raises the strength of an AE event, leading to a larger RMS value of the signal.

As illustrated in Fig. 9 (c), the rise time shows an upward tendency along with the particle size but decreases with the impact velocity. The rise time is closely related to the contact time during the impact process, depending on the particle size and particle velocity [29]. A larger particle size or a lower impact velocity extends the contact time of a collision, thus leading to a longer rise time. On the contrary, the count and the duration for the AE signal are more related to the contact force during collision. A greater contact force leads to a longer decay time for the AE signal. As a result, both the count and the duration increase with the impact velocity and the size of the particle.

Though all the AE parameters are affected by the impact velocity and the size of the particle, not all of them are appropriate for particle size measurement, particularly in consideration of measurement accuracy and applications to consecutive impacts of particle flow. The peak amplitude and the energy both yield better repeatability with relatively smaller normalised standard deviations, which are within 4% for most particle impact events. Despite the similar increasing trends with the impact velocity and the size of the particle, the count, the duration and the RMS value are inappropriate as the parameters for particle sizing due to the higher normalised standard deviation (mostly more than 10%). This issue becomes even worse, if simultaneous collisions in practical applications are taken into account as it is difficult to extract these parameters from a resulting AE signal. Moreover, the rise time shows the least potential to be chosen as the parameter for particle size measurement as its normalised standard deviation is greater than 20%. The possible reason for this is because the rise time from a collision event is usually at microsecond level, making it difficult to obtain precise values under the current experimental conditions. In general, when the impact velocity is known, it is appropriate to determine the particle size from the peak amplitude or the energy of the AE signal.

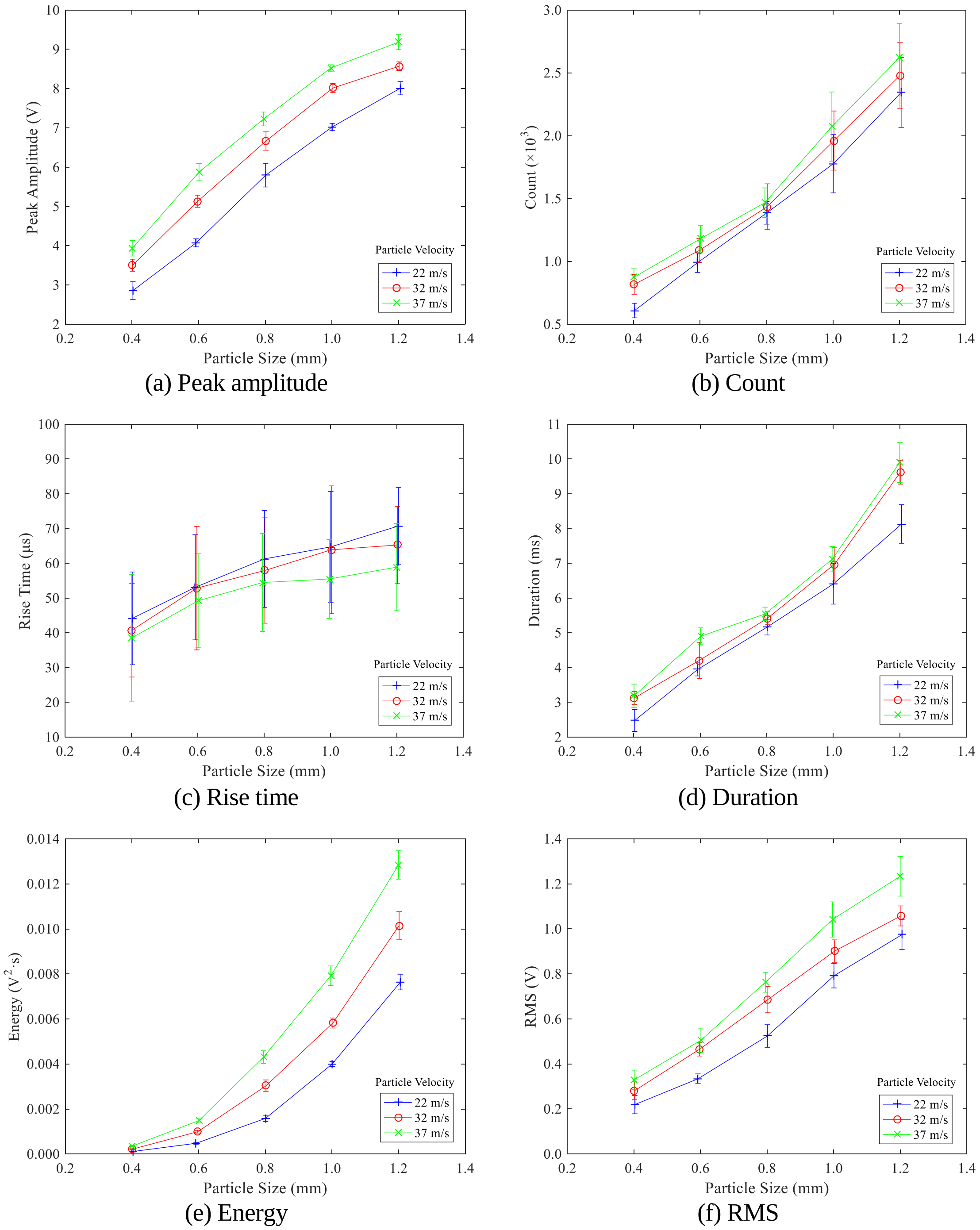


**Fig. 9.** AE signal parameters under different conditions.

### 4.2. Particle size inversion

According to the aforementioned discussion, the peak amplitude and the energy are most suitable for particle size measurement. In consideration of the complex impact dynamics, it is impractical to establish an explicit relationship between the AE peak amplitude and particle size. In this paper, the theoretical model, as illustrated by equation (11), which is based on AE energy, is adopted for particle sizing.

The results of particle size inversion are plotted in Fig. 10. It is found that the measured particle sizes generally agree well with the reference values for all tested glass beads at various velocities. For the 0.4 mm glass beads, the measured particle sizes are smaller than the references. A possible reason for this is that small particles at low velocities are easily interfered by the air disturbance after being launched, leading to larger relative errors in measured particle size. In addition, the use of the micrometer to obtain the reference values of the particles also yields larger errors for smaller particles. Besides, the results of particle sizing for 1.2 mm glass beads are also not close to the reference values at the speed of 37 m/s. This is attributed to the slight breakage occurring in the surface of glass beads during impact with a high velocity. The AE energy will increase due to particle breakage, resulting in larger measured particle size. The influence of the particle fragmentation on the energy dissipated as elastic waves during collision needs to be investigated further, but this is not the focus of this article.

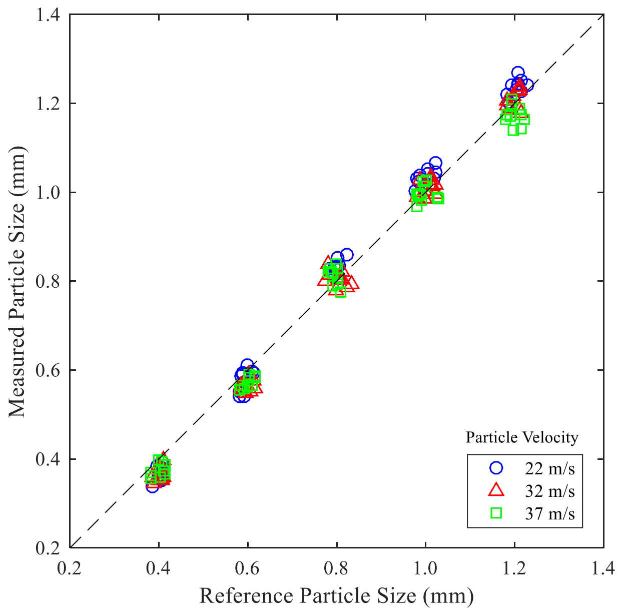


**Fig. 10.** Particle size inversion results.

Fig. 11 shows the relative error of inversion results for the particle size. As can be seen, the worst relative error of the measured particle size is -13%. The relative error exhibits a decreasing trend when the particle size increases. For the particles with various sizes over the velocity from 22 m/s to 37 m/s, the relative error of the measured result is found to be mostly within $\pm 10\%$. For 0.4 mm and 0.6 mm particles, the error is relatively large, which is due to the fact that the experimental conditions are less controllable for smaller particles, leading to a larger error. However, the results obtained have demonstrated that the theoretical model based on AE energy performs well for on-line particle size measurement.

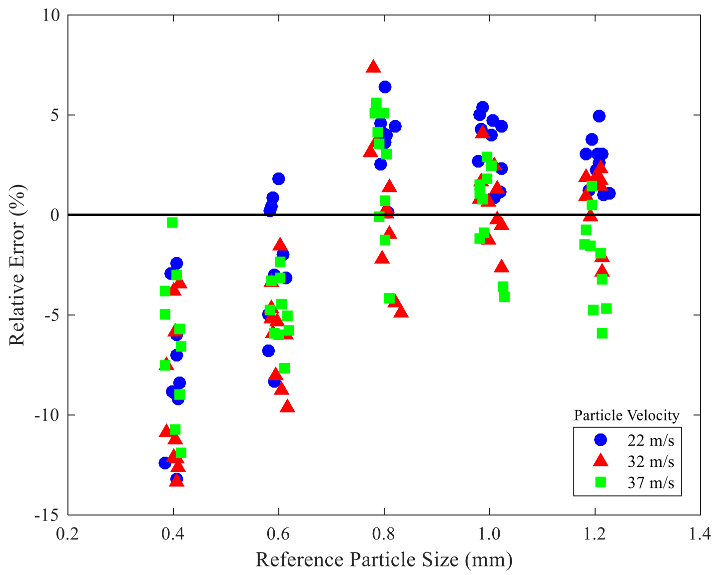


**Fig. 11.** Relative error of inversion results for particle size measurement.

It is worth noting that this paper aims to enhance the understanding of particle sizing through the AE method under well-controlled conditions. The proposed measurement model based on AE energy is also assessed on the single-particle test rig. However, significant further work is required in order to make the proposed methodology operable under practical industrial conditions. The proposed method is expected to be operable for on-line continuous particle size measurement where the volumetric concentration of solids in the pipe is dilute [30], as multi-particle collisions may still be present, which brings difficulties to separate individual impacts for the recovery of particle size information. The chance of simultaneous collisions may be reduced by controlling the length of the waveguide protruding into the flow or reducing the active area of the AE sensing element. Meanwhile, the AE sensing head should be installed on a vertical pneumatic conveying pipe where the particle distribution is relatively more homogeneous and steadier. At such a location the vast majority of collisions between upwards particles and the waveguide take place in the direction normal to the surface of the waveguide. Further work will be conducted in the near future to assess the efficacy of the technique for on-line continuous particle sizing on full-scale power stations.

## 5. Conclusions

This paper has presented the parametric analysis results of AE signals due to the impacts of individual particles at normal incidence. The quantified AE parameters have contributed to the in-depth understanding of the sensing mechanism of the AE-based technique applied to in situ particle size measurement. Different AE parameters have different potentials for on-line particle sizing regarding to measurement accuracy. The rise time has shown the least potential whilst the peak amplitude and the energy have been found to be the most appropriate AE parameters for on-line particle size measurement.

The energy dissipation due to elastic waves during plastic impacts has been estimated, which is dependent on the strength of the collision. When plastic deformation becomes severer, the energy absorbed by elastic waves tends to increase. According to the relationship between the energy contained in elastic waves and the AE energy, a theoretical model has been established to recover the particle size information. Experiments with particles of 0.4, 0.6, 0.8, 1.0 and 1.2 mm in diameter at velocities from 22 m/s to 37 m/s have verified the feasibility of the proposed method. The relative error of the measured result is found to be mostly within $\pm10\%$ . Experimental results obtained with glass beads have demonstrated the practicable operability of the technique for on-line continuous sizing of pneumatically conveyed particles.

Further research will be conducted to investigate the effect of the incident angle between the direction of the incoming particles and the surface of the waveguide on the measured AE quantities. This will help quantify the impact of less than ideal installation of the waveguide on a pipeline and to extend the applicability of the technique to a wider range of industrial processes.

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