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Measuring turbulence in a flotation cell using the piezoelectric sensor

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ABSTRACT

Turbulence and its distribution are of great importance in flotation processing and has been the subject of much research. However, there is no mature technique to measure turbulence in three phase (liquid–solid–gas) systems. In this research, the Piezoelectric Vibration Sensor (PVS) was developed, based on previous research, as a promising tool for turbulence measurements in industrial flotation environments. A frequency response model was established to calculate force applied to the sensor. Experimental results and comparison with Laser Doppler Anemometry (LDA) measurement data showed that the PVS can measure intensity of kinetic energy fluctuation (σ_{v^2}), which has been found in experiments to correlate with turbulent kinetic energy (TKE), a parameter often related to flotation performance in the literature. The sensor was then applied to a 60 l laboratory batch cell running at different impeller speeds and air flow rates to obtain turbulence profiles. Results showed that the piezoelectric sensor is fully capable of measuring turbulence in a multi-phase environment.

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1. Introduction

Turbulence has long been considered an important factor affecting flotation performance (Fallenius, 1987; Schubert, 1999; Xia et al., 2009; Tabosa et al., 2012). To study turbulent fluid flows, a number of experimental measurement techniques can be applied as well as computational methods such as 'Computational Fluid Dynamics' (CFD). Examples are Constant Temperature Anemometer (CTA) (Sherif, 1997, 1998; Ardekani and Farhani, 2010; Pappas et al., 2011), Laser Doppler Anemometry (LDA) (Morud and Hjertager, 1996; Mudde et al., 1998; Ng et al., 1998; Doudou, 2007; Sad Chemloul and Benmedjedi, 2010) and Particle Image Velocimetry (PIV) (Grant and Smith, 1988; Grant et al., 1989; Greated et al., 1992; Laakkonen et al., 2005; Brady et al., 2006, 2009). All these techniques have their own unique advantages in measuring turbulence in one or two phase turbulent environments. In the case of low concentration of seeding particles, LDA and PIV can be used to measure transparent turbulent flows. However, in an aggressive and abrasive three phase system such as an industrial flotation cell, none of the above techniques can be applied. As a result, the turbulence distributions in these environments are largely based on conjecture or, at best, model simulations. In 2012, a new approach was proposed as a promising method to measure turbulence in industrial flotation cells (Tabosa et al., 2012). This approach was based on a piezoelectric vibration sensor that was used to measure velocity fluctuation in the turbulent fluid and then convert the fluctuation into electrical signals for processing. Their measurement data showed that the turbulence profiles obtained by the piezoelectric sensor were similar to turbulence profiles obtained from LDA measurements reported in the literature. However, the work on the piezoelectric sensor by Tabosa et al. (2012) was preliminary in nature. Therefore, the aim of this work is to further develop this technique, which includes an investigation of the mechanism of the piezoelectric vibration sensor, development of a reliable calibration method to obtain the frequency response of the sensor, a test of the assumption made by Tabosa et al. (2012) that the sensor can measure velocity fluctuation, the validation of its readings against LDA measurement results, and the sensor's application in a water/air system.

2. Literature review

2.1. General review of turbulence's role in flotation

Flotation is one of the most important processes used in the mining industry. It selectively separates valuable minerals from gangue by attaching hydrophobic particles to air bubbles, which float to the surface and discharge over the lip of the cell, while hydrophilic particles settle to the bottom to be discharged

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(Nguyen, 2013). In the flotation process, turbulence plays an important role since it affects three main micro-processes: air dispersion, particle suspension and bubble-particle collision. Entrainment is affected by turbulence, too (Schubert, 1999). Turbulent flow consists of many rotating eddies of varying size and velocity, resulting in fluctuating fluid velocities. To describe turbulence in a flotation cell, a number of quantities may be needed (Mathieu and Scott, 2000).

Assuming fluid velocity is V_i in a certain direction, the following turbulent related parameters can be defined:

- $\overline{V_l}$, time averaged flow velocity in this direction.
- $v_i = V_i - \overline{V_l}$, fluctuating velocity in this direction.
- $v_i' = \sigma_{v_i}$, measured as the standard deviation of u_i.
- $\mathrm{TKE} = \frac{1}{2}(v_1'^2 + v_2'^2 + v_3'^2)$, turbulence kinetic energy (TKE). TKE is calculated from the root mean square of fluctuations of the turbulent fluid velocities in all directions.

Among the above turbulence parameters, TKE has long been considered an important measure of turbulence intensity (Mathieu and Scott, 2000), and researchers have demonstrated that TKE is an important parameter related to flotation performance. Li et al. (2010) used TKE as one of the critical flow-field parameters in CFD simulations for a Cyclonic-Static Microbubble Flotation Column. Massey et al. (2012) suggested that turbulent energy dissipation rate, the rate at which TKE is converted into heat, is directly correlated with flotation rate. Amini et al. (2013) used TKE to explain the change of Sauter mean diameter (d_{32}) in different scaled flotation cells.

To evaluate these turbulence related quantities, experimental techniques that can measure in turbulent flows must be applied. In the flotation environment, specifically, a measurement technique that can work in multi-phase flows is needed.

2.2. Brief review of measurement techniques for turbulent flows

There are a number of measurement techniques that can be used to study turbulent flows. They can be categorised into two groups: the intrusive techniques and the non-intrusive techniques. Widely used non-intrusive turbulence measurement techniques include Laser Doppler Anemometry and Particle Image Velocimetry. These techniques involve measuring the trajectory of seeding particles using optical imaging or photon detective devices. They have the advantage over intrusive measurement techniques in that they do not disturb the fluid flows when measuring. With the help of modern signal processing techniques, they can achieve high-speed, high temporal and spatial resolution in measurements (Brady et al., 2006; Sad Chemloul and Benmedjedi, 2010). But the disadvantages of these techniques is that they can only apply to transparent or semi-transparent laboratory systems (Wikipedia, 2013), which is not the case in industrial flotation cells processing slurries which are not optically clear.

One of the widely used intrusive techniques is Constant Temperature Anemometer. It is based on the cooling law of convective heat transfer from a heated sensor to the fluid in which the sensor is applied (Jorgensen, 2002). The advantage of the CTA technique is that very fine wire sensors and electronics with servo-loop techniques can be used to measure fine scale velocity fluctuations at high frequencies. Since the output of the CTA sensor is an analogue voltage with very high temporal resolution and no information loss due to sampling, it is ideal for measuring turbulent spectra. However, as CTA is sensitive to environmental factors such as temperature, pressure and particle contamination (Sherif, 1997; Jorgensen, 2002; Ardekani and Farhani, 2010), it is fundamentally a single phase flow measurement technique which is not suitable for measuring turbulence in industrial flotation environments.

2.3. Previous research on piezoelectric vibration sensor's application in turbulence measurement

To measure turbulence in the abrasive and aggressive slurry flotation environment, a robust intrusive probe may be a better choice. Tabosa et al. (2012) used a piezoelectric vibration sensor as a probing method to obtain velocity fluctuation information in a Metso $3\mathrm{m}^3$ Flotation Test Cell. According to its technical manual (MEAS, 1999), the piezoelectric film sensor has the following advantages:

- Wide frequency range—0.001–10^9 Hz, enough to analyse the turbulence spectrum.
- Vast dynamic range.
- High elastic compliance—highly responsive to turbulent flow.
- High voltage output—large signal that facilitates data acquisition and analysis.
- High mechanical strength and impact resistance (10^9–10^{10} Pascal modulus)
- High stability—resisting moisture, most oxidants, chemicals and radiation.

These features make the sensor suitable for collecting turbulent flow property information in slurry flotation cells.

The piezoelectric sensor is a transducer that converts mechanical vibrations to AC voltage signals, as is depicted in Fig. 1. When the film deflects back and forth, an AC voltage signal is generated.

To calibrate the sensor, Tabosa et al. (2012) used a variable speed electrical drill combined with an eccentric shaft (Fig. 2) to establish the relationship between the film sensor's running frequency (f), which is the vibration frequency of the sensor, displacement (D) and maximum signal amplitude (A). Four displacements were chosen and for each displacement, the sensor was tested for three different running frequencies. Therefore, 12 combinations of displacement and signal amplitude were evaluated.

Then by correlating displacement with the ratio of amplitude to frequency, a linear relationship (Fig. 3) was proposed as $D \propto A/f$. This correlation implied that at a certain displacement, the signal amplitude was proportional to the frequency, which meant that the frequency response of the piezoelectric sensor is a straight line. However, this calibration result is not accurate, as will be discussed in Section 3.1.1 of this paper.

From the correlation between the displacement and amplitude to frequency ratio, Tabosa et al. (2012) calculated the velocity fluctuation of a certain measurement position in the flotation cell:

(1) The signal was processed with a Fast Fourier Transform (FFT) algorithm to obtain the spectrum.
(2) For each spectrum component f as well as its amplitude A, the displacement D was obtained.
(3) $f \times D$ was calculated for each frequency.
(4) A set of Root Mean Square (RMS) values was calculated from these product values at all frequencies.

These RMS values were considered to be the representation of the velocity fluctuation at the measurement positions, which was then used to derive the turbulence profile along the measurement axis. Results of Tabosa et al. (2012) showed that the profile thus derived was similar in shape with LDA measurements normally found in the literature. Further tests in the Metso $3\mathrm{m}^3$ Flotation Test Cell were also carried out under different air flow rates, impeller designs and impeller speeds. Results showed that the piezoelectric sensor was capable of reflecting hydrodynamic change in the flotation cell. This work has laid a good foundation for the piezoelectric sensor's potential application in flotation cells. However, development of the piezoelectric probe is still considered to be in a preliminary stage. There is a need to validate the measurement

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