

# Measurement and prediction of turbulence in floatation cells engineering essay

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## Introduction

Up till now, understanding of flotation cell operation is insufficient and imperfect. Phenomena affecting operation of flotation cells are widely investigated, but panorama is still vacant. New sizes of flotation cells can be faultlessly built based on scale-up laws, some of which are quite clear in principle such as the criterion for the suspension of solids and the air flow number and the K-Sb relationship, etc. Micro-phenomena in flotation cell operation have also been fairly well studied. The intensity of turbulence prevailing in the flotation cell space is mainly dependent on a parameter, rotational speed of flotation cell mechanism. According to previous research (Fallenius, 1987), recovery and grade of concentrate depend highly on the dimensionless impeller speed, as is depicted in figure 1. Fig 1. Recovery and Concentrate Grade as functions of (Fallenius, 1987) At optimum impeller speed, the recovery is close to maximum value and the concentrate grade is rather high as well. Though the optimum speed is ultimately decided by economic calculations, some researchers have put stress on the importance of turbulence controlled processes in flotation cells (Schubert, 1999), because three effects of turbulence are important in flotation, namely the turbulence caused transport phenomena (suspension of particles), air dispersion and particle-bubble collisions. Though the suspension of particles is controlled by macro-turbulence, the last two effects are all controlled by micro-turbulence. Specifically, the particle-bubble attachment occurs almost exclusively in the turbulence zone, zone of high energy dissipation rates near the impeller. This phenomenon is highly dependent on the movement of particles and bubbles in the turbulent fluid,

which is in turn determined by velocity fluctuation of turbulence in the fluid, thus turbulent fluctuation of velocity is a crucial factor in flotation. On the other hand, entrainment, which is the micro-process that slurry enters the layer of the flotation froth, goes upward and ultimately leaves the flotation cell. As the slurry contains particles that are more or less equally suspended independently of their hydrophilic or hydrophobic properties, the hydrophilic particles thus transported consequently lead to a reduction of the separation efficiency and the grade of concentrate. To reduce entrainment, previously proposed approaches deal with water spraying the froth, alterations of the froth height, change of the froth thickness, applying vibrations to the froth layer and using grids and barriers to modify the transport phenomena within the froth. However, a turbulent distribution with high local energy dissipation rates in the impeller region (high turbulence) and less turbulent upper cell zone can form a comparatively stable froth layer and a favourable suspension state in the pulp zone, leading to a reduction of the entrainment. Consequently, turbulence is also a deterministic factor that affects entrainment. In terms of flotation cell scale-up, Gorain et al. (1997) demonstrated that aside from the K-Sb criterion, turbulence must also be taken into consideration when scaling from highly turbulent laboratory cells to much less turbulent industrial cells. This is in accordance with the fact that turbulence is important for both bubble-particle attachment and entrainment processes. To characterise turbulence in flotation cell, Fallenius (1987) gave analytical expressions of turbulent velocity fluctuation which agreed well with data collected in production cells, and the peripheral velocity of the impeller was found to be increased only slightly for given turbulent velocity

fluctuation in different scaled cells. To obtain a clear understanding of turbulence distribution in various scaled flotation cells, CFD models were employed. As for micro turbulence, the intensity and structure depend on energy dissipation rate  $\epsilon$  and kinematic viscosity  $\nu$ . The mean dissipation rate can be formulated as:  $\epsilon = \frac{P}{m}$ , where  $P$  is the input power and  $m$  is the mass of the fluid system. But the maximum dissipation rate normally is many times higher than the mean value and is generally observable near the impeller region. Kolmogorov investigated the scale of micro turbulence:  $\lambda = \left(\frac{\nu^3}{\epsilon}\right)^{1/4}$ . And experiments have demonstrated that eddies that are  $10 \sim 15$  in size are themselves turbulences. While eddies less than  $\lambda$  can no longer exist. Also it was also suggested (Schubert, 1999) that the intensity of micro turbulence be characterized by the RMS value of the fluid velocity fluctuation  $u'$ . Whatever kind of model to describe turbulence, measurement data must be collected as foundation for model validation and improvement. There are quite a number of measurement techniques that can be used in measuring fluid turbulence. Name a few measurement techniques, Constant Temperature Anemometer (CTA), Laser Doppler Anemometer (LDA) and Particle Image Velocimetry (PIV). CTA makes use of convective heat transfer, which is primarily related to the fluid velocity, from the heated sensor to the surrounding fluid. LDA is based on the Doppler shift effect of two crossed laser beams to measure the velocity in transparent or semi-transparent fluid flows. In PIV measurements, the fluid being measured is seeded with tracer particles which, for sufficiently small sizes, are assumed to faithfully follow the flow dynamics. The fluid with entrained particles is then illuminated and photo-pictured and the motion of the seeding particles is used to calculate

the velocity of the flow being studied. All these measurement techniques have their advantages and disadvantages; it is arbitrary to decide which one is better than others. However, when it comes to turbulence measurement in flotation cells, three phase systems are involved and neither of these techniques can be effectively performed. The CTA can be used in gas or liquid but not a combination of the two, let alone circumstances when solids are added. This is because the cooling law for two or three phase systems is different from that of in liquid or gas, causing the technique hard to implement in such systems. LDA and PIV can only be used in transparent or semi-transparent environments, which is impossible in real flotation cells. Fortunately, in recent years researchers have proposed some new techniques that can be used in measurements of turbulence in three phase systems. Tabosa et al. (2012) demonstrated the possibility of using piezoelectric vibration sensor as a tool to measure turbulence distribution in flotation cells. The general shape of the turbulence obtained by piezoelectric sensor agrees with known results in literatures. Another promising technique that can be used to measure turbulence in flotation cell is Electrical Resistance Tomography (ERT). Xie et al. (2004) showed that bubble size in an opaque flow can be determined by ERT through foam liquid content and conductivity measurements, which is a good illustration that ERT can be used in flotation environments. In this research, investigation on different measurement techniques and comparison of their strengths and weaknesses will be given. More importantly, piezoelectric sensor and ERT will be developed as tools in flotation cells turbulence measurements. Large amount of data will be collected by applying these two techniques in different

flotation cells with various hydrodynamic parameters. A clear understanding of turbulence distribution in flotation cells can be obtained based on which modelling works can be implemented.

## **Review of turbulence measurement techniques**

In this part, several measurement techniques that can be used in fluid turbulence measurements will be reviewed and compared for their features, application fields, strengths and weaknesses. Based on their characteristics, whether they can be used in flotation turbulence measurements will be analysed. These techniques are: Constant Temperature Anemometer, Laser Doppler Anemometer, Particle Image Velocimetry, Piezoelectric Vibration Sensor and Electrical Resistance Tomography.

## **Constant Temperature Anemometer**

### **General Introduction**

Constant temperature anemometer is also known as hot-wire anemometer. The CTA anemometer is based on the cooling law of convective heat transfer from a heated sensor to the fluid in which the sensor is applied. The faster the fluid velocity, the sooner the sensor will be cooled down. By measuring the energy supplied to the sensor to keep its temperature constant, combined with the cooling law of the probe in the fluid, turbulent velocity can be calculated straightforwardly. The beauty of the CTA technique is that very fine wire sensors and electronics with servo-loop technique can be used to measure fine scale velocity fluctuations at high frequencies. Since the output of the CTA sensor is analogue voltage with very high temporal resolution and no information loss due to sampling, it is ideal for measuring

spectra. Compared with LDA and PIV, the CTA technique is easy to use and of low cost. A typical CTA measuring setup is depicted below in Fig 2: Fig. 2 Typical CTA measuring chain(Jorgensen, 2002)The setup consists of a probe with probe support and cabling, a CTA anemometer (Wheatstone bridge and servo loop), a signal conditioner, an A/D converter and a computer for processing signals. There are four types of sensors available to CTA. Wire sensors include miniature wires which is suitable for measurements in air flows with turbulence intensities up to 5~10% and gold-plated wires for applications in air flows with turbulence intensities up to 20~25%. As for fibre-film sensors, they can be used in air and water and generally have inferior frequency response than wire sensors. Film sensors can also be used in air or water but at even lower fluctuation frequencies. The CTA sensors can also be configured as arrays that can measure two-dimensional flows. Both amplitude and direction of velocity vectors can be obtained by applying sensor arrays. An example of sensor arrays is depicted in Fig 3 below. Fig 3. CTA sensor arrays(Jorgensen, 2002)The selection of anemometers involves making sure that the anemometer has required bandwidth, low noise and drift to generate stable and reliable signal and sufficient power to heat and keep the sensor at constant temperature when flow velocity is high. Linked with the anemometer is the signal conditioner for high-pass or low-pass filtering and amplification of the signal. The amplified signal is then converted to digital signal by an A/D converter and processed by a computer.

## CTA setup

The CTA measurement chain has to be correctly setup before any measurements can be carried out. In terms of hardware setup, overheat adjustment, square wave test, low-pass filter and gain settings are needed. The overheat adjustment decides the operating temperature of the sensor. If the fluid temperature keeps constant throughout the calibration and data acquisition, the overheat is adjusted only once at the beginning. Otherwise, either the overheat is readjusted by measuring the probe resistance before calibration and each round of data acquisition to minimise the impact of varying temperature, or the temperature is measured during calibration and data acquisition in order to make corrections on the calculated anemometer voltages. The square wave test is also known as bridge balancing. It serves two purposes: bandwidth optimisation of the sensor and anemometer circuit or an inspection of the stability and sufficient bandwidth of the servo-loop. A square wave signal is applied to the bridge top and bandwidth of the system can be determined by measuring the time it takes for the system to get into balance. Low pass filtering is used to remove noise and fend off folding back of higher frequencies. Otherwise a faulty energy peak may appear in the power spectrum due to interference from higher frequencies. Also high-pass filtering may be required to clean the signal if FFT spectra analysis is needed. Finally the CTA signal may need to be amplified so as to exploit the resolution of an A/D convertor. Sometimes when background turbulence intensity is less than 1%, amplification can improve the measurability of the signal.



## **Calibration**

What the calibration does is to correlate the CTA output with the flow velocity. The sensor is exposed to a series of preset velocities and the voltage output of the sensor is recorded. A curve fit will then be done with all the data points of (velocity, voltage), and the result is known as transfer function of CTA which can be used to convert data records from voltages to velocities in measurements. Calibration may be implemented either in a special purpose probe calibrator or in a wind tunnel with a referencing velocity monitor such as a pitot-static tube. As for multi-sensor probes, directional calibration needs to be carried out to give individual sensitivity coefficients, which are then used to calculate calibration velocities into velocity components.

## **Data conversion**

Upon measurements, data acquired by the sensor are sampled voltage values; they need to be converted into velocity values using the calibration transfer function. For multi-sensor probes, velocity values are then decomposed into component velocity values in the coordinate system. The data conversion process consists of four steps, namely re-scaling, temperature correction, linearization and velocity decomposition. If DC-offset and amplification exist, the CTA signal has to be re-scaled before linearization. Also if overheat ratio has not been readjusted, temperature correction must apply to CTA output voltage to offset the influence of possible temperature variations. In these circumstances, the fluid temperature needs to be acquired during the DAQ process. The third step is linearization, which is conversion of CTA output voltages into velocity values.

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In this step the calibration transfer function applies. The transfer function is curve fitted during the calibration as either a polynomial or a power law equation, as shown below (Jorgensen, 2002).  $U = C_0 + C_1E + C_2E^2 + C_3E^3 + C_4E^4$  (Polynomial)  $U = (E^2/B - A)^{1/n}$  (Power law) Where  $C_i$ ,  $A$  and  $B$  are calibration coefficients,  $E$  is output voltage of CTA sensor and  $U$  is velocity. After the velocity has been acquired, based on whether the probe has multiple sensors, decomposition of velocity may apply. Take 2-D flows measured with cross probes as an example (Jorgensen, 2002), velocities  $U_1$  and  $U_2$  in the wire-coordinate system can be calculated as below: Where  $U_{cal1}$  and  $U_{cal2}$  are calibration velocities,  $k_1$  and  $k_2$  are yaw coefficients. To convert the wire-coordinate system velocities into probe coordinate velocities, the following formulae apply:

## Data acquisition and analysis

As CTA signal is analogue voltage, it needs to be sampled at a rate of more than two times the expected maximum signal frequency. The sampled data are then digitized and collected for analysis. The data analysis can be categorized into three types according to process techniques. The first type is amplitude domain analysis, in which mean velocity, standard deviation velocity and turbulence intensity can be calculated. The second type of analysis is time domain analysis in which auto-correlation function can be evaluated. The third kind of analysis is in spectral domain, in which distribution of signal energy with respect to frequency can be obtained through applying FFT to the signal.

## **Factors that can affect measurements**

There are a number of factors that can affect the CTA measurements and bring errors into results. The most important origin of error is temperature variation of the fluid being measured. This error of measured velocity can be from 2% for wire probes to 10% for film probes per 1 oC temperature variation(Jorgensen, 2002). In order to eliminate this error, researchers have conducted many investigations on different techniques. Sherif (1997) proposed that mathematical compensation can be applied based on probe cooling law, and that calibration curve obtained at one temperature can be used at other temperatures. Also temperature correction equation can be derived from the principles of heat balance, relationship of resistance-temperature of the sensor and transfer function. With advancement of micro-computing systems and their use in DAQ systems, this mathematical approach certainly will be more easily implemented and effective. But as cooling law of the probe may be quite different in three phase (solid, liquid, gas) systems which have different composition from that of the water, the technique may contribute little to measurement corrections in flotation cells. Another important factor that affects CTA measurements is particle contamination. Particles adhered to sensor surface will reduce the heat transfer rate and drive the transfer function downward. Therefore, the sensor needs to be recalibrated often if it is used in measuring three phase systems where solid particles prevail. As frequent recalibration is time and cost unaffordable, Ardekani and Farhani (2010) proposed that correction factors can be applied and voltage offset of the sensor can be considered to reduce recalibration. But in some cases, correction factors cannot mend the

measurement problems, and recalibration is needed. Also, measurement range cannot be extended beyond the calibration range with the use of correction factors. Therefore, particle contamination is hard to overcome if CTA is applied to flotation systems.

## **Summary of CTA**

CTA is a cheap and easy to implement tool that can be used in fluid velocity measurements. It is delicate in size, extremely high in frequency response and fine in spatial resolution compared to other measurement techniques. It is now almost universally exploited in the study of turbulent flows or where rapid velocity fluctuations exist. However, as it is susceptible to environmental temperature variation and particle contamination, it is not suitable to be used in measuring agitated flotation cells.

## **Laser Doppler Anemometry**

### **General introduction**

Laser Doppler Anemometry (LDA) is also called Laser Doppler Velocimetry. It utilises the Doppler shift effect in a laser beam to acquire velocity values in transparent or semi-transparent fluid environments. In the early 1960s, the helium-neon laser was made available with its unique properties of highly monochromatic, collimated and coherent, which is ideal for the research of fluid flow properties when scattered by entrained particles in the fluid. In its most frequently implemented form, LDA equipment splits a laser beam into two beams which are then conducted and crossed at their waists where straight fringes generated due to interference. When entrained particles pass through the fringes, laser light is reflected and then collected and focused on

a photo-detector by receiving optical structures. Usually visible lasers with wavelength 390~750 nm are used to show the beam path. As the entrained particles carry velocities themselves, Doppler shift will be incurred between the incident and reflected light, which in turn determines the fluctuating frequency of the intensity of scattered light. Thus the fluctuating frequency reflects the projection of the particle velocity on the plane determined by the two laser beams. If three devices with different wavelengths are employed at the same time, three velocity components can be obtained simultaneously. The LDA measurements have the following advantages(DantecDynamicsA/S, 2006):

- Non-intrusive: The LDA device can sense the fluid velocity without disturbing the flow, provided that the medium being measured is transparent with a certain concentration of entrained tracer particles, contained in a windowed vessel. If a submerged probe is used due to opaque vessel, the disturbance to the flow can also be ignored as the measurement point is a distance away from the probe itself. No drift, no calibration needed.
- Impervious to the environmental factors such as temperature and pressure, the optical waves have absolutely stable and linear response to fluid velocity. This feature makes calibrations that are usually needed in other measurement techniques unnecessary for LDA.
- Well-defined directional response: What the LDA measured is in fact the projection of the velocity vector on the direction determined by the spatial orientation of the optical device. Thus clearly defined is the angular response of the system.
- High temporal and spatial resolution: The highly concentrated and directional laser beams make it possible to define a very fine measuring volume, which means high spatial resolution. When combined with high speed signal

processing electronics, LDA can achieve excellent bandwidth and temporal resolution in analysis of fluctuating velocities. The only factor that can limit the bandwidth of the LDA measurement system is the concentration of seeding particles. Multi-component, bi-directional measurements The colour, polarization and frequency shift of laser beams can all be used to separate component signals from different LDA systems with common optical modules being assembled together. Reversing velocities of fluid flow are measurable based on acousto-optical frequency shift.

## **Fundamentals of LDA**

### **Laser beam**

Laser beams are highly coherent both spatially and temporally, which make them ideal for measurement in fluid flow studies. The intensity along the cross section of the laser beams follows Gaussian distribution. The beam width is defined such that the border intensity is 13% ( $1/e^2$ ) of the centre. There is one minimum cross section along the laser beam and this position is called beam waist. A typical laser beam is shown below in figure 4. Fig 4. Typical Laser beam (DantecDynamicsA/S, 2006) Size  $d_0$  in the figure represents the minimum cross section in the laser beam which is the beam waist. Assuming  $z$  representing distance from the beam waist and  $\lambda$  being the wavelength, we can get the following formulae (DantecDynamicsA/S, 2006): Beam divergence angle:  $\alpha = 4 \lambda / (\pi d_0)$  Beam diameter: Wave front radius: To get optimal performance of LDA, measurements should be taken at the beam waist as the wave front is flat in the beam waist and bent elsewhere, making it possible to apply plane waves theory at beam waist which can greatly simplify calculations.

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## Doppler Effect

The LDA technique is based on Doppler shift of the light reflected by a seeding particle in motion. The Doppler shift can be illustrated in the following figure 5. Fig 5. Scattered light from a moving particle and Doppler Effect(DantecDynamicsA/S, 2006)The particle is moving at velocity  $U$ ,  $e_i$  and  $e_s$  represent the incoming and scattered light unit vector respectively.

Seeing from the receiver, the scattered light has a different frequency with that of the incoming light due to the movement of the particle. If the frequency of the incoming light is  $f_i$ , the frequency of the scattered light can be formulated as(DantecDynamicsA/S, 2006): As  $U <$  Intersecting beams  
When two beams are intersecting at their beam waists, the wave fronts are nearly flat and the interference generate paralleled planes of light and dimness as is shown in the following figure 7, this part is called measuring volume. Fig 7. Two laser beams interfere with each other(DantecDynamicsA/S, 2006)The light and darkness alternating planes in the measuring volume are called fringes and the distance between the neighbouring planes is  $\lambda$ . When seeding particles enter the measuring volume and pass through the planes, reflected light received will fluctuate in intensity. The frequency of this fluctuation is proportional to the x-component of the particle velocity  $u_x$ ,  $f = u_x / \lambda$ , which is the same result with the Doppler analysis.

## Backscatter and forward scatter

Due to the reason that the bulk of the scattered light transmit forward as compared with the direction of incoming light, early LDA systems were mostly forward scattering ones. As technologies have advanced, back

scattered faint light can also be gathered and measured using the same optical structure that sends the light, saving the operator a lot of time and efforts to align separate optical devices as they do in forward scattering measurements. Nowadays backscattering equipment has become prevalent and forward scattering systems are used only in faint light, high data-rate and low signal level applications such as measuring high speed flow, transient phenomena or very low intensity turbulence.

## Measuring Volume

The measuring volume is the intersection of the two incident laser beams.

The following figure 8 shows this volume. Fig 8. Measuring Volume

(DantecDynamicsA/S, 2006)The size of the measuring volume is defined such that the border intensity is  $e^{-2}$  times of the centre. Assuming the beam waist diameter is  $d_f$ , then we can get the following sizes:

,

Total number of fringes can be calculated as: This number is the fringe number across the centre of the measuring volume. At the outskirts of the measuring volume, the fringe number will be less than  $N_f$ , so if a particle passes through the outskirts, less periods of the intensity fluctuation will be recorded. Normally a LDA system will need between 10 and 100 fringes to calculate the speed of the particle.

## LDA signals

LDA signals are collected from photo detector as current pulse which contains information about the particle velocity. Also contained in the signals is noise which is originated from photo detection shot noise or unwished

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photons reaching the photo detector. When shot noise account for absolute advantage in the noise, LDA can achieve its optimal performance. Also attention should be paid to bandwidth selection for the measured velocity range by using filters. The typical signal of LDA can be represented by a Gaussian intensity distribution modulated AC signal with DC-component, as is shown in Figure 9 below. Fig 9. Typical LDA signal(DantecDynamicsA/S, 2006)This figure shows the signal burst when only one particle is in the measuring volume. If multiple particles exist at the same time, the signal would be the sum of each individual signals. As a result of random distribution of the particles in the measuring volume, random phases will be introduced and the envelope and phase of the added up signal will fluctuate.

## **Seeding particles**

These particles must be sufficiently small to trace the velocity of the flow while big enough to reflect sufficient photons to be detected by the receiver. F. Durst (1981) described the desired properties of seeding particles as follows: Good follower of the flowCompetent light scatterersEasy to makeLow price and cleanAvirulent , non-corrosive and non-abrasiveNon-volatileWith chemical passivity

## **LDA measurements in stirred vessels**

As the LDA is a non-intrusive measurement tool that can make multi-component and bi-directional measurements with high temporal and spatial resolution, it is widely used in study of the turbulent fluid in stirred vessels. One of the studies investigated a two phase system (solid-liquid suspension) with low solid volumetric concentration (less than 2%); a LDA device

incorporating an electronic logic system is employed to distinguish signals from water and solid particles (Sad Chemloul & Benmedjedi, 2010). The beauty of this approach is that electronic logic is employed to speed up the signal processing but still it cannot overcome the intrinsic weak point of LDA's sensitivity to solid concentration. Morud and Hjertager (1996) carried out another measurement with the help of LDA to give mean and turbulent part of gas bubble velocities in a liquid-gas stirred vessel and compared the result with CFD predictions. General agreement has been found between the LDA measurement of gas velocities in three dimensions and the CFD predictions. Mudde et al. (1998) proposed that in bubble liquid flow, LDA has to discriminate the motion of the gaseous bubbles (with maximum fraction of 25%) and the liquid by implementing one of the three approaches:

- Discrimination based on the form of the bursts
- Signal analysis and light blocking
- Difference in velocity distribution

A comparison between forward scatter and backward scatter is made and it is shown that in backscatter generally the seeding particle velocities are measured. These studies show that LDA has the ability to distinguish between solid velocities, gas bubble velocities and seeding particle velocities and thus can be used as a powerful tool in investigation of fluid properties in two-phase systems. One of the many reasons of making LDA measurements is to validate CFD model predictions. Morud and Hjertager (1996) used a two-dimensional CFD model with a standard  $k-\epsilon$  model to predict the gas-liquid flow and verify the numerical results with LDA experimental data. Both mean gas velocity and turbulent gas velocity (RMS value) are compared between LDA measurements and CFD predictions and accordance was found. Ng et al.

(1998) reported the LDA measurement and CFD prediction of mean velocity field and turbulence field quantitatively of a flow in a stirred vessel. As a consequence of lack of impeller blades geometry in the CFD model, inconformity was found near the impeller blades, but in general the results agreed. Turbulence spectra can also be obtained with LDA measurement data. But due to fluctuating velocity, LDA data are sampled irregularly in time even with a fixed density of the seeding particles. With resampling method (RM), sample and hold(S&H) interpolator or direct method (DM), etc. velocity spectrum can be evaluated. Cenedese et al. (1992) evaluated the turbulent properties extremely near the wall with spectral domain analysis. Doudou (2007) estimated the spectra of fluctuating velocity with different turbulence level, flow type and free flowing and found each flow type demonstrate a particular type of data rate, velocity offset and noise level. But different from CTA evaluation, LDA spectral analysis is bandwidth limited due to the fact that the number of seeding particles passing through the measuring volume in a unit time is limited by a given particle concentration and fluid velocity.

## **Summary of LDA**

LDA is widely used in studying the characteristics of fluid flows benefited by its non-intrusive, multi-component and bi-directional ability in making measurements. As it can render high temporal and spatial resolution, many research works have been carried out using LDA to study turbulent flows both in time and in frequency domain. Also some works have been done to validate CFD models with LDA measurements. But due to the fact that it is an optical technique, LDA cannot be used in three phase systems. Another

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problem with LDA measurements is that its spectral analysis must implement additional data processing techniques to smooth its irregularly sampled data.

## **Particle Image Velocimetry**

### **General Introduction**

Particle Image Velocimetry (PIV) is an optical technique used in flow visualisation. In terms of being a non-intrusive, optical approach, PIV is similar with LDA as it utilises seeding particles to obtain velocity fields of fluid flows. The difference between them is that PIV is a two dimensional method in which seeding particles in a specific area are illuminated and photographed with a timing schedule to record their positions from which velocity field can be calculated based on position change and timing, while in LDA (a one dimensional method) only seeding particles pass through the measuring volume can be measured for their velocities. In terms of particle concentration, PIV requires that individual particle can be identified in a single image but not necessarily tracked between images. This can be achieved with a medium concentration of seeding particles, relative to low seeding concentration in Particle Tracking Velocimetry or high particle concentration in Laser Speckle Velocimetry. Figure 10 below gives a typical PIV system. [http://www.engr.uvic.ca/~poshkai/research/images/piv\\_schem.jpg](http://www.engr.uvic.ca/~poshkai/research/images/piv_schem.jpg) Fig 10. A typical PIV system (<http://www.engr.uvic.ca/~poshkai/research/systech.html>) Normally a PIV device consists of a digital camera with a CCD chip, a laser or a strobe with certain illumination pattern to define the region to be photographed, an external trigger to

manage the camera and laser, the seeding particles and the fluid in which the particles are infused.

## **Fundamentals of PIV**

### **Seeding particles**

In most cases seeding particles in PIV are glass beads, polystyrene, aluminium pieces and oil droplets if PIV is employed in gas. Particles should have different reflectance from the fluid so as to reflect off incident laser sheet and causing laser to be scattered toward the camera. Assuming that the particles are spherical in shape and the flow's Reynolds number is very low, the difference of the particle's density to the liquid's density as well as the square of the particle's diameter determines proportionally the particle's ability to trace the fluid flow. On the other hand, the scattered light is also proportional to the square of the particle's diameter. Thus the particles' sizes need to be chosen carefully so as to balance the ability to trace the flow with the ability to reflect the laser. Typical sizes of the particles lie in the range from 10 to 100 microns, within which particles are small enough to trace the flow and big enough to reflect enough photons.

### **Camera**

PIV cameras should have the ability to capture picture frames at very high speed. For moderate Reynolds numbers ( $10^3 \sim 10^5$ ) and small length scales, the sampling frequency required to reveal turbulence properties is in the order of 1,000 Hz. Recent technology advancements have made it possible to capture two frame shots at high speed of 4,000 frames per second with analogue based kilohertz frame rate PIV camera, which has compensated the

inadequacy of low temporal resolution compared with high spatial resolution. However, one difficulty of typical camera is that the fast speed is limited to a pair of shots as they have to be transferred to storage device. On the other hand, digital high speed CCD or CMOS cameras are available but at very high prices.

## **Optical parts**

Lasers are ideal to PIV measurements as they have the ability to produce high power beams within very short time durations. This feature of laser beam enables short exposure times for PIV pictures. The laser light maybe directed to the experimental system via an optical fibre or liquid light guide. The imaging part includes a spherical lens and a cylindrical lens. The laser is first expanded into a plane by the cylindrical lens and then compressed into a filmy sheet. This sheet is not an ideal two dimensional plane but with a thickness in the order of wavelength of the laser light. From where the sheet is positioned, optimum measurements can be carried out.

## **Synchronizer**

A synchronizer is an external simultaneous trigger for the camera and the laser. Managed by a computer, digital synchronizers today can arrange the timing of CCD camera framing sequence in conjunction with eruption of laser beam with a precision of less than 1 Nano-second. Timing information is critical in PIV analysis as velocity of the fluid need to be determined based on these information. Constant temperature anemometer (CTA) can be used in isothermal flow turbulence measurement. But if the flow is non-isothermal, temperature correction must be done to the signal. Linearized response of

CTA depends much on temperature. In doing calibration, the ambient temperature may be different to real measurement temperature. To compensate this effect, two approaches exist. The first is electronic compensation, in which proper configuration, cost or temperature compensating range may cause it difficult to implement. The second one is mathematical compensation, in that probe cooling law must be known, and that calibration curve obtained at one temperature can be used at other temperatures. Based on the principles of heat balance, relationship of resistance-temperature of the sensor, the probe cooling law and the specific anemometer transfer function, temperature correction equation can be derived. Strength: Microcomputers are more extensively used in DAQ Weakness: Not clear Opportunities: Can be used in air and liquid velocity measurement Threats: May not be able to use in three phase floatation measurement, cooling law may be different. (Ardekani & Farhani, 2010) CTA can be used in measuring flow characteristics in turbulent region. However, ambient conditions and contamination of sensor strongly affect the working of CTA and its non-linear calibration curve. In order to minimize these consequences, the CTA must be recalibrated from time to time, which is time and cost unaffordable. To reduce recalibration, correction factors have to be applied, and voltage offset of the sensor considered. But in some cases, correction factor cannot improve the measurement, and recalibration is needed. Also, use of correction factor cannot extend the measurement range beyond the calibration range. Strength: CTA is based on convective cooling effect of a fluid stream passing over a hot film/wire sensor, high frequency response and small probe size, capable of measuring a wide range of flow

velocities. Weakness: affected by ambient conditions (temperature and variation, pressure, contamination due to accumulation of dust particles), need to be recalibrated often, which means that it may not be suitable in three phase systems. Opportunities: Not clear Threats: recalibration is time and cost unaffordable. (Sherif, 1997) In non-isothermal fluids, it is hard to measure fluid velocity with CTA, because the anemometer response depends on the temperature of the medium. Corrections must be made to compensate the temperature drift and fluctuation. (How CTA works) CTA employs a Wheatstone bridge along with a differential amplifier to maintain a constant sensor temperature (resistance) regardless of the velocity of the fluid. Both velocity increase and temperature decrease will cause the sensor to cool down sooner, which leads to sensor resistance change and triggers the bridge to supply more electric current to keep the sensor temperature constant. Thus, to successfully use CTA in a non-isothermal medium, the effects caused by temperature fluctuation must be deducted from the overall influence before velocity and turbulence effect can be caught. Temperature compensation is needed when the calibration temperature is different to measurement temperature or the measurement temperature itself fluctuates. Four methods exist: electronic compensation, mathematical correction, manual adjustment of the probe hot resistance and directly velocity and temperature calibration. This article compares the four calibration approaches. (Pappas et al., 2011) A highly linear output-voltage versus resistance-variation is implemented using a second generation current conveyor. This one is simpler than the voltage-mode one and features higher performance in terms of circuit size, simplicity, linearity and



overall power consumption. Strength: simpler, smaller, and linear Weakness: not clear Opportunities: Very new, small error deviation Threat: not clear (Watmuff, 1995) CTA is the most widely used means to measure velocity fluctuations, but many aspects of the behaviour of the instrument cannot be explained by current theories. In some applications, 250KHz frequency response can be achieved, but the phenomenon called strain-gauging often contaminate experimental results. This research developed an algorithm for deriving the transfer functions of the CTA. (Sad Chemloul & Benmedjedi, 2010) A combined electronic logic was put at the reception of the LDA to distinguish between signals from the continuous phase and (water) and that of the solid particles (glass beads) and thus to detect larger than wavelength particles. At present, the volumetric concentration has to be less than 2%, to prevent the suspension from becoming a very diffusing medium. Strength: electronic logic to process signal automatically, LDA technique, 2-phase Weakness: volumetric concentration must be less than 2% Opportunities: as one development of LDA technique Threats: Only an experimental setup. (Mudde, Groen, & Van Den Akker, 1998) As bubble flows are frequently encountered in industrial applications, CFD need to be used to study the field of dispersed multiphase flows. However, the use of CFD is still hampered by the lack of understanding of the basic flow phenomena, and the simulation results need to be validated. Both call for detailed experiments on the flow properties. Because multiphase flow is difficult to access and very sensitive to disturbance caused by intrusive measuring probes, thus the use of LDA could be beneficial. In bubble liquid flow, LDA has to discriminate the motion of the gaseous bubble and the liquid. Three

approaches are generally used: Discrimination based on the form of the bursts  
Signal analysis and light blocking  
Difference in velocity distribution  
To measure bubble speed in the two phase flow, backscatter is used, in which the liquid velocity is predominantly measured. Data rate drops exponentially with distance from the wall, in agreement with theoretical considerations.

Strength: LDA is a non-intrusive measurement tool, can measure bubble speed in forward scattering, liquid speed in backscattering. Weakness: can only work with 2 phase systems (Morud & Hjertager, 1996) This work is a measurement and prediction for two phased flow in a stirred vessel. Mean and turbulent part of gas velocities are measured with LDA. Turbulent velocities at radial, axial and tangential mean and turbulent velocities are investigated against various gas flow rates and impeller speeds. A two-dimensional CFD model, with a standard k- $\epsilon$  model is used to predict the gas-liquid flow. Numerical results are verified against the experimental data. Both mean gas velocity and turbulent gas velocity (rms value) are compared against CFD simulation results and general agreement is found. As LDA can measure velocity in three dimensions, the velocity has positive and negative values. In terms of modelling, improvements should be made to better handle swirling flows, effect of bubble motion on the liquid turbulence, mechanisms of bubble break-up and coalescence as well as three dimensional models. Strength: LDA can measure both mean and turbulent fluctuation of gas velocity in three dimensions, results agree with CDF simulations Weakness: can work only with 2 phase, can measure only gas velocity Opportunities: Not known Threats: not known (Ng, Fentiman, Lee, & Yianneskis, 1998) LDA measurement and CFD prediction of the flow in a

stirred vessel are reported. Mean velocity field is well reproduced quantitatively by CFD model. Turbulence field is well predicted across the whole vessel qualitatively and in the bulk flow region quantitatively. Differences are observed near the impeller blades. Due to the fact that previous CFD simulation did not take into account the geometry of the blades, discrepancies were observed in both the mean velocity and turbulence energy. Strength: Prediction of good accuracy can be obtained across most of the flowfield Weakness: calculation of value  $K$  near the blade tip needs to be improved Opportunities: CFD modelling need to be improved Threats: not known (Doudou, 2007) turbulent spectra of fluctuating velocity are estimated from LDA measured data. Three flow setups are used, they are different in turbulence level, flow type, free flowing, etc. Datasets for each flow type gives fluctuating velocity of different data rate, velocity bias and noise level. Due to fluctuating velocity, LDA data are sampled irregularly in time even with a constant density of the seeding particles. Signal noise includes the stochastic nature of light generation, scattering and detection, electronic noise and noise due to random arrival of particles in the probe volume. It is generally assumed that in the spectral domain, velocity fluctuation caused by noise is white noise. In Frequency Domain Analysis, LDA data have to be resampled at equal time interval so as to perform FFT. This method is called resampling method (RM). But RM will produce a low pass filter on the PSD, also sample and hold (S&H) interpolator will introduce a step noise in the PSD. Another method is called direct method (DM) which makes adjustment to the direct Fourier Transform. However, the PSD was not alias free beyond the Nyquist frequency, and the PSD variance increases

so quickly with frequency. The data rate of LDA depends on the velocity, as particles pass through the probe volume every unit time is proportional to velocity. Other techniques used in evaluation LDA spectrum include: local normalized slotting technique(LNST), the fuzzy slotting technique(FST), etc. These can be compared to piezoelectric sensor spectrum processing techniques. Strengths: New data processing techniques introduced, ACF variance reduced and spike due to noise removed. Weakness: complicated techniques must be applied to remove effects of velocity bias, which does not exist in piezoelectric sensor signal processing. Opportunities: not known Threats: not known.(Brady et al., 2006) RMS velocities of bubbles and particles were calculated and compared to experimental and theoretical models that are based on turbulent dissipation rate. Despite the advances in improving the spatial resolution and accuracy, the temporal resolution of the DPIV systems is only about 30Hz, which is insufficient for resolving flotation fluctuation. For moderate Reynolds number( $10^3$ — $10^5$ ) and small length scales, the sampling frequency necessary in order to resolve adequately the turbulent characteristics of the flow is in the order of 1000Hz. Recent analogue based kilohertz frame rate PIV systems are capable of recording up to 4000fps. However, fast switch of film tend to cause film alignment errors that are added to on the common digitization errors, which is the reason for development of super resolution, iterative and hybrid DPIV algorithms. Also CMOS is used instead of CCD to prevent leakage effect and provide high spatial resolution as fine as 60 microns. Another technique employed is Particle Tracking Velocimetry(PTV), which tracks individual particle locations across multiple frames to determine velocities with any order of accuracy

required. Strength: can measure 3 phase flotation cells, bubble and particle velocities are measured simultaneously; several models are compared against the measurements Weakness: not known Opportunities: not known Threats: not known (Grant & Smith, 1988) Unsteady nature of many flows implies that their full experimental description requires simultaneous, multipoint measurement. Also the predictive modelling need to be validated by benchmark tests. A number of developments have been proposed, and unsteady flow structures such as vortex interaction or breaking wave fields are found to be well imaged by PIV. This article can be used to introduce PIV. Strength: a large number of data points can be obtained simultaneously at a mesh of measuring positions distributed through the fluids. Non-intrusive, Weakness: low time resolution, certain area. (Grant et al., 1989) The main disadvantages of LDA systems are: maintaining alignment and traversing extended flow fields; obtaining of acceptable signal to noise ratios; cost and complexity of multi-component and multi-probe systems. In PIV, images of local seeding particles are obtained, the displacement between the various double images can be used to measure the direction and magnitude of the local fluid velocity. The use of fringe visibility as a means of turbulence measurement has been considered. Strength: when sufficient fringes are visible, estimates of turbulence intensity may be reasonably made to an accuracy of 10% Weakness: practically difficult to implement as 10-15 fringes is a 'high' number in a typical experimental design. (C. A. Greated et al., 1992) PIV is based on stroboscopy in that a two-dimensional plane of a flow containing small seeding particles is illuminated. A double (or multiple) exposure of photograph of this plane is taken. Local velocity is calculated by

compare the differences of particle positions on the film. Flow velocities over a grid of points covering the whole field can be obtained. The process contains two stages: acquisition, analysis. Matters need to be addressed in acquisition (photography) are: Seeding, Camera and lens, Film, illumination interval, shutter speed, focus, photographic magnification, exposure, etc. This article can be used as a description of basics about PIV. (Laakkonen et al., 2005) PIV was used to measure local bubble size distributions, gas-liquid interfacial areas, gas holdups and flow velocities simultaneously. Agitated gas-liquid vessels are widely used as reactors in chemical, biochemical, petroleum and mining industries. Gas-liquid mass transfer is a common rate-determining step in agitated reactors. Local mass transfer areas depend on the bubble sizes and concentrations and vary notably even in small stirred tanks. This motivates the use of bubble size distributions (BSD) rather than averaged bubble sizes in the reactor simulation tools. Population balance is a fundamental approach for the modelling of local BSDs. Computational fluid dynamic (CFD) tools along with population balance models give insight into local vessel conditions and are therefore useful for the design and scale-up of industrial agitated reactors, in which mass transfer conditions vary, often notably. Gas-liquid CFD models are still uncertain and need validation against local experimental information. The measurement of turbulent gas-liquid dispersions is challenging and many experimental techniques are available. Optical imaging techniques have been used commonly to investigate bubble sizes in stirred tanks. Particle image Velocimetry (PIV) is a versatile optical technique, which can be used to investigate flow fields and turbulence quantities in gas-liquid systems. The aim of the present work was

to investigate several interesting properties of gas-liquid flow simultaneously in order to produce more consistent experimental information for the validation of simulation tools for agitated gas-liquid reactors. Local BSDs, gas-liquid interfacial areas and gas holdups were measured from air-water and CO<sub>2</sub>-n-butanol systems in gas-liquid systems. The aim of the present work was to investigate several interesting properties of gas-liquid flow simultaneously in order to produce more consistent experimental information for the validation of simulation tools for agitated gas-liquid reactors. Local BSDs, gas-liquid interfacial areas and gas holdups were measured from air-water and CO<sub>2</sub> systems in a laboratory stirred tank with a PIV apparatus. A simple method was developed to correct bias errors of the measurement technique. Flow fields and turbulence quantities were investigated simultaneously and have been reported. (Wilkinson et al., 2005) Design of a sixteen electrode high-speed (1000 frames/s) ERT system, with real time visualization. Switched DC current pulse technique in conjunction with parallel data acquisition is implemented to achieve the high data capture rates. Newton-Raphson method is used in reconstruction algorithm which executes in under 1 ms. Principle of 4-electrode current pulse technique High speed current pulse ERT data capture configuration (Wilkinson et al., 2006) A multi-plane current-pulse electrical resistance tomography data capture system, which is implemented by extending a single plane system with 16 electrodes to a system capable of acquiring data sequentially across multiple planes, is presented. Multiplexer modules were inserted between the device and the electrode array. With this system, dual plane cross-correlation velocity measurements can be

achieved; 3D data sets can also be yielded with more complex current injection and measurement sequences. A embedded microprocessor was used to control the measurement timing and multiplexer measurement sequences, which were downloaded at start-up. This make it possible to specify data acquisition sequences and timing required for specific applications with all the hardware and software unchanged. Quantification is carried out on the effect of measurement noise on the estimated conductivity; discussion is made for the case of a 2D online imaging algorithm. Verification of the instrument is provided by reconstructing recorded data sets. This is just what I will use for my work. Should give long introduction in review.(Xie et al., 2012) Foams are prevalent in industrial processes and researches on foams has a history of more than 100 years. As rapid response, low cost and non-invasive are the basic requirements for measuring foams, ERT come into the sight. An ERT system with a switched bi-directional constant current source is employed to generate a measurement sequence of 104 independent measurements. Results showed that the ERT system could identify coarse foam regions and coalescence areas in the foam column. A digital camera was used to provide comparison images and agreement was found under different experimental conditions using different orifice diameters, input gas flow rates, concentrations and alternative surfactants.(Khanal & Morrison, 2009) A least square regression modelling method has been used to process ERT data collected in industrial hydrocyclone. Location and size of disturbance in the system have been investigated by applying regression modelling to potential differences measured. Results showed that position of the disturbance can be well



calculated both in concentric and off-centric cases, while size of the disturbance still need to be determined with more advanced method when off-centred. This method is simple, fast, computationally efficient and less demanding on data files sizes. It may be useful in determining bubble position and movement speed in ERT measurements. Strength: simple, fast, computationally efficient, less demanding on data files. Suitable for large scale industrial applications. Weakness: do not work well with non-circular cross section, cannot determine size of non-centric disturbance.

Opportunities: may be improved in SNR to get more accurate size and position information  
Threats: hardware and software both need

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