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# Advance optical fiber probe for simultaneous measurements of solids holdup and particles velocity using simple calibration methods for gas-solid fluidization systems

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ABSTRACT

Advanced gas-solid optical fiber probe technique that can measure simultaneously solids velocity, solids concentration related quantity, and their time series fluctuations has been implemented with simple and new calibration methods for both solids holdup and particles velocity measurements in gas-solid spouted bed and gas-solid fluidized bed. The needed signal and data processing programs have been developed in our laboratory. New, simple, and reliable calibration methods and the related experimental setups have been established to convert the solids concentration related signal to solids holdup which is a meaningful hydrodynamic parameter and to determine the effective distance between the two tips of the probe for the solids velocity measurements. The new calibration methods have been employed to cover a wide range of particle sizes which usually used in gas-solid spouted beds and gas-solid fluidized beds. Selected results have demonstrated the appropriateness of the advanced optical fiber in measuring both solids holdup and particles velocity in the experimental setups of the gas-solid spouted and fluidized beds. The measurements have been compared against independent techniques of gamma ray computed tomography (CT) and radioactive particle tracking (RPT).

## 1. Introduction

Various types of optical fiber probes have been developed and used to measure solids concentration or solids velocity and their fluctuations in gas-solid fluidization systems. These systems have found significant applications in industry related to chemical, petrochemical, petroleum, pharmaceutical, energy, and environmental processes. In these applications gas-solid fixed fluidized beds, transported beds, circulation fluidized bed, and spouted beds have been employed using various types of solid particles with a range of variation in density, size, and shape. (e.g., Circulating fluidized beds: [27]; fluidized beds: [13]; fluid catalytic cracking (FCC) gas-fluidized beds: [36], and spouted beds: [3], and others).

Various types of optical fiber probes have been developed and implemented to advance the understanding these gas-solid fluidization systems by investigating the effects of various design and operating parameters on solids holdup and solids velocity. However, the studies that implemented optical fiber probes for the measurement of solids concentration related quantity have been different from those for the measurement of solids velocity [25,39]. Additionally, these so-called "older generation" gas-solid optical fiber probes were plagued by the presence of blind regions and lesser measurement volumes, which affected their measurements. These drawbacks were addressed by the newer improved design probe systems as it will be outlined below [21,22,37]. In addition, Liu et al. [21,22] reported on a successful simultaneous measurement of both solids holdups and velocity. Also, they reported the instantaneous solids flux measurements. However, for probes that only measure the solids concentration related quantity and have been reported in the literature, calibration is needed to convert the measurement to solids volume fraction. These concentration probes have large measurement volumes which make it difficult for the probes to identify the individual particles for velocity measurement. In a typical situation, the concentration probe measures signals that are related to the amount of particles in the measuring volume. Due to the

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**Nomenclature**

| | |
|---|---|
| $x_i$ | Data series for velocity measurement from Tip A |
| $y_i$ | Data series for velocity measurement from Tip B |
| $\bar{x}$ | Average value of 1 data series |
| $\bar{y}$ | Average value of 2 data series |
| N | Total number of data points in the entire sampling time |
| $R_{xy}$ | Cross-correlation coefficient |
| $S_x$ | Standard deviation of x data series |
| $S_y$ | Standard deviation of y data series |
| T | Sampling time for velocity measurement, s |
| Vi | Voltage from the probe tips, V |
| $V_{avg}$ | Average Voltage, V |
| $V_{min}$ | Minimum Voltage, V |
| $V_{max}$ | Maximum Voltage, V |
| x | Normalized voltage values from the probe |
| y | Solids holdup from the calibration curve |
| $L_e$ | Effective distance |
| $V_p$ | solid particles velocity |

*Greek letters*

| | |
|---|---|
| $\tau$ | Delay time, s |

design of the concentration probes, two separate signals are impossible to achieve to cross correlate them in order to obtain velocity information. The electronics of concentration probes are all single channel and signal processor making it difficult to use them for velocity measurements. On the other hand, Velocity probes are designed in such a way that there is a fixed distance between the single light emitting fiber and two receiving light fibers, unlike the concentration probes which are arranged in a fixed fashion to increase the measuring volume. The electronics of the velocity probes consist of two signal processing channels.

Due to all the reasons mentioned above concentration probes, could not be used to measure both solids concentration related signal and solids velocity, and vice versa. Thus, there is a need to measure simultaneously and at the same point the solids velocity, solids concentration related quantity and their time series fluctuations, where the solids concentration related measurement should be converted to solids holdup which is a useful hydrodynamic parameter. Such need has been addressed by Liu et al. [21,22] and further extended in this work by introducing advanced optical fiber probe system which is manufactured by the Institute of Process Engineering of the Chinese Academy of Sciences (PV-6 particle velocity analyzer) based on our specifications. Our laboratory (multiphase reactors engineering and applications (m-Real)) has developed the data and signal processing algorithms to allow this advanced probe to measure simultaneously solids velocity, and the signal that is related to the solids concentration and their time series fluctuations. The measured signal that is related to the solids amount or concentration at the point of measurement needs to be converted through reliable calibration to solids holdup (volume fraction of solids at the probe location) which is a meaningful hydrodynamic parameter. Additionally, the solid holdup is considered one of the important hydrodynamics parameters in the design, operation, and process efficiency of the gas-solid fluidized bed. As well, understanding the solid holdup is also useful in the calculations of heat and mass transfer of the gas-solid fluidization systems [17]. Therefore, the reliability of optical fiber probe measurements strongly depends upon the accuracy and reliability of the calibration process. Moreover, the complexity of the fluidized bed systems due to the gas-solid interactions required a reliable calibration method to ensure that the solid holdup measurements are reliable. Also, the measurement of the solids velocity must be calibrated before the probe is being used. The conversion of solids concentration related signal or quantity to solids volume fraction is dependent on calibration, which in previous studies reported in the open literature involves elaborated experimental set-ups like a circulating fluidized bed, thereby increasing the cost and time of the experimental procedures besides the uncertainty is questionable due to the way the solids volume was measured [1,32].

Hence, a simple and reliable calibration method for the optical probes in general, and our advanced one in particular for gas-solid fluidization systems is needed. This type of calibration method has been recently addressed and developed in our laboratory. Therefore, the focus of this work is to discuss the advanced optical fiber probe, the simple calibration methods for spouted bed and for fluidized bed range of particle sizes and the signal processing methods that relate the measured signals to both solids holdup and solids velocity. Such development has been successfully demonstrated and implemented at this time on gas-solid spouted bed and fluidized bed where selected results related to solids holdup and particles velocity that are measured simultaneously are presented and discussed.

Therefore, in this work two gas-solid fluidization systems have been used, namely spouted bed and fluidized bed, which are considered as the desirable gas-solid contactors for many recent industrial applications. Spouted bed which uses coarse, sticky and irregular shape of particles have been employed in different commercial processes such as coating (e.g., TRISO nuclear fuel particles coating for the 4th generation nuclear energy), gasification (coal/biomass), drying, etc. In gas-solid spouted beds, the gas phase is injected as a jet through a small opening at the conical bottom of the bed to spout the particles. Under proper conditions, the gas phase penetrates the bed of particles as a jet, creating a central spout region by pulling the particles from the annulus region along the spout height, a fountain region above the spout forms where the solids disengage from the gas phase and fall down. The annulus region formed from the falling particles in which the particles move downward surrounding the spout. Hence, three distinct regions exist in gas-solid spout beds which are spout, fountain and annulus regions. Fluidized beds are largely utilized as a part of numerous industrial applications, such as petroleum refining, chemical synthesis, food processes, pharmaceutical production and power generation. In gas-solid fluidized bed, an upward flowing gas through distributor or sparger to a bed that containing small size of solid particles at high superficial gas velocity, which is enough to expand the bed and suspend the solid particles in which the suspension of the gas and solid particles behave as a fluid.

Due to the complexity of movement of both gas and solid particles in these types of gas-solid fluidization systems, sophisticated measurement techniques such as the advanced fiber optical fiber probes that use are introducing in this work are needed to advance the understanding of these systems, in order to properly advance the related industrial applications mentioned above.

## 2. Overview of the literature reported gas-solid optical fiber probes

Optical fiber probes work based on either forward scattering or back scattering of light principle with emitting and receiving optical fibers. The backscattering probes have found more applications in gas-solid fluidization systems because of their simpler design and less intrusion [12] and therefore, they are discussed in this section. These probes can be further classified into two separate categories based on the type of measurements. These are probes to measure solids concentration related signal and probes to measure solids velocity as discussed below: