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Applications of Fiber-Optical Sensor in Multiphase Reactor

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Abstract- This work presents a brief introduction on the basics of fiber-optical sensors and an overview focused on the applications to measurements in multiphase reactors. The most commonly principle utilized is laser back scattering, which is also the foundation for almost all current probes used in multiphase reactors. The fiber-optical probe techniques in two-phase reactors are more developed than those in three-phase reactors. There are many studies on the measurement of gas holdup using fiber-optical probes in three-phase fluidized beds, but negative interference of particles on probe function was less studied. The interactions between solids and probe tips were less studied because glass beads *etc*. were always used as the solid phase. The vision probes may be the most promising for simultaneous measurements of gas dispersion and solids suspension in three-phase reactors. Thus, the following techniques of the fiber-optical probes in multiphase reactors should be developed further: (1) online measuring techniques under nearly industrial operating conditions; (2) corresponding signal data processing techniques; (3) joint application with other measuring techniques.

Keywords- fiber-optical sensor; probe; multiphase reactor; local flow characteristics

1. INTRODUCTION

Multiphase reactors are the most important equipment in the chemical industry, where chemical reactions take place involving several reactants in different phases. To describe and design multiphase reactors, traditional approaches based on empirical rules and correlations rely to a large extent on the measurements made under conditions as relevant as possible to industrial practice. Modern computational fluid dynamics (CFD), which has been extensively used for the numerical simulation of multiphase reactors [1–5], also requires the information on local and transient flow characteristics to build precise physical models. Reliable measuring techniques are therefore needed for the rational description and design of multiphase reactors. The measurement techniques for multiphase reactors can be classified as invasive (such as fiber-optical probes [6,7], impedance probes [8,9], heat transfer probes [10,11] and ultrasound probes [12,13]) and non-invasive techniques (including optical techniques [14–18] and tomography [19–23]). Boyer *et al.* [24] have reviewed and compared them in detail. Invasive measuring techniques cannot be avoided though non-invasive techniques are intensively developed for the analysis of multiphase flows. This is particularly true for highly turbulent systems, due to two main reasons: (i) in case of nearly industrial operating conditions (particular physico-chemical environment, opaque walls, high gas holdups or solid concentrations, *etc*.), non-invasive techniques become ineffective; (ii) non-invasive techniques are often difficult and expensive for industrial applications. In all of non-invasive techniques, fiber-optical probes may be the most promising ones because of their inherent advantages such as harsh environment tolerance and very small size, which will be discussed in Section 2.1. Benefitting from great developments in the optoelectronic and fiber-optical communications industries, great progress has also been made in fiber-optical sensor technology with vastly improved optical and mechanical properties and lower cost of the components over the past 30 years. As a result, the ability of fiber-optical sensors to displace traditional sensors for rotating, accelerating, electric and magnetic field measurements, temperature, pressure, acoustics, vibration, linear and angular positions, strain, humidity, viscosity, chemical measurements, and a host of other sensor applications has been enhanced [25]. A number of useful reviews such as those by Kersey [26], Grattan and Sun [27] and Lee [28], and monographs such as those by Yin *et al*. [29] and Udd *et al*. [30] have been produced over the years. Progresses in fiber-optical sensor technique open a door for the measurements of multiphase reactors and can offer many important measurement opportunities and great potential applications in this area. The aim of this paper was to review the most significant developments and applications of fiber-optical probes for multiphase reactors. The remainder of this paper is organized as follows: in the next section, the basics of fiber-optical sensors are presented. Then, significant developments and applications of fiber-optical sensors/probes for multiphase reactors (involving gas-solid, liquid-solid, gas-liquid, liquid-liquid, gas-liquid-solid systems) will be introduced. Finally, the future research trends in the field of fiber-optical sensors/probes for multiphase reactors will be discussed and summarized.

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2. BASICS OF FIBER-OPTICAL SENSOR

2.1. Why Fiber-Optical Sensors?

The inherent advantages of fiber-optical sensors range from their: (1) harsh environment capability to strong EMI (electromagnetic interference immunity), high temperature, chemical corrosion, high pressure and high voltage; (2) very small size, passive and low power; (3) excellent performance such as high sensitivity and wide bandwidth; (4) long distance operation; and (5) multiplexed or distributed measurements, were heavily utilized to offset their major disadvantages of high cost and end-user unfamiliarity [29].

2.2. Compositions of Fiber-Optical Sensors

As shown in Figure 1, a fiber-optical sensor system consists of an optical source (laser, LED, laser diode, *etc*.), optical fiber, sensing or modulator element transducing the measurand to an optical signal, an optical detector and processing electronics (oscilloscope, optical spectrum analyzer, *etc*.) [25]. The advent of laser opens up a new world to researchers in optics. Light sources used to support fiber-optical sensors produce light that is often dominated by either spontaneous or stimulated emission. A combination of both types of emission is also used for certain classes of fiber-optical sensors.

2.3. Fiber-Optical Sensor Classifications

Fiber-optical sensors are often loosely grouped into two basic classes referred to intrinsic, or all-fiber and extrinsic, or hybrid sensors. The intrinsic fiber-optical sensor has a sensing region within the fiber and light never goes out of the fiber. In extrinsic sensors, light has to leave the fiber and reach the sensing region outside, and then comes back to the fiber [29]. Furthermore, fiber-optical sensors can also be classified under three categories [25]: the sensing location, the operating principle and the application, as seen in Table 1.

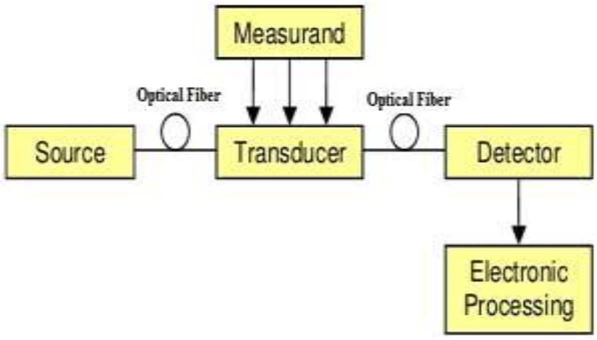

Figure 1. Basic components of a fiber-optical sensor system [25].

Table 1. Fiber-optical sensor classifications under three categories.

Category	Class	Trait
sensing location	point sensors	with a sensitized tip in the measurands field to measure along the length of the fiber itself "in between" point and distributed sensors
	distributed sensors	
	quasi-distributed sensors	
operating principle	intensity sensors	
	phase sensors	
	frequency sensors	
	polarization sensors	
application	physical sensors	for temperature, stress, velocity, *etc.*
	chemical sensors	for pH, gas analysis, spectroscopic studies, *etc.*
	bio-medical sensors	for blood flow, glucose content, *etc.*

2.4. Current Applications

Fiber-optical sensors have been the topic of considerable amounts of research for the past 30 years and their application fields are being extended continuously in two major fields, *i.e.*, as a direct replacement for existing sensors and the development/deployment of fiber-optical sensors in new areas. To date, the most highlighted application fields of fiber-optical sensors are in large composite and concrete structures, electrical power industry, medicine, chemical sensing, and gas and oil industry. A wide range of environmental parameters such as position, vibration, strain, temperature, humidity, viscosity, chemicals, pressure, current, electric field and several other environmental factors have been widely monitored. More detailed information on the applications can resort to references [25] and [29].

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3. APPLICATION OF FIBER-OPTICAL PROBES IN MULTIPHASE REACTORS

A multiphase system with gas as the dispersed phase may be a gas-liquid or gas-liquid-liquid or gas-liquid-solid system. Due to the too small differences in refractive index between gases and organic liquids, fiber-optical probes are rarely utilized in experimental studies on the measurement of gas-phase characteristics in a gas-liquid-liquid system. So the discussion on this system is combined with the gas-liquid one. The gas-liquid-solid system has two dispersed phases and the complicated effects between different phases make the experimental studies more difficult. In gas-liquid reactors, more information about the local gas-phase characteristics such as bubble-size distribution, bubble velocity, local gas holdup and bubbling frequency is useful for monitoring the homogenization of aeration in the whole volume of the reactor and for predicting the mass-transfer characteristics between gas and liquid. Needle probes are always used. Single-tip probes lead to gas fraction and double-tip probes allow measurements of bubble velocity, time-averaged local interfacial area and mean bubble chord length. As a needle probe, an infra-red light beam is conducted along the fiber to the needle tip, where the thin fibre ends usually as a sharp cone so as to pierce small bubbles. Following optic laws, this tip transmits the light beam away when submerged in liquid, or reflects it back to the electronic receiver when it is surrounded by gas. An optoelectronic device (phototransistor) delivers an analog output signal in proportion to the received light intensity [24]. The techniques using fiber-optical probes in this area are more developed. Over the past decades, there have been a number of designs developed for the fiber-optical probes in measurement of gas-liquid flows, such as mono-fiber probes, double-tip optical probes, U-shaped probes and prism-linked probes. The solids concentration, the particle velocity and the corresponding solids flux are considered as the main parameters of characterizing gas-solid and solid-liquid two-phase flow structures. The local solids holdup is measured using the optical fiber solids concentration probes and the local particle velocity is measured by the optical fiber particle velocity probe. The principles also rely on the difference in refractive index of the probe and the surrounding media. A classic optical fiber solids concentration probe made by our group (shown in Figure 2) has a 3.8 mm o.d. stainless steel probe tip, containing approximately 8,000 emitting and receiving quartz fibers, each 15 mm in diameter. These fibers are arranged in an array consisting of alternate layers of emitting and receiving fibers, within a 1.5 mm square area at the center of the probe tip. A bundle of fiber projects light onto the passing cluster of particles. The other interspersed fibers in the bundle act as light receivers transmitting the light reflected by the particles to a photo transistor which converts the light into an electrical signal. An amplifier increases the resulting signal to a voltage range 0–5 V and then to an A/D converter. The relative error of the probe measurement is 1/256 of the full range for εs measurements. The particle velocity probe uses one or more fibers (or fiber bundles) to project light (e.g., laser) on the flow and two or more fibers (or bundles) to detect the reflected light.

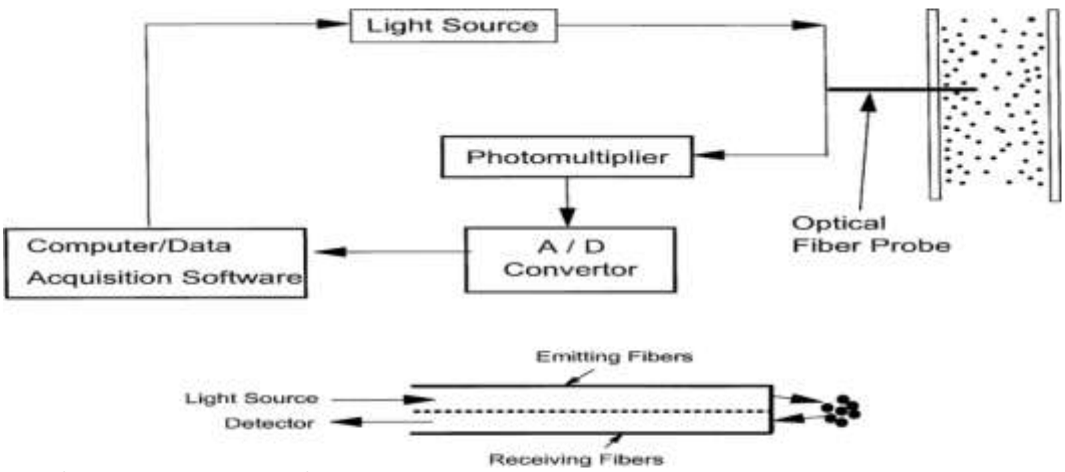

Figure 2. The fiber-optical probe system for solids holdup measurement.

4. CONCLUSIONS AND PERSPECTIVES

This work presents a brief introduction on the fiber-optical sensor basics and an overview focusing on the applications to the measurements in multiphase reactors. Relatively, the fiber-optical probe techniques in two-phase reactors are better developed but more efforts are still needed to make them perfect.

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