

# ATOMIZATION OF HIGHLY VISCOUS FLUIDS

Nasser Ashgriz

Department of Mechanical and Industrial Engineering

University of Toronto, Toronto, Canada

## Summary

A methodology for the atomization of high viscosity fluids is provided. This methodology comprises of the following steps: (1) Characterizing the fluid; (2) determining the objectives and the application area of the spray that also dictate the desired flow conditions, including the mass flow rates and pressures; (3) determining a suitable atomization mechanism; (4) choosing the atomizer type and scaling it to the flow conditions, and (5) determining the droplet or particle sizes after atomization. A brief outline of the material that will be provided in the final report is provided in this summary.

### 1 Liquid Properties

The liquid properties (density, viscosity, surface tension, as well as chemical composition) influence the atomization process in various ways. High density liquids require more inertial input to accelerate them to high velocities; high viscosity liquids dissipate the input energy, and high surface tension liquids require more energy to form the required surface energy of the small drops. In other words, the higher the value of any of the three liquid properties, the more difficult it is to atomize them and more energy is needed for their atomization. Among all the liquid properties, viscosity has the largest influence on the choice of the atomizer. A high viscosity liquid is only a relative term. When compared to water with 1cp, a high viscosity liquid may be referred to a liquid with a viscosity of 10s cp or one with 1000s cp. The atomization of a liquid with 10cp is very different than that with 1000 cp. Therefore, it is important to quantify the level of viscosity.

The liquid may also be a Newtonian or a non-Newtonian liquid, or behave as a Newtonian liquid in certain pressures and temperatures and behave as non-Newtonian in other conditions. The atomization of a non-Newtonian liquid is very different than those of Newtonian liquid and the atomizer has to be specifically selected for this type of liquid.

Many high viscosity liquids also have solid suspensions. For instance, coal-water slurry, bitumen, black liquor, etc. all have small solid particles. It is shown that solid particles not only change the effective viscosity of the liquid, but also have added atomization complexity. For instance, larger solid particles may separate from the liquid after atomization resulting in a bimodal droplet size distribution.

### 2 Application Areas of High Viscosity Liquids

High viscosity liquids are used in a wide range of industries, and their specific application dictates specific requirements. For instance, small size sprays are used in automotive engine applications, whereas very large sprays are used in furnaces. In addition, in some applications, the liquid viscosities are high but orders of magnitude less than some other applications. Here, a brief review of different applications of high viscosity liquid atomization is provided. The applications range from powder production for pharmaceutical applications to droplet production of biofuels for combustion and propulsion systems.

**Pharmaceutical Applications** – This application ranges from tablet coating to particle production. The fluids used are complex, many are non-Newtonian and may also have polymers and solid suspensions.

**Powder Production from Melts** - Viscous melts such as glass melts or liquid slags, are used to produce powders of the same. They have high viscosity and low surface tension. These liquids have to be atomized rapidly before they cool and solidify. Rapid cooling may result in ligaments and fibers rather than spherical particles. Increasing the melt temperature to prevent rapid cooling may result in an increase in the viscosity and, therefore, poor atomization.

**Engine Applications**- Biooils and biofuels are high viscosity liquids (10 to 100 cp) that are being used as alternative fuels in engines. There are a wide variety of biooils with different chemical compositions. Their use without altering the engine has shown several problems, including clogging of the filters, pipes and nozzles; polymerization and oxidation of the fuel; deposition on the walls, and corrosions. Special attention should be given to the atomization of such liquid.

Another group of high viscosity fuels are High Energetic Fuels. In order to increase the energy content of fuels for long range military application, such as rockets and missiles, slurry or gelled slurry fuels of high energetic material are produced. Boron, beryllium, carbon, aluminum, and silicone are the elements with the five highest volumetric heat capacities. In order to prevent their separation from the liquid in the slurry phase, they are made into a gel for prolong storage. In this application, very small droplets are needed for efficient combustion.

**Furnace and Power Generation Applications** – Furnaces for power generation are usually very large facilities which may use high viscosity fuels, such as coal-slurry and petroleum coke as the fuel. Petroleum Coke Slurries are by-product of refineries and contain a significant amount of energy. They are used in furnaces to generate more energy. These liquids are viscoelastic non-Newtonian fluids and difficult to atomize by common atomizers. Petroleum coke has strong hydrophobic surface and solid-liquid separation occurs during the atomization process.

**Recovery Furnace Applications** – Many complex fluids may contain materials that has to be recovered through heating and evaporation. Black liquor and Bitumen are among these fluids. For instance, Bitumen is injected in cokers to produce synthetic crude oil. Bitumen is a very viscous liquid that is usually mixed with steam to allow it to be atomized. And, Black Liquor is a by product of (sulfate) pulping process. Organics, including lignin, are separated from the wood fibers using white liquor (an aqueous solution of NaOH and Na<sub>2</sub>S) in a digester. The spent solution is called weak black liquor. Black liquor is burned in recovery boilers to recover the inorganic chemicals and generate steam..

### **3 Atomization Mechanisms**

The atomization process is a very complex process, which is mainly due to a turbulent mixing and fragmentation from liquid-gas interfaces. A brief review of different mechanisms that may be responsible for the atomization is provided.

The atomization process occurs due to the breakup of liquid masses from the liquid-gas interface. Therefore, the first objective of the atomization process is to generate a liquid gas interface. The first obvious choice is by injecting a liquid into a gaseous environment. Since a liquid is carried through pipes, the first choice is to inject a liquid jet that issues at the end of a pipe into a gaseous chamber. If the jet velocity is low, the jet will only breakup based a capillary instability

generating droplets which are about 2 times of the jet diameter. And since the pipe diameters are usually large (orders of mm), the droplet sizes will be large. However, the main objective of most atomization processes is to generate droplets of the order of microns or at the most mm range. For instance, in engine applications and particle production, droplets are in the order of 10-100 microns, and in craft recovery boilers, the droplets are in the orders of couple of mm. For relatively low speed jets, the length scales are the jet diameter and the wavelength of the fastest growing waves that cause the jet to breakup. These wavelengths are generally larger or about the same length of the jet diameter. Therefore, in order to generate small droplets, the liquid jet diameter has to be reduced. This is usually achieved by passing the liquid through a small orifice. However, small orifices have very large pressure drops, and more importantly, they can be easily plugged by impurities, making them impractical. For instance, in order to have a 20 micron droplet, the orifice size has to be 10 micron, which is difficult to maintain open.

**Liquid Jet Atomizers-** One method to reduce the droplet size is by increasing the jet velocity. Increasing the jet velocity to such a high level that the length scales in the turbulent flow become the dominant scales of atomization. If the jet is injected into a quiescent ambient, the jet has to become highly turbulent. It is difficult to have a highly turbulent small diameter liquid jet. Turbulence is significantly dissipated in small liquid jet diameters. Therefore, effective atomization of small 150-micron diameter liquid jets are achieved only at injection pressures of orders of 1000psi. Diesel engine nozzles are of this type of atomizers.

**Liquid Sheet Atomizers-** Another method of reducing the diameter of the droplets, without reducing the orifice diameter, is to spread the liquid and make a thin liquid sheet. In this case, the droplet diameter would be in the order of the liquid sheet thickness. Fan, swirl, and splash plate nozzles are of this type of atomizers.

**Gas Turbulence Induced Atomizers-** Since the droplet sizes formed from an atomization process depend on different length scales in the flow, theoretically, one can generate a highly turbulent flow with a small turbulent length scale in order to generate small droplets. As noted, it is difficult to generate a highly turbulent small diameter liquid jet, but is easier to generate a highly turbulent gas jet. Therefore, a common method of atomization is to generate a high turbulent gaseous flow at the liquid interface. The gas turbulence will then break the liquid into small droplets.

#### **4 Atomizer Types**

**Diesel Type Nozzles** - These types of atomizers use high pressures to achieve high quality atomization. For instance, in Diesel engine, high quality atomization is achieved by increasing the injection pressure up to 20,000 psi. Such high pressures are produced using a common rail type injection system which is driven by the engine. At such a high injection pressure, generating a very high relative velocity between the liquid and the gas is formed and the liquid is immediately shattered because of the significant shear at the liquid-gas interface. At such high relative velocities between the liquid and the gas, even if there are any large droplets, they will breakup into smaller droplets, through the so called secondary atomization process. Clearly, this type of atomization method is only useful in cases that such high pressures are available. Because of high pressures, a one order of magnitude change in viscosity does not have much effect on the atomization process. Therefore, biodiesel fuels are effectively used in diesel engines without any nozzle modification. However, for higher viscosity liquids, the work needed to pass the liquid

through small orifice of a diesel nozzle become problematic. Generally, nozzles which are designed for good atomization of low viscosity liquid are not effective for high viscosity liquids.

**Fan Nozzles**– These types of nozzles use a slot with a certain thickness to generate a liquid sheet. By having a diverging section inside the nozzle, the liquid is forced to spread out as a fan. As the fan becomes larger, the thickness of the liquid sheet forming the fan becomes smaller. Theoretically, the sheet can be made very thin, and therefore, it is possible to generate very small droplets by spreading the liquid for long distances. Practically, surrounding disturbances break up the sheet before it becomes very thin, yet it is possible to generate small droplets with this type of Fan Nozzles.

**Pintle Nozzles** - Another method of generating a liquid sheet is to place a small diameter solid surface on the exit of the nozzle. Therefore, the liquid is forced to spread radially outward. Again, a liquid sheet is formed that becomes thinner as it spreads. Once the sheet breaks, droplets in the order of sheet thickness are generated. One issue with the pintle nozzles is that the spread angle depends on how efficiently the pintle guides the liquid in the radial direction. For high flow rates, this flow redirection is not effective.

**Splash Plate Nozzles** – Where pintle nozzles are used on small diameter orifices, splash plate nozzles are used for very large diameter pipes. In order to spread the liquid radially outward to make a liquid sheet, a plate is placed in front of the exit of a pipe or a nozzle. The plate is usually welded to one side of the pipe at an angle. The liquid impacting on the plate is spread radially forming liquid sheet. Splash plate nozzles are commonly used for high viscosity liquids. The pressure losses for high viscosity liquid can be significant if the pipe or the orifice diameters are small. Therefore, diameters are kept in the order of mm and a splash plate is used at their exit point to form the sheet.

**Swirl Nozzle** –Another method of making a liquid sheet is by swirling the liquid forming a vortex. As the swirling vortex flows outwardly, the swirl action spreads the liquid in the form of a diverging cone, reducing the liquid cone thickness. Swirling nozzles are very effective, not only because of their ability to generate thin liquid sheets, but also for their good mixing abilities. The swirling action increases the mixing process between the liquid droplets and the surrounding fluids. Therefore, they are commonly used in large combustion engines.

**Rotary Cup Nozzles**- These nozzles combine the effects of a splash plate and a swirl nozzle. They are very effective for generating small diameter droplets for high viscosity fluids. They are commonly used in pain sprays.

**Impinging Liquid Jets**- Impingement of two liquid jets on each other has the same effect as a splash plate nozzle. When the two jets collide, the liquid on each jet is spread radially outward forming a liquid sheet. These types of atomizers are commonly used in liquid propellant rocket engines, where a liquid fuel and liquid oxidizer are impinged on each other. This provides not only atomization of the two fluids, but also a rapid mixing between them.

**Twin Fluid Nozzles** – Nozzles that use a secondary fluid (usually air or steam) to atomize a liquid are referred to as twin fluid nozzles. A nozzle chamber is designed in which a gas jet and a liquid are brought together at very high relative velocities. **Internal Mix Nozzles** are the types that the gas and the liquid are brought together inside the nozzle chamber, and **External Mix Nozzles** are the ones that they are brought together outside of the nozzle. There are a wide variety of both internal and external mix nozzles. For low viscosity liquids, the internal mix can be achieved by using a liquid jet injected in between a high velocity gas, followed by forcing both

fluids to go through a small exit orifice. If the liquid is viscous, then an annular jet is generated that is sandwiched in between an inner and outer flowing gas, the mixture is then forced through the exit orifice. The same can be achieved in external mix nozzles.

The main objective of these types of nozzles is to achieve an efficient transfer of gaseous turbulent kinetic energy into the liquid. In the internal mix nozzles, the transfer is more efficient than the external mix nozzles. However, because of the high velocities, the time for energy transfer is very short. Therefore, they are only useful for smaller liquid flow rates, or small nozzles. For larger liquid flow rates, one has to use longer nozzles, or use external mix nozzles.

Twin-fluid atomizers are also categorized according to relative mass flow rates of liquid and atomizing gas. **Air-Assist** atomizers use low mass flows of gas at high velocity, and **Air-Blast** atomizers use high mass flows at low velocity.

**Liquid-Gas Mixture Atomizers** – Another method of atomization is to mix a high pressure gas with a liquid and forced the mixture out of an orifice. The liquid-gas mixture ratio is kept at a level that the mixture is a bubbly flow. After leaving the nozzle, the bubbles expand, shattering the liquid from the inside. **Effervescent** Atomizers use this type of atomization. Effervescent atomizers are used to atomize high viscosity liquids. In this type of atomizers, high air injection pressures can decrease the viscous fluid mass flow rate and enhance the air bubbles blast, which results in smaller atomized droplets.

**Electrostatic Atomizers** - A high voltage applied on a liquid can break the liquid into small droplets. This is referred to as electrostatic atomization. Electrostatic atomization is commonly used in paint sprays to guide the flow of droplets. Electrostatic atomization is commonly used in mass spectrometers. They can produce uniform size spray with droplet sizes as small as few microns.

**Compound Atomizers**- These nozzles combine several different atomization mechanisms. For instance, a twin fluid swirl nozzle, combines swirling effect and the turbulent atomization effect. The swirl action in such nozzles acts as a better mixer, rather than a sheet generator. A pre-filming air blast atomizer combines sheet formation and twin fluid as well.

**Other Effects**- Other effects can influence the atomization process. For instance, in high pressure nozzles, **Cavitation** may occur in regions with sharp corners, where there is a sudden pressure drop, reducing liquid pressure below its saturation conditions. In such cases, a cavitation bubble is formed inside the nozzle that can significantly increase the flow velocity and thus improve the atomization. In addition, a sudden pressure drop in fluids that are at temperature close to their saturation temperature can form small nucleation bubbles inside the liquid, which may rapidly grow and result in flash boiling. This type of atomization is referred to as **Flash Atomization**. Flash atomization can occur inside the nozzle or outside of the nozzle depending on where the pressure drop occurs and how fast the bubbles are formed and grown.

## 5 Spray Droplet Sizes

The main objective of any spray nozzle is to generate a spray with a desired droplet size distribution. Since the atomization process is very complex, the size distribution is mainly determined experimentally. There are numerous empirical correlations for sprays generated from different spray nozzles and at different operating conditions. Yet, most of these correlations are in conditions which are not the same as those in real applications. For instance, since it is not possible to measure droplet sizes in a furnace, a furnace nozzle is tested in cold conditions and

its results is assumed to be the same as those inside the furnace. Another problem with spray nozzles is that there are not easily scalable. Therefore, it is difficult to extrapolate small scale tests to large scale industrial applications. Therefore, some form of theoretical model is needed to help in either predicting the spray droplet sizes or extrapolate or generate proper empirical correlations.

Theoretical models to predict droplet sizes depend on the type of atomization and the atomizer. For instance, Rayleigh instability criterion is used to predict the droplet sizes produced by jet type nozzles. The droplets produced are further broken into smaller droplets by secondary atomization of drops using Taylor Analogy Breakup (TAB) model. In addition, sheet instability criterion is used to predict the ligament sizes produced by sheet type nozzles. The ligaments are then broken into droplets using Rayleigh instability model and then to smaller droplets using TAB model. In turbulent mixing nozzles, turbulent length scales are used to provide a characteristics size for the spray. Such information can then be used together with other models, such as Entropy Maximization models, to generate a size distribution for the spray. Such distributions can be the first step in determining the possible size distribution from a nozzle.

International Fine Particle Research Institute (IFPRI) Review Summary  
**In-Line Sensors for Real-Time Measurement and Analysis of Bulk Powders**

Wuqiang Yang, The University of Manchester, UK  
Jan. 2017

## **1. Introduction**

Particle/solids/granular materials constitute over 75% of raw materials in the manufacturing industry. Powders are a type of dry bulk fine particles, such as pulverized coal in coal-fired power plants, some pharmaceutical materials, some industrial chemicals, flour, ground coffee, powder milk; cement, copy machine toner, gunpowder and cosmetic powder. Typically, a powder can be loosened into a large range of bulk density. When a powder is deposited by sprinkling, it may be very light and fluffy. Some common powder behavior includes segregation, stratification, jamming and unjamming, fragility, loss of kinetic energy, frictional shearing, compaction and Reynolds' dilatancy. In many cases, powders are dangerous to deal with. For example, in a flour mill, blockage of a pneumatic conveyor by flour may cause explosion.

Because accurate measurement and efficient control of powder flows and processes have a direct bearing on the operational efficiency of manufacturing plants, it is important to understand what sensor technologies are available for real-time in-line characterization of the properties of bulk dry powders and real-time in-line measurement of powder flows and processes, aiming to improve the operation efficiency and reduce waste, thus meeting the environmental demands and tackling the increasing costs of raw powder materials. The following are three examples showing the importance of in-line sensors for real-time measurement and analysis of bulk powders.

In the **power industry**, a major challenge in coal-fired power plants is to measure the pulverized coal flow rate in each nozzle accurately. Due to the reliance on fossil fuels worldwide, improving the coal combustion efficiency has become an urgent issue. There are three major challenges in pulverized coal flow rate measurement: (1) the volume concentration of pulverized coal in the air stream is low, typically less than 5%; (2) the flow regime is unpredictable, e.g. stuck on wall and roping; and (3) the flow velocity is high, up to 20 m/s. In modern coal-fired power plants, circulating fluidized beds (CFBs) are used for clean coal combustion. Although fluidized beds have been used in industry for many years, the understanding of the fluidization processes is rather limited because of the lack of in-line sensors to measure the particle size distribution, flow regime and the dynamics of the fluidization process. As a result, CFB combustors are currently operated by trial-and-error, resulting in poor combustion efficiency and causing pollution to the environment. This problem is particularly serious in China and has been commonly known as PM2.5 problem.

In the **pharmaceutical industry**, the operation of drug manufacturing facilities is based on conventional technologies that suffer from a number of limitations, particularly with regard to the overall efficiency of both development and manufacture as well as the transfer and scale-up of a process. A drug product is currently manufactured by batch processing, for which silos are commonly used for feeding and fluidized beds are used for drying, granulation and coating of drug materials. In the drying process, because of the lack of in-line sensors to measure the moisture of powder and powder/air distribution, the fluidized bed dryers are also operated by trial-and-error and hence the operating efficiency is low, resulting in longer processing time and more power consumption than necessary. To improve the overall efficiency, continuous processing of pharmaceutical products is now emerging.

This step change would reduce both development and manufacturing costs by 30–50% and would have a huge economic impact on the pharmaceutical industry. One of the key difficulties hindering continuous processing of drug products is the lack of accurate online powder flow meters.

In the **chemical industry**, there is a greater reliance on continuous than batch production, because batch production becomes increasingly unattractive from an economic standpoint as production volumes increase. Thus, continuous production in the bulk chemical industry is imperative to remain competitive. One of the main difficulties for industrial chemical production is to ensure good mixing quality, and hence a uniform, consistent product, when different powders are blended. The industrial mixing of powders remains poorly understood, partly due to the limitations in experimental approaches used to quantify the effectiveness of mixing and partly due to the large number of factors, which affect mixing quality – including differences in particle size, shape or density, moisture content and the presence of other interaction forces such as electrostatic forces.

Although in-line sensors for real-time measurement and analysis of bulk powders are very important to industry and researchers have been continuously making effort on developing new technologies for this purpose, unfortunately very few types of such sensors are commercially available for industrial applications. The aim of this review is to summarize sensor technologies for real-time in-line measurement and characterization of the properties of bulk dry powders. It is organized in four sections:

- (1) In-line analysis of power properties
- (2) In-line power flow measurement with conventional sensors
- (3) A new non-intrusive and non-invasive tool – electrical capacitance tomography (ECT) for powder flow/process measurement
- (4) In-line sensors for fluidized beds.

## **2. In-line analysis of power properties**

Powder properties include particle size (and distribution), density, blend composition, moisture content, and their spatial distribution. To measure the moisture content of powders, three types of sensors are commonly used: (1) capacitance, (2) microwave and (3) near infrared.

(sensors for measuring other powder properties will be included)

## **3. In-line power flow rate measurement with conventional sensors**

Powder flow meters based on conventional techniques include capacitance (not tomographic), microwave, electromagnetic, impact plat, differential pressure, radar, radioactive, ultrasonic, weighing system (i.e. load cell), and electrostatic cross correlation. The meters reviewed in this section are commercially available, and manufactured by world leading instrumentation companies, such as Endress+Hauser, Emerson (Rosemount and Fisher), SWR Engineering, Siemens, ABB, Promecon and Ramesey. To measure a powder flow rate accurately, in principle, the concentration profile and the velocity profile should be measured. To measure concentration, the following methods are used: attenuation, optical fiber, resonant (including magnetic resonant and microwave resonant), capacitance and electrostatic. The following are two examples, one based on electrostatic sensors and the other based on capacitance sensors.

PfMaster is a type of pulverized fuel flowmeter, developed by ABB. Signal-sensing utilizes the detection of electrostatic energy, which is naturally present on the pf particles. This passive sensing eliminates any dangers, which might be present with systems based on ionizing radiation, such as

microwave techniques. The sensors, being a spool-piece, provide high performance in the presence of roping and mal-distribution of pulverized coal. Each sensor features a smooth internal bore, which enables long interval between inspections, with an expected life in excess of ten years. The concentration and velocity measurements are made. Sensor connection to the signal-processing computer is by a single low-voltage multi-core cable, the design of which has been optimized to provide high rejection of interference signals in a plant. Another feature of the sensor electronics is the incorporation, as standard, of barrier circuits, to make sure that no energy is transmitted into the pipe, preventing any hazardous voltage from igniting the explosive atmosphere present in the pipe-bore.



Ramsey Granucor Solids Flow Measurement System from Thermo Scientific is based on capacitance sensors. The meter was originally designed by Endress+Hauser. It consists of two major units: DC13 capacitance sensors for solids concentration measurement and DK13 capacitance sensors for flow velocity measurement by cross correlation. The declared features include easy installation, non-intrusive and no moving parts, no effects from pressure, temperature and vibration, and displaying of solids mass flow, solids velocity and solids concentration. The declared applications include measuring mechanically conveyed plastic pellets and pneumatically conveyed solids in coal-fired blast furnaces; balancing feed among nozzles in blast furnaces, improving blast furnace efficiency, as well as iron quality and consistency; measuring flow of plastic granules in injection molding facilities or pelletizers; and controlling flow of various additives. The problems with this flow meter are (1) the concentration sensor with a single pair of capacitance electrodes has non-linearity problem and is flow-regime-dependent, and (2) the cross correlation sensor can give superficial velocity only, which can be very different from true solids/powder velocity.

The applications mainly cover belt conveying, pneumatic conveying and gravity-dropping. In pneumatic conveying, the products for both dense- and lean-phase flow measurement will be included.

In this section of review, the following aspects will be included:

- (1) Principles of operation
- (2) Areas of application
- (3) Mass or volume flow measurement
- (4) Advantages and disadvantages of different type of sensors
- (5) Manufacture's data, including accuracy, reliability, and calibration methods
- (6) Feedbacks from the customers/end users based on the data from the public domain.

#### **4. Electrical capacitance tomography (ECT)**

ECT provides opportunities for in-line real-time measurement of powder flows/processes. The measured parameters include powder fraction (and profile), flow regime, velocity profile and

volumetric flow rate. Although ECT-based powder flow meters are in their infancy, it would challenge conventional powder flow meters in the near future, because ECT can provide unique spatial information, such as powder/air distribution, which the conventional powder flow meters are unable to provide. ECT is not hindered by the opacity of powder flows, nor is it affected by the powder acceleration, which enables to interrogate some very turbulent zones in a powder flow. It is a non-intrusive and non-invasive method and also free from blockage and erosion. Therefore, it is one of the most promising tools for powder flow fraction measurement.

Another distinct advantage of ECT is its ability to display parameters on every local point, yet to produce a profile of the whole flow channel with the fastest speed of all scanning methods, providing a unique means of multi-pixel powder velocity profile measurement. Because of the ability of fast multi-grid representation of variation of flow parameters, ECT can provide detailed indication of local transient flow patterns. Since acceleration of powder generates “added weight” and hence marked errors in the “static weight” measurement methods, the pressure difference method does not work with strong acceleration. ECT is not based on the measurement of motion-force or momentum-pressure relationship. Therefore, it is not affected by the acceleration of particles.

### **5. In-line sensors for fluidized bed measurement**

Fluidized beds are widely used in the power, chemical, pharmaceutical and food industries. The main advantage of using fluidized beds is that they provide efficient heat and mass transfer and can mix gas and powders to produce uniform distribution. However, in a fluidized bed reactor, many parameters affect the operation efficiency and the end-point product quality strongly depends on in-line parameter measurement. Quantities that need to be measured in fluidized-bed systems include powder volume concentration, powder velocities, powder mass flow rate, powder distribution, lateral distribution of fluidizing gas, temperature and pressure. However, due to the complicated multiphase flow hydrodynamics, single point measurement, such as pressure and temperature probes, cannot provide details information on parameters and distribution in a cross-section, resulting in difficulties in process control. In-line monitoring of the above parameters are challenging. To provide effective approaches to in-line monitoring and fault diagnosis in a fluidization process, ECT combined with single point measurement are introduced to fluidized bed process measurement.

The advantage of ECT has been demonstrated on a CFB. When the acceleration of solids is relatively small in the packed bed and bubbly fluidized bed regimes, ECT measurements agreed well with pressure measurements within 1%. In the slugging regime, however, pressure measurements presented 30% over-estimate. It is believed that the difference is due to the acceleration effect on the pressure measurements, but not on ECT measurements. This implies that an ECT sensor can be positioned in very chaotic regions, such as the bottom section of CFBs, which would be very difficult for pressure difference methods.

Flow regime identification is also related to fluctuation analysis. An example is to measure the transition of flow regimes in CFBs. For a CFB of a certain size, fluidization can evolve through a series of stages as packed bed, bubbly bed, slugging bed, turbulent bed, and pneumatic transport, as the gas flow rate increases. Flow parameters, such pressure and solids fraction for each of the above stages are characterized by certain fluctuations in frequency and magnitude. By analyzing the fluctuation signals, through certain criteria such as Kolmogorov Entropy, the fluidization regimes can be distinguished. However, due to the chaotic nature of fluidization, such transition of flow regimes may not happen simultaneously throughout the whole region, i.e. it may occur in different time and/or at different locations. Usually, pressure taps are mounted on the wall of a CFB to extract fluctuation signals. As

such signals only represent averaged behavior over a volume across the bed, it is difficult to distinguish the localized onset of regime transition by such conventional transducers. With ECT, the variations of powder fraction can be recorded for a large number of virtual pixels in the bed, which effectively provides information on the powder fraction fluctuations in all discrete locations, allowing analysis of fluctuation characteristics on every selected local point, thus enabling the localized transition of flow regimes to be identified.

In-line powder moisture measurement based on different principles and approaches are compared and the measurement results in a typical fluidized bed dryer are given and validated with reference measurement. Based on those measurement results, an example for feedback control and process optimization is given in a batch fluidized bed drying process to increase the operation efficiency and improve product quality. In the end, the potential application of ECT in fluidized beds with high pressure and high temperature is reviewed.

