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Review

Sensing in fluidized bed processes — from capturing details to monitoring the operation

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This article offers an opinion and a perspective on the future development of sensing techniques in fluidization technology. The direction of the field is exemplified by a handful of techniques, pointing at the advancements that revolve around two aspects. First, increasing the basic understanding of multiphysics at meso- and microscales, thereby enabling the investigation, development, and scaling up of processes of increased complexity; characteristics that demand high temporal and spatial resolutions and sensitivity, phase differentiation, nonintrusiveness, and the simultaneous acquisition of multiple variables. And second, enhancing operability in response to industry demands for safer, more flexible, and resilient operation as processes are expected to deal with variable boundary conditions (feedstock, load, energy input/output). Beyond the development of instruments, integrated data analysis tools based on artificial intelligence and machine learning are becoming constitutive parts of the ongoing capability building by optimizing data processing, enhancing accuracy, and improving efficiency.

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Introduction

While the development of fluidized bed (FB) technology has traditionally been experience-based and following incremental progress, the current paradigm seeks a transformative development based on understanding, with the potential for generalization. Progressing hand in hand with the advances in modeling, the accurate and affordable characterization of the gas–solid flows under application-relevant conditions is envisioned. In this context, experimental research and direct monitoring of industrial FBs remain indispensable for two main reasons: resolved simulations of large units are prohibitive, while reduced-order simulations have limited accuracy, and measurement data at different levels is highly demanded to drive the knowledge mining.

In addition to the expected volume and quality of data, the requirements set on measurement techniques are progressively changing as processes transition towards more compact and effective systems and equipment, more flexible operation modes, and tailored bed materials. With this, the sensing tools are currently evolving:

- from acquiring global parameters (averaged or for large volumes) to describing local phenomena with high spatial resolution;
- from measurements under steady-state conditions to the accurate capture of the dynamics;
- from intrusive probe measurements to noninvasive methods;
- from sampling-based measurements (online or offline) to inline measurements that can be incorporated into control loops.

These transitions are facilitated by advances in: (i) electronic components, which enable smaller, cheaper, more sensitive, and faster sensors, and (ii) artificial intelligence (AI) tools (machine learning [ML] and deep learning [DL]), which boost data processing [1] and support model development [2] and automation routines.

Measurement techniques can be classified depending on whether they serve fundamental investigations to improve basic understanding or monitoring industrial units to improve operation. They can also be categorized according to the type of variable targeted. The aim of this work is to outline the overall perspectives of diagnostics and monitoring in FBs, displaying the current trends (over the last 5 years) and the potential these developments hold. A small number of techniques is used to illustrate these trends and perspectives. The selection does not intend to make any value judgment, nor does it entail an exhaustive review of techniques. Although every technique has grown alongside specific applications, their general capabilities to contribute to the field are considered here; therefore, no specifications are made regarding the type of FB or industry.

Improving understanding

This section connects with dedicated research activities. Here, strong focus is set on accuracy, resolution, and specificity of the experimentally acquired data, which in the best case can be combined with models (deterministic or ML) to improve understanding of the underlying mechanisms of mass, momentum, and heat transfer. As these are the three fundamental interplaying transport phenomena acting in FBs, this section is organized according to the measured aspect: solids flows, chemical composition, and temperature.

Solids flow

Trajectory-based techniques

These techniques track the motion of individual particles, allowing the calculation of instantaneous velocity and acceleration, based on which the characteristics of the interaction with the surroundings can be inferred. Underlying is the idea that large amounts of tracking data provide statistical robustness to characterize the fluid dynamics of the whole population or a volume. The validity of this approach is better met at steady state conditions when the tracked particle is representative (in terms of size, density, and shape) of the solids phase studied. Despite the inherent difficulties in meeting the latter condition, these techniques have achieved significant spatial and temporal resolutions and are opening up the possibility of directly characterizing particle-particle and particle-media interactions as a function of the regime and the characteristics of the particle and media involved. The following are examples of such advancements:

Multiple wireless microelectromechanical systems (MEMS) [3] can be assembled or packed into a single chip or tracer particle (mm-sizes), able to register multiple variables (magnetic fields, acceleration, gas

composition, temperature, and pressure), and allowing the sampling of parameters connected to the multi-physics interplay in particle-to-bed transport phenomena [4]. Future developments will focus on further miniaturization and design of the tracer so it can better represent specific solid phases, as a full match of density and size has not yet been achieved.

Positron emission particle tracking (PEPT) [5] uses isotope-doped tracers whose trajectory can be reconstructed from the signal sensed by scintillator arrays. It offers resolutions in the range of kHz and spatial accuracy of 0,5 mm [6]. Enhanced labeling techniques are currently being investigated to achieve sufficient activity in particles in the μm size range [7]. Similarly, the simultaneous tracking of several particles is becoming possible thanks to improvements in the sensing elements [8] and signal processing approaches [9]. Together with the increase in spatial and temporal resolution, this has the potential to enable direct measurement of particle-particle and particle-wall collisions.

Magnetic particle tracking (MPT) sensors determine the position and orientation of a magnetic particle based on the sensed magnetic field. This technique can track a magnet as small as 3 mm, achieving an accuracy of 1 mm in position [10], < 2 degrees in orientation, and temporal resolutions of kHz [11]. The ability to determine the orientation, together with the comparatively lower cost, makes this technique especially useful for studying nonspherical particles. Recent years have seen developments focusing almost exclusively on trajectory reconstruction algorithms that increase the position accuracy and enable online trajectory reconstruction [12–15].

Concentration-based techniques

These methods assess the bulk of solids as a continuum. Instead of tracking specific particles, they evaluate the solids concentration and/or velocity fields. Central to these methods has been the nonintrusiveness and the temporal and spatial resolution. Further, the differentiation between phases and the ability to sense parameters simultaneously (e.g. concentration and velocity) is currently in focus. This is illustrated by three techniques outlined here:

Electrical capacitance tomography (ECT) is a soft-field technique that measures the capacitance between multiple electrodes to reconstruct the cross-sectional permittivity distribution of nonconductive matter [16]. In fluidization, ECT provides resolved real-time solids concentration [17] and has been deployed across various levels of implementation [18,19]. Recent key advancements have focused on the integration of ML-enhanced image reconstruction [17,20], while future advancements

can be expected in: (i) optimizing sensor designs for large-scale implementation and to mitigate fringe effects; (ii) real-time 3D image reconstruction; and (iii) multimodality tomography integrated with intelligent algorithms for a combined assessment of flow, thermal, and chemical properties.

X-ray imaging is a hard-field technique that measures the attenuation of high-energy electromagnetic radiation as it passes through matter in order to infer the density and composition, thereby enabling the quantification of phase distributions [21]. For FBs, two modalities dominate: (i) X-ray digital radiography (XDR), which records time-resolved (kHz) 2D projections of global bed dynamics in large reactors (~ 3 kV/cm diameter), and (ii) X-ray computed tomography (XCT), which uses multiple projections to create 3D maps of solids concentration, but typically limited to laboratory-scale and quasi-static conditions. Quantitative X-ray imaging velocimetry has also been achieved, allowing for the study of flows in highly opaque and refractive systems [22]. Recent developments have focused on enhancing spatiotemporal resolution and quantitative accuracy, thanks to advances in detector technology, high-speed pulsed X-ray sources, and neuronal network -based reconstruction algorithms [23–25].

Millimeter radars (GHz-THz) can be used to measure the concentration of particles (μm size range) along the beam with mm-scale and tens of Hz resolution. By integrating Doppler, these systems additionally determine the distribution of solids velocities in the direction of the beam, enabling the spatially resolved measurement of solids flux [26,27]. This hard-field technique is not constrained by temperature limits and has the ability to penetrate several meters into gas-solids suspensions. The high resolution of radar-acquired data makes it suitable for validating sub-grid momentum balance closures in CFD models [28]. In the midterm, multi-frequency systems are envisioned to differentiate among particle sizes and compositions.

Chemical composition

Important advances have been made in the assessment of composition in multiphase systems in terms of sensitivity and selectivity. Today, resolution in space and the possibility of inline measurements are pursued to solve the small-scale phenomena and their dependency on fluid-dynamic and thermal parameters. Three techniques are discussed here to outline the current state and future perspectives in this field:

Fourier transform infrared (FTIR) spectroscopy is a real-time, multicomponent method that measures gas composition based on the interaction of the sample with an IR beam. FTIR has been deployed to monitor reactions in FBs for diverse applications [29]. Most

recent advancements focus on yielding whole-field imaging in pseudo-2D FBs, which is challenged by strong scattering and attenuation from the solids phase. AI (principal component analysis; partial least-squares discriminant analysis; ML-based models) is increasingly being used to accelerate the interpretation of complex spectra, improve selectivity, and compensate for overlapping bands and matrix effects [30]. Future efforts will focus on the combination with other diagnostics to correlate the fluid dynamics with gas composition. Advancements in hyperspectral 3D absorption imaging and the coupling with tomographic methods (snapshot projection optical tomography and Fourier transform spectroscopy, SPOT + FTS) are also anticipated [31,32].

ECT also serves as an indirect method to monitor composition-related changes in non-conductive bed materials. In well-defined solids mixtures where the components have distinct permittivities, ECT can map the solids phase concentration, the temperature, and the moisture distributions [16,33], thus allowing for tracking of heterogeneous reaction rates in space and time. These ideas are yet to be matured, while future research will focus on combining ECT with spectroscopic methods (near-infrared [NIR] or Raman) to enable direct chemical analysis.

X-ray imaging is also being increasingly used for spatially resolved study of chemical reactions at the particle or intra-particle level, due to its penetration capacity and the range of different possible interactions (absorption, diffraction, fluorescence). An example of this is the characterization of catalysts through X-ray absorption spectroscopy, X-ray diffraction spectroscopy, and X-ray photoelectron spectroscopy [24,34]. Sufficient spatial and temporal resolution to cope with highly dynamic systems such as FBs is yet to be achieved.

Temperature

Understanding of heat transfer in FBs requires assessment of the temperature field in terms of inter-phase differences, spatial gradients, and dynamics. Although thermal homogeneity is often assumed, temperature gradients can be significant at the meso- and microscale and at different time scales [35]. Assessment of temperature based on convection (contact) methods, such as thermocouples, is intrusive, lacks accuracy, and suffers from poor spatial and temporal resolution. Consequently, replicating thermal conditions becomes difficult, and connecting them to conversion variables requires rough assumptions. Current research targets spatial and temporal resolution to ultimately assess heat transfer coefficients. Some examples of techniques that contribute to these aims are:

Infrared (IR) thermography assesses the temperature of a body based on its emissivity and infrared radiance. Sensor arrays are used to obtain 2D measurements with good accuracy (2% deviation) and a temporal resolution of tens of hertz. IR thermography has been of common use in pseudo-2D FBs [36,37] and in assessing heat transport and bed-to-surface heat transfer [38]. Deriving from this technique is the modulated photothermal radiometry, which has been implemented in the direct assessment of thermal transport in FB solar receivers [39]. AI is becoming fundamental to making these measurements faster and more accurate (reducing the dependency on emissivity). Recent advancements involve the development of multi- and hyperspectral imaging, which yields IR spectra at every position (pixel) and opens the possibility for simultaneous identification of the concentration and temperature of different materials.

Color pyrometry measures thermal radiation in the visible or near-infrared spectrum using two or more discrete wavelength bands. It assesses temperature based on the ratio of the emitted intensities. Multispectral cameras are used to assess 2D temperature fields. Increasing the number of bands reduces the dependence on emissivity and background radiation for more robust measurements, especially in turbid environments. This technique has been particularly useful to study FBs in high-temperature processes (e.g. fuel devolatilization) [40–42]. Color pyrometry is developing towards higher spatial (hundreds of μm) [43] and temporal (ns) resolutions.

Improving operability

In the large-scale, current developments in sensing techniques are slowly opening up the possibility of directly acquiring variables of interest (residence times, flow rates, particle temperature, stage of conversion), instead of inferring them indirectly from global parameters (product quality, process temperature, pressure drop), and having a positive impact on the reliability of such measurements. Furthermore, given the growing interest in developing processes suited to handle unforeseen disruptions and operate flexibly, it is clear that future monitoring systems will require high sensitivity, fast response times, and in-line implementation in order to achieve pertinent reaction times and to guarantee safe operation. Here, a few techniques are discussed in terms of their readiness and capability levels.

Vertical pressure drop is the most commonly used monitoring parameter in industrial FB units, as it correlates with the mass of fluidized material. Advanced pressure-based measurements exploit this

principle and combine it with the statistical treatment of the signal, both in the time (time-averaged pressure, standard deviation, cycle length) and the frequency (spectrum, fast Fourier transform, and wavelet) domains [44], to investigate transient phenomena or malfunctions in industrial units [45–48], and for fluid-dynamic characterization [48]. The ambition is to formulate methods robust and sensitive enough to be incorporated as regular control parameters or as an alarm protocol. The success of these ideas relies on achieving adequate signal quality (including tap maintenance and signal denoising protocols) [48,49].

Millimeter radars are well known in industry for contactless level measurements in tanks, silos, and blast furnaces. Less well known is their use for monitoring vibrations in industrial equipment. Since the radar signal is unaffected by temperature and the beam can penetrate distances of several meters, it holds potential to assess of solids flows in large-scale FBs. Achieving real-time signal processing appears as a natural development for this type of radar measurement.

The THz laser exploits the fact that water (a polar molecule) absorbs THz radiation strongly enough to measure water content and water distribution through spectroscopy and imaging techniques, respectively [50,51]. Recently, measurements of the water content were achieved at 250 °C in raw gas using the quantum cascade method to generate the laser. THz laser yields high penetration with low energy; most importantly, it can be used at comparatively high temperatures in an online fashion. This measurement would greatly aid the control of processes like thermochemical conversion, metal reduction, and drying. Nevertheless, the interaction between water molecules and the THz waves needs to be fully understood to achieve the required accuracy.

Among the tomographic techniques tested or implemented in industrial installations, ECT stands out in comparison to magnetic resonance imaging and X-ray tomography for its ability to differentiate solids and estimate moisture content at a comparatively lower cost, and despite its lower temporal and spatial resolutions [52]. Its lower complexity and potential hazard are also valued for incorporation in industrial process control strategies. Recent advancements have focused on developing robust sensor designs capable of withstanding high temperatures and pressures and improving the quality of the reconstructed images [19,20]. Yet to be overcome is the high computational requirements needed to produce high-resolution images in real-time, for which the incorporation of dedicated hardware accelerators is being considered [52,53].

Table 1

Summary of the techniques included in the present work, illustrating current development fronts and potentially achieved capabilities in the sensing and monitoring of fluidized beds.

Aspect assessed	Technique	TIL*	Main feature/s	Main current limitation/s	Currently under development	Potential for
Improving under-standing	Solids flow					
	Trajectory-based techniques					
	Microelectromechanical systems (MEMS)	R-P	Simultaneous assessment of fluid properties (pressure, temperature, chemical composition)	- Desired tracer size and density not always achievable - Power supply - Tracer does not withstand abrasion and high temperatures - High safety requirements	Further reduction of tracer size	Simultaneous assessment of particle-surroundings mass, momentum and heat transfer
	Positron emission particle tracking (PEPT)	R	Temporal resolution (kHz) and spatial accuracy of up to 0.5 mm		- Labeling of μm size particles - Increasing sensitivity and accuracy	Direct assessment of particle-particle and particle-wall collisions
Concentration-based techniques	Magnetic particle tracking (MPT)	R-P	- Study of nonspherical particles - Low cost	- Measurement accuracy decreases with distance from sensors - Temperature limitation - Non-uniform sensitivity - Demanding protocols for quantitative image reconstruction - Expensive instrumentation - High safety requirements	- Reducing tracer size - Increasing spatial accuracy	Online trajectory reconstruction
	Electrical capacitance tomography (ECT)	P-I	- Low cost - High speed - High penetration		- Optimization of sensors design for large-scale 3D image reconstruction	Multi-modal tomography for comprehensive flow property measurement
	X-rays imaging	R-P	High spatiotemporal resolution		- Increasing temporal resolution - Fast and large-scale tomographic measurements	Highly resolved 2D images in dense bed for reactive systems
	Millimeter radar	P	Simultaneously acquired solids concentration and velocity distribution	- Multiple scattering and signal attenuation in dense regions - Complex calibration and signal processing	Generalized methods for assessment of concentration	Resolution of the particle-scale momentum equations
Chemical composition	Fourier Transform Infrared (FTIR) spectroscopy	I	Multicomponent (simultaneous assessment of several species)	- Spectral overlaps among chemical species - Dust interference - Difficult quantitative calibration in heterogeneous systems - Indirect measurement	- Improving selectivity - Overcoming limitation of overlapping spectra	3D mapping - Coupling with tomographic methods
	Electrical capacitance tomography (ECT)	P-I	(Limited) chemical specificity		Mapping temperature and moisture distribution	Multi-modality tomography, combining ECT with spectroscopic methods, like NIR or Raman
	X-rays imaging	R-P	High penetration	- Limited chemical selectivity - Comparatively high cost	- Improving sensors and algorithms for higher selectivity 2D multi- and hyperspectral images	- Simultaneous assessment of local hydrodynamics and reaction progress - Simultaneous identification of materials
Temperature	IR thermometry	I	High accuracy	- Surface-temperature only - Affected by emissivity uncertainty		
	Color pyrometry	D-I	Robust in turbid environments	- Requires optical access - Permissivity uncertainty affects accuracy	Increasing resolution	Dynamic measurements

Table 1 (continued)

Aspect assessed	Technique	TIL*	Main feature/s	Main current limitation/s	Currently under development	Potential for
Improving operability	Advanced pressure-based measurements	I	– Robustness	– Indirect information only – Sensitive to sensor placement and condition	– Improve signal quality – Refinement of signal treatment	– Inline methods
	Millimeter radar	P	– Direct acquisition of solids concentration, velocity, flux	– High attenuation in dense regions – 1D resolution	– Adjusting instruments to industrial constraints	– Real-time signal processing
	THz laser	R-P	– High penetration – Online	– Strong attenuation by moisture and dense particle clouds	– Improving accuracy	– In-line implementation
	Electrical capacitance tomography (ECT)	P-I	– Comparatively lower complexity (among tomographic techniques)	– High equipment cost – Computational demanding reconstruction protocols	– Improving sensor robustness – Improving image quality	– High-resolution, real-time images

* TIL: Technology Implementation Level (R=research scale, P=pilot scale, D=demonstrated at industrial scale, I=commercially implemented or routinely used in industry).

Conclusion and outlook

Sensing in the field of fluidization has extensively benefited from the advances in micro-component fabrication and particle and electromagnetic radiation technologies. In the research, this has led to a definitive shift towards non-invasive methods, while the significant increases in temporal and spatial resolution (reaching μm -mm and ns-ms scales) enable knowledge mining at the meso- and microscales. Although challenges remain in terms of signal quality, where sensitivity needs to be increased along with the volume of data and the data processing speed, methods for online mapping of variables (3D for fluid-dynamics and 2D for thermal and chemical parameters) are now a reality. The combination of techniques is being attempted as a general strategy for understanding the interplay of multiphysics, and particularly to assist the investigation of reactive systems and multicomponent beds. In industrial operations, more direct, nonintrusive techniques are becoming available for use at high temperatures and increasingly larger volumes. Further testing under industrial conditions is essential to improve robustness and confirm reliability. No less important is to accelerate data processing algorithms to enable inline measurements. Common to most of the techniques and levels of implementation is the need for fast handling of large data flows, for which ML (especially DL) emerges as an essential tool. Table 1 summarizes the main features, expected developments, and potential of the techniques discussed here to illustrate the progress of sensing methods in FBs.

Data Availability

No data were used for the research described in the article.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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