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# Measurement of ferromagnetic particle concentration for characterization of fluidized bed fluid-dynamics

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ABSTRACT

A method based on indirect measurement of magnetic properties of solids is proposed and investigated to be implemented in existing cold flow models of fluidized beds as a system for the determination of bed density and particle residence time distribution. The current work reports the fundamental principles for the measurement method and presents a first approach to the practical implementation which is based on inductance measurement of a simple coil. The characterization of the materials is reported and the fluid-dynamic suitability of the chosen ferromagnetic tracer particles is confirmed. The results clearly show the reproducibility of the measurement and evidence the capability to measure the concentration of tracer particles in an accurate way. The bed density of a fluidized bed was successfully determined using the designed apparatus. The method proposed appears promising and easily implementable for measurements of void fraction, residence time distribution of solids (RTD) and circulation rate in fluidized bed cold flow models.



## 1. Introduction

The use of gas–solid reactors is widely spread in numerous industries; more precisely, circulating beds are present in many applications and processes. The optimization of profitability in such processes strongly depends on the contact efficiency and the contact time between gas and solid phases and hence on the residence time of gas and particles. Given the characteristics of the reactions taking place and the expected product yields, the unit itself and the operating conditions must be set in order to achieve the necessary residence times. However, the complexity of the flow structure in circulating fluidized beds (CFBs) often makes residence time distribution (RTD) analysis difficult for both, experimental and theoretical attempts.

The present work investigates the feasibility of a measurement method for the determination of tracer concentration, which entails the necessary characteristics to be applied as a technique for residence time measurements at cold flow model conditions (room temperature, atmospheric pressure). The following features are sought:

- Non invasive: the measurement should be possible externally.
- High resolution: detection of small amounts of the tracer material should be possible at a time resolution in the range of milliseconds.
- Online measurement: monitoring of the tracer concentration should be possible in real time.
- Fluid-dynamic consistency: neither the selected tracer particles nor the measurement should modify the flow conditions.

Regarding these guidelines, a simple coil arrangement is proposed as first approach to the system and its ability for quantitative detection of ferromagnetic particles is evaluated. Furthermore, the system is tested under fluidized bed conditions.

## 2. Background

### 2.1. Tracer measurements in fluidized beds

In gas–solid fluidized bed, the residence time for each of the phases is important for many applications. In general, gas residence time has been comparatively more widely studied; results for diverse experimental units and operating conditions have been reported [1]. The techniques for tracer gas injection and detection are numerous; this is primarily due to the facility for finding a tracer gas with a fluid-dynamic behavior similar to the original fluidization medium, and to the ability to introduce such tracer without perturbing the global performance of the unit.

On the side of the solids, tracer experiments are not always simple to perform. Although several systems have been developed and studies have been carried out, most of these techniques are not transferable to other units or operating conditions. Harris et al. [2] compiled a detailed review of the most suitable methods used until now in the measurement of solid RTD and mixing behavior in circulating fluidized beds (CFBs). They proposed a classification of techniques in disruptive and non-disruptive of the flow conditions of the system.

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Disruptive techniques are considered those introducing contaminants in the solid inventory. Whereas non-disruptive are techniques not adding permanent contaminants to the bed; which are in general more desirable methods. Table 1 presents a summary of the techniques reviewed by Harris et al. along with their principal characteristics.

From the review of the reported experimental methods, advantages and disadvantages can be disclosed. Considering them and in addition to the fact that the system is planned to be implemented in cold flow models, the requirements and expected features of the RTD measurement system, can be determined. In an impulse-response tracer measurement, a very small amount of the tracer material is added to the system under stable operating conditions and its concentration is measured at a certain point downstream.

Regarding tracer particles, it is required that they hold very similar fluid-dynamically-relevant properties in comparison with the bulk of bed material and that neither the materials nor the devices should involve health risks. And with regard to the measurement system, some of the most important conditions desired are listed below:

- The measurement should be reproducible and repetitions should be possible within reasonable periods of time.
- Ideally, calculation of tracer concentration (and hence RTD) should be possible without need of intricate assumptions or corrections.
- The detection device or method should not imply any disruption of the internal flow pattern (particularly, pressure and inventory should not be effected).
- Measurement should be possible under steady state operation conditions.
- The response of the detection method should be fast enough to capture the features of RTD, which are usually very short.

Concerning magnetic tracer measurements, Fitzgerald et al. [14] made a first reported test of magnetic tracers for study of solids mixing

**Table 1**
State of the art in solids mixing and solids residence time distribution methods. Based on the work of Harris et al. [2].

| Classification | Measurement principle | Author(s) | | Details of method (advantages and disadvantages) |
|---|---|---|---|---|
| Disruptive techniques | Chemically different tracers | Rhodes et al. | [3] | Impulse injection of sodium chloride tracer, sampling at three positions and determination of concentration by conductivity. Not suitable for fast response, time consuming procedure. Intrusive sampling and injection devices. |
| | | Bader et al. | [4] | Impulse injection of sodium chloride tracer, multi-injection system (four injection points), sampling at three positions. Not suitable for fast response, time consuming procedure. Intrusive sampling and injection devices. |
| | | Zheng at al. | [5] | Pulse injection with high pressure air of FCC catalyst saturated with sodium chloride. Sampling at various positions and concentration determined by conductivity. Intrusive sampling and injection devices. Maximum resolution of 0.5 s. |
| | | Talmor und Benenati | [6] | A cation exchange resin in sodium form is used as tracer, the bed material is the same resin in hydrogen form. Concentration determined by chemical analysis. Procedure is time consuming and disruptive to the flow. Bed material and tracer of very similar properties. |
| | | Bai et al. | [7] | Bed material soaked in an organic substance injected as tracer using a pulse of air. Solid concentration calculated from the gas phase analyses (entails considerable uncertainty). |
| | Radioisotope tracers | Patience et al. | [8] | Radioactive sand ($Si^{28}$) injected with an air pulse. Detection using a sodium iodide scintillation counter. Injection could not be optimized. Fast time response, potential health risks. |
| | | Ambler et al. | [9] | Pneumatic injection of $Ga^{68}$. Detection by scintillation. Fast time response, potential health risks. |
| | | May | [10] | Tagged FCC catalyst (by $I^{132}$) injected (steady state injection). Monitoring by scintillation counters at various locations. Fast time response, potential health risks. |
| | | Hull and von Rosenberg | [11] | Tagged FCC catalyst (by $Zn–Nb^{95}$) injected. Fast time response, potential health risks. |
| | | Lin et al. | [12] | Particles containing radioactive $Mn^{56}$ used as tracer. Fast time response, potential health risks. |
| | Magnetic tracers | Avidan and Yerushalmi | [13] | Ferromagnetic tracer powder injected by air pulse. Detection based on a bridge circuit previously developed (Fitzgerald et al. [14]). |
| | | Sutherland | [15] | Nickel as tracer material separated after sampling using a roll magnetic separator. Not suitable for fast response. |
| | Subliming tracer particles | Bellgardt and Werther | [16] | Pellets of solid $CO_2$ as tracer fed using a screw feeder. Concentration measured whether by temperature or by composition of the gas phase. Inferred concentration contains uncertainties. Bed material and tracer are not fluid-dynamically similar. The method was also used for simulation of reacting particles. |
| | Particle sampling | Bai et al. | [17] | Non-isokinetic sampling. Sampling error $\pm 20\%$. Sampling method disturbs the flow. |
| | | Chesonis et al. | [18] | Petroleum coke tracer in an alumina bed. Sampling at five locations along the riser. Non-steady state sampling. Sampling method disturbs the flow. |
| | | Hirschberg et al. | [19] | Mixture of quartz sand and iron ore. Continuous sampling at different locations in the riser. Sampling method disturbs the flow. Uncertainties of the method not quantified. |
| | Particle sizing techniques | Wang et al. | [20] | Particles of a narrow size interval used as tracer. Sampling at the cyclone underflow, concentration determination by sieving. |
| | Colored tracer techniques | Lim et al. | [21] | Colored bed particles as tracer. Detection by image analysis method (DDC video camera and computer recording system). Only suitable for measurements close to the wall. |
| | | Bi et al. | [22] | Orange colored lignite pellets. |
| Non-disruptive techniques | Optical methods | Brewster and Seader | [23] | Particles covered with a phosphorescent pigment are illuminated and injected with an air pulse. Detection is done with a series of photomultimeter tubes. Cost effective but not suitable for high pressure systems. |
| | | Roques et al. | [24] | Phosphorescent pigment particles are activated with a high intensity pulse of light and detected using several light detectors. |
| | | Wei et al. | [25] | Bed particles covered with phosphorescent material exited by a light source. Light detectors used to determine concentration. |
| | | Kojima et al. | [26] | Fluorescent dye-tagged FCC particles introduced in the system and detected at various stages by optical fiber probes. The injection air pulse method introduces uncertainties. |
| | Thermal methods | Thiel and Potter | [27] | The bed is heated and cooled at different positions simultaneously. The temperature is measured at different points and the heat transferred to the bed is calculated. |
| | | Valenzuela and Glicksman | [28] | Heated bed particles used as tracer. Temperature is measured. Needs complicated assumptions for RTD calculation. |
| | Single particle tracers | Weinell et al. | [29] | The trajectory of a single radioactive particle is monitored along the unit using scintillation detectors. |
| | | Stellema et al. | [30] | |
| | | Abellon et al. | [31] | |
| | | Godfroy et al. | [32] | |
| | | Matsuda et al. | [33] | High speed video system (2000 to 3000 frames/s) for recording particle clusters. |