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# Characterization of the pneumatic behavior of a novel spouted bed apparatus with two adjustable gas inlets

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**Abstract**

Recently the importance of spouted bed technology has significantly increased in the context of drying processes as well as granulation, agglomeration or coating processes. Within this work the fluid dynamics of a novel spouted bed plant with two adjustable gas inlets is investigated. By analysis of gas phase pressure fluctuation spectra by means of fast Fourier transformation algorithm and quantitative particle image velocimetry (PIV) measurements, different operation ranges will be identified and depicted graphically. A stable spouting range will be identified if a uniform and circulating particle motion without occurrence of dead zones is observable resulting in equal gas phase pressure fluctuations. Particle velocity vector maps as well as root mean square (rms) velocity plots provided by the PIV measurements confirm the results of the determination of the stable spouting range by analysis of the gas phase pressure fluctuations.



*Keywords:* Spouted bed; Pressure fluctuation; *Re–G–Ar*-diagram; Fast Fourier transformation; Particle image velocimetry

## 1. Introduction

In food, pharmaceutical and chemical industry, fine and polydisperse solids are treated and produced, respectively. Analogous to conventional fluidized beds, spouted beds are well known for their good mixing of the solid phase and also for their intensive heat and mass transfer characteristics between the fluid phase (gas) and the solid phase yielding nearly isothermal conditions. The special flow structure of a spouted bed is characterized by a simple apparatus construction. The main difference of spouted beds in comparison with conventional fluidized beds is the variable cross-section area of the apparatus as a function of the apparatus height. Like the fluidized bed technology, the spouted bed technology can be applied for mixing of particulate systems, for heat and mass transfer processes, e.g. cooling, drying (Devahastin et al., 1998; Kmiec et al., 1994; Kuts and Akulich, 2002; Marreto et al., 2006), calcinations (Chebotkevich and Sidorov, 1975; Park et al., 2006), combustion, gasification as well as for complex multiphase processes like spray granulation (Hatano et al., 2004; Horio et al., 1989; Liu et al., 2005; Scheuch et al., 1996), agglomeration (Jacob et al., 2005; Kikuchi et al., 1985; Vuthaluru and Zhang, 2001), particle layering and coating (Ando et al., 2000; Kfuri and Freitas, 2005; Paulo Filho et al., 2006) and also for chemical reactions.

Contrary to conventional fluidized beds, the fluidization gas in a spouted bed is not supplied into the apparatus equally distributed over a gas distributor plate, but enters the process chamber from the bottom through the narrow slits as a gas jet with high gas velocities. Particles located in the process chamber are entrained by the gas jet to the top of the apparatus and reach then the conical-shaped annulus zone where they slide back downwards due to gravity. Subsequently, the particles enter the jet zone again where they are conveyed upwards once again, etc. Thus, a characteristic and continuous particle circulation is effected and a good contact between

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the fluid and the solid phase is achieved. Hence, the spouted bed technology is predominantly applied for solid particle systems that are difficult to fluidize in a stable manner, i.e., for particle systems with:

- a very broad particle size distribution causing segregation,
- very small and light (Geldart class C) or very big particles,
- non-spherical particles (i.e., length/diameter ratio $\gg 1$),
- sticky surfaces,
- uneven and rough surfaces.

The knowledge of the stable fluid dynamic operation range of the spouted bed, which is smaller compared with conventional fluidized beds, is of importance for operating the apparatus. In the recent literature, the pneumatic operation ranges are depicted with the aid of different diagrams, e.g. $\Delta P = f(\text{velocity})$ (Markovski and Kaminski, 1983; Olazar et al., 1992), $H_0 = f(\text{velocity})$ (Olazar et al., 1992), velocity $= f(\text{diameter})$ (Čatipović et al., 1978; Kunii and Levenspiel, 1991) or by *Re–G–Ar*-diagrams (Mitev, 1979; Piskova, 2002). The pneumatic operation ranges of spouted beds are usually characterized in a quantitative manner by analysis of gas phase pressure fluctuations.

Zhong and Zhang (2005) measured these pressure spectra with a multi-channel pressure detector and simultaneously they recorded images with a CCD-camera for visual analysis of the flow structure. Leu and Lo (2005) did extensive investigations on the pressure fluctuations in conical spouted beds. For description of the different pneumatic operation ranges, they varied the particle material size and angle of repose, as well as the initial bed height. Silva et al. (1999) also analyzed the different operation ranges by means of gas phase pressure fluctuation measurements. By performing Fourier analysis on these pressure spectra, different operation ranges were identified. Link et al. (2005a,b) did experimental investigations on the one hand and 3D-Euler–Lagrange simulations on the other hand for studying the dynamic behavior of spout fluidized beds. They concluded that the applied discrete particle model is able to predict the characteristics of the most operation ranges fairly well. However, differences between experiments and simulations were observed at the so-called "slugging" bed operation state. Link et al. (2005a,b) concluded that these deviations are probably due to small deviations in the model for the gas-particle interaction, which does not account for local inhomogeneities. Freitas et al. (2004) analyzed the pressure fluctuations by means of statistical chaos methods and concluded that different operating ranges can be identified by these fluctuations if visual observations are not possible.

Investigations on the pneumatic behavior of spouted beds have also been conducted by means of non-intrusive methods. Without influencing the processes, information of the velocity field and the distribution of the dispersed solid phase in the apparatus can be obtained, e.g. by digital imaging or by detecting radiative measurements. Link et al. (2004) applied particle image velocimetry (PIV) measurements for the investigation of the pneumatic behavior of a spout fluidized bed. Comparisons with a three dimensional discrete particle model showed similar flow structures. The main drawback of PIV measurements applied to fluidized systems is that only superficial solid velocities near the apparatus walls can be obtained. Insight into the third dimension is not possible. Karlsson et al. (2006) marked the disperse solid phase with a fluorescent fluid and subsequently they made high speed video recordings in an acryl-glass spouted bed with a central riser ("Wurster-principle") to get information about particle trajectories and maximum particle rising heights in the jet zone. Link et al. (2005a,b) also performed positron emission particle tracking (PEPT) experiments to measure particle trajectories. The spout fluidized bed was located between two detectors, which measured gamma rays that were emitted by the particles. Thus, the particle position could be obtained as a function of time. The drawback of this technique is that only one particle can be tracked and hence, the effort to gain information on the dynamic behavior of the entire bed is huge.

The focus of this work is the investigation of the pneumatic behavior of a novel spouted bed apparatus with two horizontal and adjustable slit-shaped gas inlets. By measured gas phase pressure fluctuations and Fourier analysis on these spectra, the pneumatic stable operation range will be identified and depicted in the dimensionless *Re–G–Ar*-diagram by Mitev (1979). The particle system, the gas throughput and the cross-section area of the gas inlets will be varied. With the results of this work, a comparison will be made with stable operating ranges of other fluidized beds or spouted bed apparatuses, which already have been characterized by several authors (Kojouharov, 2004; Mitev, 1979; Piskova, 2002; Piskova et al., 2003). To provide a better understanding of the flow structure and the circulating particle motion at different pneumatic operation ranges, unsteady as well as time averaged particle velocity distributions were measured through PIV experiments.

## 2. Fundamentals and types of spouted beds

### 2.1. Types of spouted bed apparatuses

Only a few publications are related to the geometric aspects of spouted bed apparatuses in comparison to conventional fluidized bed apparatuses. Particularly, there are different types of spouted bed constructions which were adapted to the special process application (Fig. 1).

The spouted bed processes in conical or cylindrical apparatuses can be distinguished by some specific features. In conical apparatuses the bed height and the dense particle region in the annulus zone are marginally influenced by the gas jet. The fluidization gas is supplied from the bottom through one or two gas inlet openings, e.g. by a nozzle. The inlet gas velocity must be high enough, that a central hollow space is formed, where the particles are entrained and upwards conveyed. At a sufficient high gas velocity, the particles located in the core jet zone are catapulted above the bed and distributed in radial direction whereas the particle velocity decreases. Then the particles fall down into the annulus zone due to the gravity, like in a