Powder Technology 292 (2016) 108–121

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Review

A review of pulsed flow fluidisation; the effects of intermittent gas flow on fluidised gas–solid bed behaviour

Emma Ireland, Kate Pitt, Rachel Smith *

Department of Chemical and Biological Engineering, The University of Sheffield, Sheffield, UK

ARTICLE INFO

Article history:
Received 10 September 2015
Received in revised form 2 January 2016
Accepted 14 January 2016
Available online 18 January 2016

Keywords:
Pulsed flow
Fluidised bed
Gas–solid flow
Fluid dynamics
Fluidisation

ABSTRACT

Pulsed flow fluidisation involves the use of either a relocating or intermittent gas stream flowing through a bed of particles, and produces a range of fluidisation effects dependent on the type and frequency of the pulsation. Pulsed flow has been shown in a range of studies to improve mixing and heat transfer, and reduce agglomeration. However these effects are dependent on the pulsation frequency, particle characteristics and other process conditions.

Research into pulsed flow fluidised beds has demonstrated a pattern for an improvement in heat and mass transfer rates, specifically in Group A and B particles, reduced slugging and channelling in wet or cohesive particles, and an improvement in the fluidisation of hard to fluidise materials such as Group C powders. In addition, reduced energy consumption from lower minimum fluidisation rates under pulsed flow further indicates a potentially significant efficiency improvement. These findings, however, highlight needs for correlations to be drawn between the effects studied and the pulsation method and frequencies applied.

Here, we present a comparison of continuous and pulsed flow fluidisation, and discuss effects such as minimum fluidisation velocity, bubble characteristics and bed expansion. Areas for future research have been identified in order to build a better picture of how pulsed flow frequencies and particle characteristics interact, aiding the development of this technology within industry.

Contents

---

* Corresponding author.
E-mail address: rachel.smith@sheffield.ac.uk (R. Smith).

http://dx.doi.org/10.1016/j.powtec.2016.01.018

1. Introduction

Fluidisation is the process of passing a fluid through a packed bed of particles at a velocity greater than that required to support the weight of the particles. This lifts the particles, entraining them in the fluid flow. Fluidised beds are widely used in manufacturing and processing industries, and common applications include heat transfer, drying, coating, combustion, fluidised bed reactors and catalytic cracking [1]. The process of entraining the particle bed in a fluid flow produces a high gas–solid interface area, which is a significant advantage over alternative technologies such as fixed bed reactors [2]. However, manufacturing intensification, such as increasing plant energy efficiency requirements, have led research and development in the technology to develop a range of improvements, such as:

- an increasing use of particles in Geldart groups C (<50 μm) and D (>2 mm), as currently fluidised beds are best suited to a particle size range of 50 μm–2 mm (A and B Geldart classification groups)
- an increased range of processes, such as drying larger biomass particles for bioenergy applications or the combustion of wide size distribution municipal waste in a fluidised bed reactor
- an increase in the efficiency of operating processes to conserve resources, notably the energy required for supplying pressurised air and heat, or eliminating the need for stirring paddles or other mechanical components

Research and development in fluidised bed design has encompassed such concepts as acoustic vibration [3], centrifugation [4], mechanical vibration [5], pre-mixing with coarse particles [6] gas injection [7] and pulsed airflow [8] to reduce energy requirements and decrease process times. Of these, pulsation of the fluidising gas flow has been found to increase mixing [9], reduce agglomeration [8], increase combustion efficiency [10] and increase drying rates [11], and is the focus of this review article.

Pulsed flow fluidisation is a specialist subject studied by many fluidisation research groups (e.g. [8,12-15]). The addition of a pulsed air flow in a fluidised bed has been investigated since the 1960s. Pulsed flow fluidised beds differ from other fluidised bed design variations because they feature an intermittent incoming gas flow in all or part of the flow.

Fluidisation is a chaotic process, characterised by complex hydrodynamic behaviour [15]. For this reason, pulsed flow fluidisation research has been frequently described as a method to introduce control [16]. For example, Coppens [17] likens pulsation to a nature-inspired method of increasing dynamic self-assembly, as it has been demonstrated to produce effects such as ordered [18] or smaller [19] bubbles.

Early research was conducted by Massimilla et al. [20] who studied the average pressure drop for different pulsation frequencies in a steady condition bed. The authors found that they could vary the fluidisation quality from intermittently fluidised to fully fluidised by increasing the pulsation frequency incrementally. Kobayashi et al. [21] continued the theme in their study on bed expansion by describing a trend for greater expansion under pulsed flow compared to continuous flow, linking increased gas velocities and higher frequencies with the highest bed expansion levels. Wong & Baird [22] also began researching pulsed flows by monitoring pressure drop over time, finding that continuous flow operating conditions produced regular pressure peaks, indicating a natural fluidising pressure frequency. Therefore, the authors were able to match the imposed pulsation frequency to that found in the continuous flow bed, producing bed expansion values greater than under any other imposed frequency.

There has been a steady increase in research output on the influence of a pulsed gas flow on fluidised bed behaviour, which has produced a range of theories and explanations for the differences between pulsed and continuous flow regimes. Both computational (e.g. Nie & Liu [23]) and experimental (e.g. Zhang & Koksal [24]) methods have been used to study these theories, using a range of indicators to support their argument, such as:

- gas–solid contact
- heat or mass transfer
- gas retention time
- slugging
- channelling
- agglomeration
- drying
- energy use

Several pulsed flow fluidisation studies have found significant improvements in bed performance when comparing pulsed and continuous flow fluidisation and have consequently been cited frequently as justification for further research. For example, Bokun & Zabrodski [25] found an increase in heat transfer coefficients for pulsed flow regimes over continuous flow regimes, and concluded that for the same heat transfer coefficient, pulsed flow used 30–40% less volumetric gas flow. Similarly, at superficial gas velocities greater than the minimum bubbling velocity, Zhang & Koksal [24] found a heat transfer improvement of up to 33% using a pulsation frequency of 7 or 10 Hz over continuous flow, and Gawrzynski et al. [26] reported a >50% energy saving when applying pulsed flow to an upscaled industrial study on drying pharmaceutical granules. Reductions in the minimum fluidisation velocity (U_{mf}) by 33% in Group A/B particles [27] and 76% in Group C particles [8] suggest further sizeable energy savings.

Despite early interest from studies including Massimilla et al. [20] and Bokun & Zabrodski [25], an increasing number of applied research projects, and a growing number of numerical simulation papers focused on the benefits of applying pulsed flow to fluidised bed systems, industrial use of the technology has been limited. This can be explained by a range of factors:

- Slow industrial machinery turnover due to long mechanical lifespans and a tendency for manufacturing plants to employ non-specialists for single machines such as fluidised bed dryers [28].
- Complexity of the pulsed flow concept related to different forms of pulsed flow generation and application to suitable particle sizes and materials.
- The effects of pulsed flow differ greatly depending on the pulsation frequency and particles studied [24].
- Many pulsed flow and material combinations show no effects on bed outcomes, and the relationship between pulsation frequency and fluidisation behaviour is frequently unclear, e.g. Reyes et al. [29].

The focus of this review is to identify the effects of pulsed flow on fluidisation dynamics. It covers fluidising gas flow pulsation, and does not attempt to broach the subjects of pulsed heat, vibration or pulsed liquid–gas-solid beds or flow in pipes, all of which are reviewed elsewhere [30–32]. In addition, the concept of a pulsed flow introduced to a fluidised bed in an opposing stream, such as that investigated by Pence & Beasley [33,34] is not considered, as the effect produced across the distributor plate is not comparable to pulsed flow introduced in the main fluidising gas flow. Computational modelling of pulsed flow fluidisation is developing into a field all of its own (e.g. [10,35]), and references are made to the results of such studies, without detailing the methods used to reach them. An introduction to the methods of installing a pulsed flow to a fluidised bed is presented in Section 2, followed by some suggestions to describe the fluid mechanic mechanisms that control bed behaviour. A review of the various fluidisation behaviour indicators is presented in Section 3, and a summary of how these relate to each Geldart particle classification group in Section 3.2.