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Vinayak S. Sutkar
Eindhoven Univ. of Technology, Netherlands

Tom J. K. van Hunsel
Eindhoven Univ. of Technology, Netherlands

Niels G. Deen
Eindhoven Univ. of Technology, Netherlands

Vitalij Salikov
Hamburg University of Technology, Germany

Sergiy Antonyuk
Hamburg University of Technology, Germany

See next page for additional authors

Authors
Vinayak S. Sutkar, Tom J. K. van Hunsel, Niels G. Deen, Vitalij Salikov, Sergiy Antonyuk, Stefan Heinrich, and J.A.M. Kuipers

EXPERIMENTAL INVESTIGATIONS OF HYDRODYNAMICS OF A SPOUT FLUIDIZED BED WITH DRAFT PLATES

Vinayak S. Sutkar[1], Tom J. K. van Hunsel[1], Niels G. Deen[1,*], Vitalij Salikov[2], Sergiy Antonyuk[2], Stefan Heinrich[2], J.A.M. Kuipers[1]

[1] Multiphase Reactors Group, Department of Chemical Engineering and Chemistry, Eindhoven Univ. of Technology, PO Box 513, 5600 MB Eindhoven, The Netherlands

[2] Institute of Solids Process Engineering and Particle Technology, Hamburg University of Technology, 21071 Hamburg, Germany

T: +31 40 2473681; F: +31 40 2475833; E: N.G.Deen@TUe.nl

ABSTRACT

In this work, the dynamics of a spout fluidized bed with draft plates is studied to identify the flow patterns by constructing a flow regime map by image analysis and a Fast Fourier transform (FFT) of the measured pressure signal.

INTRODUCTION

In the past few decades, the applicability of spout fluidized beds (also known as spout fluid bed) has been growing for a variety of applications with and without chemical reactions such as drying, coating, granulation, gasification, pyrolysis etc. This is because these beds combine advantageous features of both spouted and fluidized beds. In spout fluidized beds a high velocity stream is allowed to pass through a centrally located spout surrounded by a background or auxiliary low velocity fluidizing gas stream. This combination leads to combined spouting and fluidizing behaviour. A detailed discussion regarding the distinguishing features of spout fluidized beds can be found in Epstein and Grace, (1), Sutkar et al., (2). In spite of this, their applicability has been limited to small operational scales, owing to the complexities involved with operation and control, such as bypassing of the spout gas through the annulus, instability of the spout and limited flexibility to adjust the maximum spouting height and circulation time. These complexities can be overcome by inserting a draft tube that confine the spout gas leading to stable spouting at low flow rates. This is evident from the study of Ishikura et al., (3) and Claflin and Fane, (4). Moreover, for a given static bed height and spout dimension, it is troublesome to vary the spouting height. This operational limitation of spouted and spout fluidized beds can be minimized by inserting a draft tube, which enables flexibility in the maximum spoutable height without disturbing the stable spouting. Furthermore, the insertion of a draft tube in a spout fluidized bed provides an additional flexibility to control the particle velocity, solid fraction and gas and particle residence time by adjusting the operating and geometrical parameters such as the entrainment height (h) and the draft tube dimension.

There are few studies dealing with quantification of the hydrodynamic behaviour of spout fluidized beds with a draft tube. Recently, Nagashima et al., (5) have constructed a flow regime map for glass particles and Soma sand in a semi cylindrical spout fluidized bed with a draft tube. Their flow regime map was mainly based on visual observations and statistical analysis of the pressure drop.

The current study aims at constructing a flow regime map for a pseudo 2D spout fluidized bed with a draft tube (from now on we will refer to this as draft plates) with the aid of high speed image analysis and by measuring the bed pressure drop. The time dependent pressure signals were converted into the frequency domain by using a fast Fourier transformation (FFT). Depending on the magnitude of the mean driving frequency and the occurring events, identical particulate flow patterns were grouped to form a particular regime, which are designated by using the same terminology reported by Nagashima et al., (5).

EXPERIMENTAL INVESTIGATIONS

The dynamic behaviour of a spout fluidized bed with draft plates was determined by capturing high speed images, which are utilized for identifying the flow patterns. In this section, we introduce the experimental setup along with brief observations of the pressure measurement technique.

Experimental Set up

Experiments were conducted in a pseudo 2D spout fluidized bed of dimension $W \times D \times H = 0.14 \times 0.02 \times 1$ m^3, as shown in Figure 1 with a spout dimension of $W_{sp} \times D_{sp} = 0.01 \times 0.02$ m^2. The front wall of the bed consists of a glass plate to enable visual observation of the particulate motion inside the bed and the back wall was made of anodised aluminium. Moreover, two draft plates each with dimension $W_{dt} \times D_{dt} \times H_{dt} = 0.005 \times 0.02 \times 0.32$ m^3 were placed inside the bed at a distance of 0.045 m from the side wall and an entrainment height (h) can be varied in the range of 0.03 to 0.05 m from the bottom. Pressurized air was

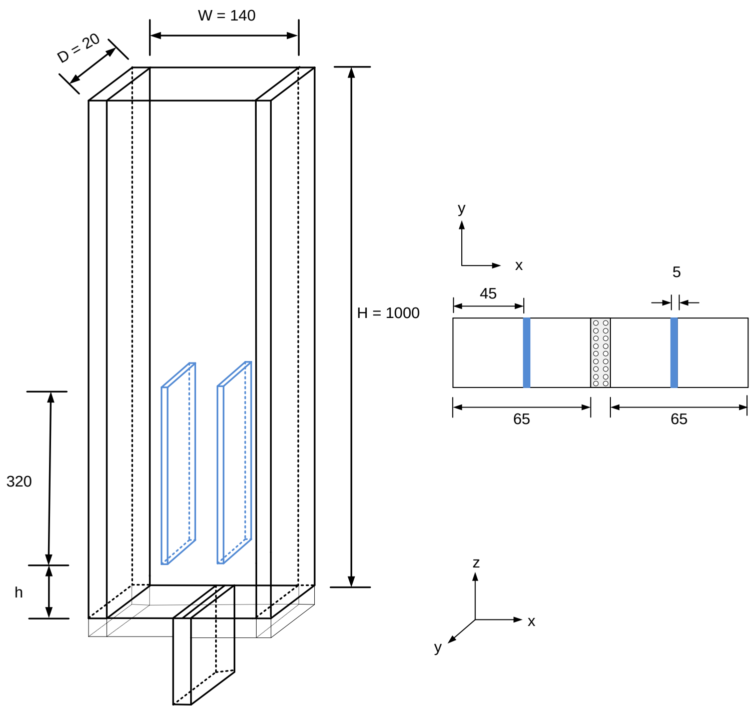

Figure 1. Schematic representation of the pseudo 2D spout fluidized bed with draft plates with an entrainment height (h) (all dimensions in mm).

fed to the bed via three sections at flow rates up to 150 m^3/hr. Electrostatic forces between particles were minimized by maintaining the relative humidity of the inlet air approximately equal to 90%. Digital images were recorded by using a high speed camera (LaVision Imager pro HS). Reflections occurring during the recording were minimised by using LED lamps, illuminating the bed at an angle of 45°. Pressure fluctuations were measured by using two pressure sensors located in the spout and annulus. Experiments were performed by considering glass particles. The physical properties are given in Table 1.

During this study, pressure measurements were done by using sensors located at the backside of the bed, which were connected to a signal convertor through a data acquisition system to a computer. The obtained signals were recorded during four minutes, with 50 Hz data acquisition rate. For each inlet flow condition, images and pressure signals were recorded and transformed into an amplitude-frequency domain. Change in the dominate frequency can be used as a basis for understanding the transitions between flows.

Table 1. Physical properties of the particles used during the experiments.

Property	Glass particle	Unit
d_p	1 ± 0.05	mm
ρ_p	2526	kg/m^3
u_{mf}	0.64	m/s
e_n	0.87	--

RESULTS AND DISCUSSION

For the construction of the flow regime map, the experiments were performed by varying the background velocity from 0 to 1.75 m/s with increments of 0.25 m/s and the spout velocity was varied from 10 to 50 m/s with increments of 5 m/s. Based on the image analysis and pressure drop measurements eight distinct flow regimes, with similar flow patterns were grouped together to from a regime. Here, it should be noted that it is difficult to evaluate the transition between the regimes solely using the image analysis. Critical values of u_{bg}/u_{mf} and u_{sp}/u_{mf} for certain regimes were determined based on the spectral analysis. Additionally, the regimes showing small differences in the FFT spectrum were analysed by visual observations and variation in the pressure drop. The eight distinct flow regimes based on the above criteria were assembled to form a flow regime map, which is shown in Figure 2, displaying instantaneous snapshots for each of the identified regimes.

The obtained flow regimes are designated as: 1. fixed bed; 2. intermittent spouting; 3. spouting-with-aeration (aggregative spout); 4. spouting-with-aeration; 5. fluidized bed; 6. fluidized bed (spout slugging); 7. fluidized bed-spouting-with-aeration (aggregative spout); 8. fluidized bed-spouting-with-aeration (dispersed spout). Each of these regimes will now be discussed briefly.

Fixed bed $(u_{sp}/u_{mf} < 5, u_{bg}/u_{mf} < 1)$

Fixed bed behaviour was observed at low spout and background velocities, in which particles do change their positions. With increasing the spout and background velocities, the bed height and pressure drop increases linearly up to a certain value with formation of a small cavity in the vicinity of spout near to the distribution plate. In this cavity, internal circulations of the particles were observed without disturbing neighbouring particles.

Intermittent spouting $(u_{sp} / u_{mf} < 30, u_{bg} / u_{mf} < 0.5)$

In this regime, considerable particle displacements were observed only in between the draft plates. As the spout velocity increases, periodic formation and collapse of bubbles takes place near the bottom plate close to the draft plates. These bubbles often propagate vertically leading upward particle movement. It should be noted that, due to the small distance between the draft plates, the bubbles get elongated along the bed height. The particles present on the top of the elongated bubble experience an upward thrust while other particles in the vicinity bubble moves downward. The bed expansion and the rate of bubble formation highly depend on the spout velocity; higher spout velocity results in a cross flow of particles from spout to the annulus above the draft plates. The particles in the annulus remain stationary, due to the low background velocity. During intermittent spouting, the particles are not continuously transported from the spout to the annulus.

Spouting-with-aeration (aggregative spout)$(30 < u_{sp} / u_{mf} < 45, u_{bg} / u_{mf} < 0.75)$
)

In this regime, the generation of a stable spout was observed, in which the particles are continuously transported in an upward direction through the draft plates. After reaching a certain height, particles loose their momentum and flow downward through the annulus forming a fountain like structure. Particle clusters can be seen at the inner surface of the draft plates and often move downwards, due to the low spout velocity. The generation of two or more clusters at the same time can lead to a zig-zag particle motion, which subsequently results in an asymmetric particle distribution at the draft plates top. The particle clusters formed on the inner surface of the left plate results in movement towards the right side of the annulus and vice-a-versa. So, the movement of the particles from the spout to annulus is highly influenced by the rate and size of formed cluster. Moreover, an uneven particle distribution was observed in the annulus due to uneven gas distribution near the draft plates. This may also be due to the presence of clusters, leading to unevenly filling of the left and right side of the annulus. This is due to the low background velocity, resulting in the creation of a path with high resistance for spout gas to pass through the annulus. The initial orientation of the solids and the rate of cluster formation play a vital role in deciding the extent of particles distribution.

Spouting-with-aeration $(u_{sp} / u_{mf} > 45, u_{bg} / u_{mf} < 0.6)$

At higher spout velocities, the particles are blown through the draft plates in a dispersed state without cluster formation. In the spout, the particles are elevated to a higher height as compared with the previous regime, showing a homogenous distribution. After reaching a certain height, particles start decelerating downwards in the annulus. This results in a circulating bed mode with high particle velocities in the spout and low velocity in the annulus. Furthermore, the particles emerging from the draft plates show a tendency towards the right. This primarily depends on the initial particle configurations in the annulus and the generation and eruption of the spout. At the start of the experiments, the spout gas was initially diverted towards the right hand side, withdrawing and transporting more particles from the right hand side.

Fluidized bed *($u_{sp} / u_{mf} < 5, u_{bg} / u_{mf} > 1$)*

In this regime, the particles move in both the spout and annulus due to the high spout and background velocities (u_{bg}, $u_{sp} > u_{mf}$). As the spout and background velocities increase, the particles in the bed are lifted with formation of slugs and/or bubbles either in the spout or the annulus. Additionally, in the annulus there is more intense particle movement due to the formation of more bubbles.

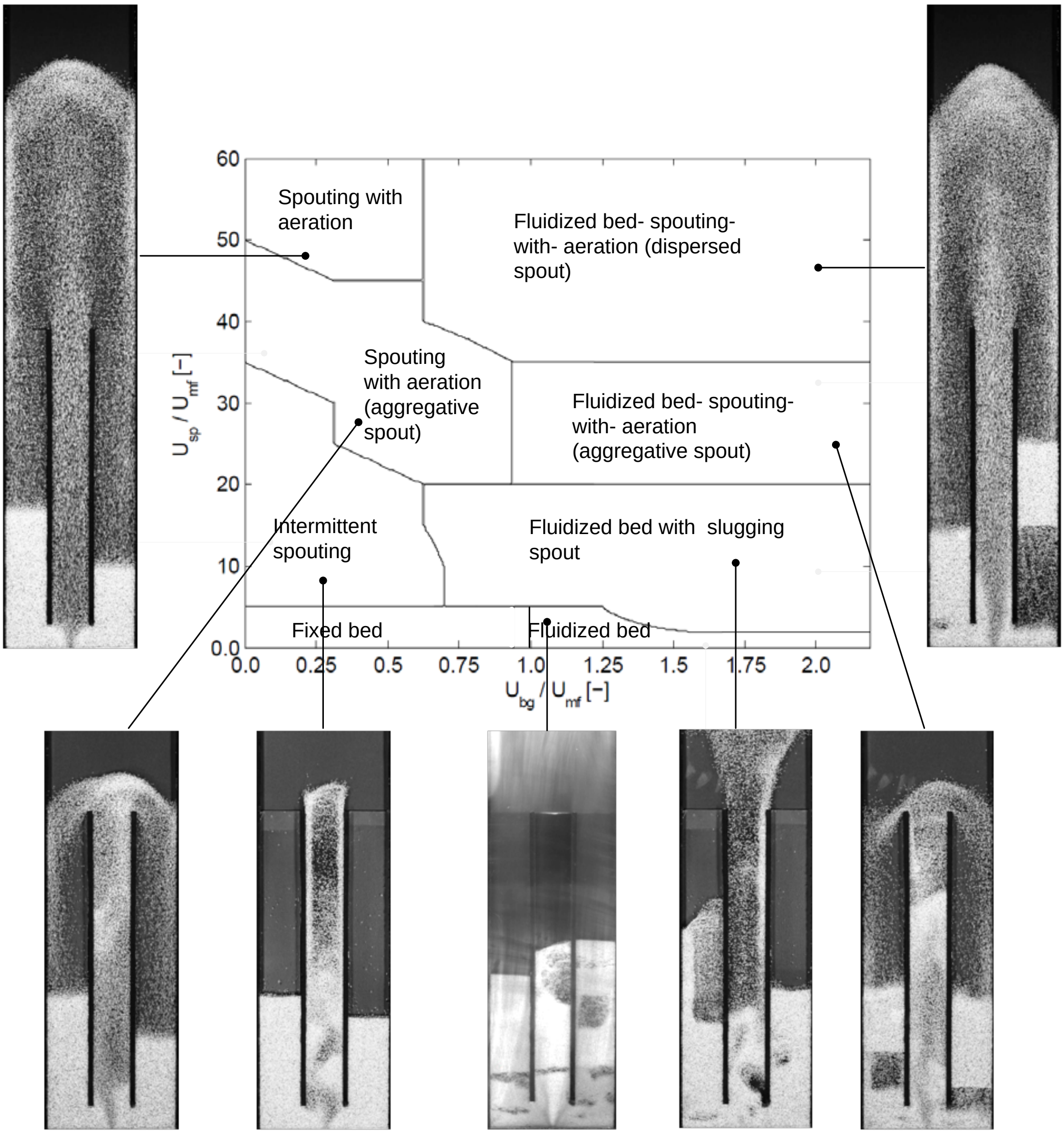

Figure 2. Flow regime map for a glass particles in a spout fluidized bed with an entrainment height of, h = 0.03 m and a static bed aspect ratio of H_0/W = 1.

Fluidized bed (slugging spout) $(5 < u_{sp} / u_{mf} < 20, u_{bg} / u_{mf} > 0.6)$

As the spout and background velocities increase, an intense particle displacement is observed in the spout and annulus with either bubble or slug formation. In this regime, periodic bubble formation was observed near the distribution plate. Furthermore, these bubbles, offer a high resistance to the spout gas by partially blocking the draft plate. This results in an increased pressure below the particles, hence encouraging the spout gas to bypass through the annulus. Moreover, due to the small distance between the draft plates, bubbles often get elongated in the vertical direction. So, during formation and elongation pressure is built up between the draft plates resulting in a sudden eruption of particles in the form of a slug. This may also be due to the lower spout velocity (not high enough to convey the particles between the draft plates). This periodic generation and collapse of bubbles via slug formation highly depends on the spout and background velocities.

Fluidized bed-spouting-with-aeration (aggregative spout)
$(20 < u_{sp} / u_{mf} < 35, u_{bg} / u_{mf} > 1)$

At a high spout velocity, the particles inside the bed are continuously elevated through the draft plates and transported from the spout to the annulus. A similar kind of circulation patterns are observed as in the spouting-with-aeration (slugging spout) regime. However, in this case, due to the higher spout velocity, particles are continuously withdraw and transported from the annulus at the bed bottom. This continuous transport of the particles ultimately leads to increasing the number of particles on the formed slug (in the annulus), leading to a static load. This increase in the load at a confined annulus results in breaking of the slugs. The particles are seen to follow a circulating path through the draft plates into the annulus. The formation, growth and collapse of bubbles takes place in a chaotic fashion leading to a wide frequency pattern without any distinct dominant peak.

Fluidized bed-spouting-with-aeration (dispersed spout)
$(u_{sp} / u_{mf} > 35, u_{bg} / u_{mf} > 0.6)$

In this regime, the particles are elevated through the draft plates in a dispersed state due to the very high spout velocity. Moreover, the background velocity is higher than the minimum fluidization velocity. This leads to an intense particle movement in the annulus with generation of bubbles near the distribution plate. These slugs often move upwards with plug, breaking/leaking in downward direction. This plug breaking mainly occurs due to particles coming from the spout, leading on top of the plug in the annulus. The total system acts like a circulating bed, where particles are elevated in the middle section and flow down in the annulus. The main distinguishing feature of this regime as compared with the fluidized bed-spouting-with-aeration (aggregative spout) and spouting-with-aeration is the continuous transport of particles at a higher bed height with a fluidized annulus.

CONCLUSIONS

A flow regime map was constructed for a pseudo 2D spout fluidized bed containing draft plates, by capturing high-speed images and Fast Fourier transformation (FFT) of measured pressure signals. During this study, eight distinct flow regimes were identified by varying the background velocity from 0 to 1.75 m/s with increments of 0.25 m/s and the spout velocity was varied from 10 to 50 m/s with increments of 5 m/s. With increasing spout velocity, particle circulation in the bed increases for the entire range of background velocities. At lower background velocities, lower particle movements were observed in the annulus. However, increasing the background velocities causes higher particle circulation through the fluidized annulus. Moreover, increasing the background velocity has a stabilizing effect on the particles in the annulus. In order to achieve particle circulations at low background velocity, the spout velocity should be sufficiently high.

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NOTATION

Symbol	Property	Unit
D	Depth of the bed	m
D_{sp}	Depth of the spout	m
D_{dt}	Depth of the draft plates	m
e_n	Normal restitution coefficient	--
d_p	Diameter of the particle	m
H_{dt}	Height of the draft plates	m
H_0	Static height of the particle bed	m
u_{bg}	Background velocity	m/s
u_{mf}	Minimum fluidization velocity	m/s
u_{sp}	Spout velocity	m/s
W	Width of the bed	m
W_{dt}	Width of the draft tube	m
W_{sp}	Width of the spout	m

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