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Introduction, History, and Applications

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1.1 Definition and Origins

Fluidization occurs when solid particles are supported and allowed to move relative to each other as a result of vertical motion of a fluid (gas or liquid) in a defined and contained volume. Most commonly, the fluid is a gas blown upwards by a blower or compressor through a perforated flat plate or a series of orifices, but many other configurations are possible. Once an assembly ("bed") of particles has been actuated in this manner, it is said to be a "fluidized bed."

The origin of fluidized beds is unclear, but liquid-fluidized beds likely preceded gas-fluidized beds. For example, early fluidization has been attributed to Agricola [1] when he described and illustrated hand jigging for ore dressing. The first industrial applications of fluidized beds were likely beds of ore particles fluidized by liquids in order to classify them by size or density in an operation known as "teetering" [2].

The first widespread application of gas-fluidized beds was in the 1920s in Germany when Winkler [3] patented a novel gasifier. However, the terms "fluidization" and "fluid bed" did not emerge until about 1940 when researchers in the United States developed gas-supported beds for catalytic cracking of heavy hydrocarbons [4, 5]. A plaque commemorating the development of the fluid bed reactor at a local oil refinery was erected at the Louisiana Art and Science Museum in Baton Rouge in 1998.

The term "circulating fluidized bed" (or "CFB") has been used since the 1980s to cover configurations where there is no upper bed surface, with particles supported by fluid contained in equipment that incorporates one or more gas–solid separator (usually cyclones), as well as recirculation piping as an integral part of the system. These have become popular, mostly for calcination, energy, and metallurgical operations [6].

Commercial fluidized bed reactors are now among the largest chemical reactors in the world. For example, in China fluidized bed combustors have reached a power capacity of 660 MW_e [7].

Essentials of Fluidization Technology, First Edition. Edited by John R. Grace, Xiaotao Bi, and Naoko Ellis.

1.2 Terminology

As in other fields, specialized terminology is used by the fluidization community. Definitions of the following terms may be helpful for those new to the field:

Agglomeration: Particles sticking together to form assemblies (agglomerates).
Attrition: Break-up of particles due to collisions or other interactions and stresses.
Bed expansion: Height of operating fluidized bed divided by static bed height or bed height at minimum fluidization.
Bubbles: Voids containing few, if any, particles, rising relative to the particles above them and behaving in a somewhat analogous manner to bubbles in liquids.
Choking: Collapse of dilute gas–solid suspension into dense phase flow when decreasing the gas velocity at constant solids flow. For different modes of choking, see [8].
Circulating fluidized bed: Fluid and particles in relative motion in a configuration where there is no distinct upper bed surface and entrained particles are continuously separated and returned to the base of a riser.
Cluster: Group of particles travelling together due to hydrodynamic factors.
Dense phase: Gas–solid region where the concentration of particles is sufficiently high that there are significant particle–particle interactions and contacts.
Dilute phase: Region where particle concentration is low enough that interparticle contacts are relatively rare.
Downer: Vessel in which particles are contacted with a fluid while they fall downwards.
Distributor: Horizontal plate with perforations, nozzles, or other openings or other means of introducing a fluidizing fluid to support the weight of particles and cause them to move while also supporting the dead weight of the particles when the flow of fluid is interrupted.
Elutriation: Progressive selective removal of finer particulates by entrainment.
Fines: Relatively small particles, typically those smaller than 37 or 44 μm in diameter.
Fluid: Either gas or liquid, usually the former in the context of fluidization.
Freeboard: Region extending from dense fluidized bed upper surface to top of vessel.
Geldart powder group: See Chapter 2.
Grid: Alternate name for gas distributor supporting the fluidized bed and assuring uniform entry of gas at its base.
Loop seal: Common configuration (see Chapter 11) for recirculating solids to the bottom of a fluidized bed or riser without reverse flow of gas.
Membrane walls: Containing wall consisting of vertical heat transfer tubes connected by parallel fins, commonly used in combustion applications (see Chapter 14).
Membrane reactor: Reactor containing solid surfaces (“membranes”) that are selectively permeable to one or more component of the gas mixture.

Plenum chamber: Pressurized chamber below the distributor of a fluidization column from which fluidizing fluid is fed into the bed above the distributor.
Riser: Tall column in which particles are carried, on average, upwards by an ascending fluid.
Segregation: Tendency for particles of different physical characteristics (e.g. different size, density, and/or shape) to preferentially become more concentrated in different spatial regions.
Solids: Generic term referring to solid particles.
Superficial velocity: Volumetric flow rate of fluid divided by total column cross-sectional area.
Voidage: Fraction of bed volume or local volume occupied by fluid.
Windbox: Same as plenum chamber, but only when the fluidizing fluid is a gas.

Other terms are introduced and defined as needed in the text.

1.3 Applications

Gas-fluidized beds account for most of the commercial applications of fluidized beds. Relative to packed beds, gas-fluidized beds commonly offer the following advantages:

- Temperature uniformity (with variations seldom exceeding 10 °C in the dense bed and elimination of “hot spots.”)
- Excellent bed-to-surface heat transfer coefficients (typically 1 order of magnitude better than in fixed beds and 2 orders of magnitude better than in empty columns.)
- Ability to add and remove particles continuously, facilitating catalyst regeneration and continuous operation.
- Relatively low pressure drops (essentially only enough to support the bed weight per unit cross-sectional area.)
- Scalable to very large sizes (e.g. there are commercial fluidized bed reactors hundreds of square metres in cross-sectional area.)
- Excellent catalyst effectiveness factors (i.e. very low intra-particle mass transfer resistances): With particles 1 order of magnitude smaller than in fixed beds, i.e. catalyst particles smaller than 100 μm, effectiveness factors usually approach 1.
- Good turndown capability: The gas flow rate can be varied over a wide range, typically by at least a factor of 2–3.
- Ability to tolerate some liquid: For example, in a number of processes, such as fluid catalytic cracking, liquids are sprayed into the column where they vaporize and then react.
- Wide particle size distributions (typically with a ratio of upper to lower decile particle diameter, d_{p90}/d_{p10}, of 10: 20).

These advantages must be significant enough to compensate for some significant disadvantages of gas-fluidized beds:

- ❖ **Substantial vertical (axial) mixing of gas**: Gas is dragged downwards by descending particles resulting in "backmixing" and large deviations from plug flow, with typical axial Peclet numbers of order 5–10.
- ❖ **Substantial axial dispersion of solids**: Vigorous motion of particles and their clusters results in substantial axial dispersion and backmixing of solids. As a result, in continuous processes, some particles spend very little time in the bed, while others spend much longer than the mean residence time.
- ❖ **Bypassing of gas**: Gas associated with a lower-density phase, e.g. rising as bubbles, passes through the bed more quickly and with less access to particles than gas associated with a denser phase in which there is better gas–solid contacting.
- ❖ **Limitations on particles that can be successfully fluidized**: Particles of extreme shapes (e.g. needle or flat disc shapes) or smaller than about 30 μm in mean diameter are difficult, or even impossible, to fluidize.
- ❖ **Entrainment**: Particles, especially fine ones, are carried upwards by the exhaust or product gas and leave the column through the exit. To minimize their losses, entrained particles must normally be continuously captured and returned to the bottom of the vessel.
- ❖ **Attrition**: Particles can break or be abraded when they collide/interact with each other and with fixed surfaces.
- ❖ **Wear on surfaces**: Particle motion tends causes erosion/wastage of fixed surfaces.
- ❖ **Complexity and risk**: Fluidized beds are more complex to design, operate, and model than comparable fixed bed reactors. As a result, there is greater risk of problems and less than desired performance.

The advantages identified above have been found to outweigh the disadvantages in a number of industrially significant processes. The most important of these processes are listed in Table 1.1. Useful reviews of the early years of these processes were provided by Geldart [9–11].

Practical information related to many of the processes listed in Table 1.1 was summarized by Yerushalmi [12]. For information on a recently commercialized process, see Tian et al. [13]. For applications related to food processing, see Smith [14]. The typical operating range for catalytic fluidized bed reactors are summarized in Table 1.2. Particles tend to be larger and gas superficial velocities to be higher in the case of physical operations and for gas–solid reactions than for catalytic processes.

Applications of liquid-fluidized beds, spouted beds, and gas–liquid–solid (i.e. three-phase) fluidized beds are covered in Chapters 3, 21, and 22, respectively.

1.4 Other Reasons for Studying Fluidized Beds

In addition to being useful in many commercial applications, as summarized above and as outlined in later chapters, there are other reasons for interest in the behaviour of fluidized beds:

Table 1.1 Industrial applications of gas-fluidized beds.

Physical operations	Solid-catalyzed reactions	Gas–solid reactions
Drying of particles	Fluid catalytic cracking	Combustion and incineration
Granulation	Acrylonitrile	Gasification
Coating of surfaces by Chemical Vapour Deposition	Ethylene dichloride	Pyrolysis
Particle mixing/blending	Catalytic combustion	Torrefaction
Preheating and heating	Ethanol dehydration	Roasting of ores
Steam raising	Ethylene synthesis	Reduction of iron oxide
Freezing	Maleic anhydride	Polyolefin production
Quenching/tempering	Fischer–Tropsch synthesis	Fluid coking and flexicoking
Carburizing, nitriding	Aniline	Calcination
Constant temperature baths	Methanol to olefins	Catalyst regeneration
Filtering of particles	Methanol to gasoline	Chlorination, fluoridation
Feeding of particles	Oxidative dehydrogenation	Hydrochlorination of silicon
Sorption of harmful gases	Phthalic anhydride	Silane decomposition → pure Si
Treatment of burn victims	Catalytic reforming	Carbon nanotubes via Chemical Vapour Deposition
	Tar cleaning	Gas–solid fermentation
	Steam reforming	Melamine production
	Methanation	Titanium dioxide pigment

Table 1.2 Usual operating ranges for solid-catalyzed gas-phase reactors.

Variable	Range and comments
Sauter mean particle diameter	50–100 μm
Particle size distribution	Broad, e.g. 0–200 μm
Reactor diameter	Up to ~7 m
Pressure	Up to ~80 bars
Temperature	Up to ~600 °C
Superficial gas velocity	~0.3–12 m/s
Static bed depth	1–10 m
Immersed surfaces	May contain horizontal or vertical heat transfer surfaces
Gas–solid separation	Heavily reliant on gas cyclones

Table 1.3 Summary of proceedings of major fluidization and CFB conferences.

Year	Designation	Conference location	Editor(s)	Publisher
1967	International Symposium on Fluidization	Eindhoven, Netherlands	Drinkenburg	Netherlands University Press
1975	Fluidization Technology	Asilomar, California	Keairns and Davidson	Hemisphere
1978	Fluidization	Cambridge, UK	Davidson and Keairns	Cambridge University Press
1980	Fluidization	Henniker, NH, USA	Grace and Matsen	Plenum Press
1983	Fluidization	Kashikojima, Japan	Kunii and Toei	Engineering Foundation
1985	CFB I	Halifax, Canada	Basu	Pergamon Press
1986	Fluidization V	Lyngby, Denmark	Ostergaard and Sorensen	Engineering Foundation
1988	CFB II	Compiègne, France	Basu and Large	Pergamon Press
1989	Fluidization VI	Banff, Canada	Grace, Shemilt, Bergougnou	Engineering Foundation
1990	CFB III	Nagoya, Japan	Basu, Horio, Hasatani	Pergamon Press
1992	Fluidization VII	Gold Coast, Australia	Potter and Nicklin	Engineering Foundation
1993	CFB IV	Hidden Valley, USA	Avidan	AIChE
1995	Fluidization VIII	Tours, France	Large and Laguérie	Engineering Foundation
1996	CFB V	Beijing, China	Kwauk and Li	Science Press, Beijing
1998	Fluidization IX	Durango, USA	Fan and Knowlton	Engineering Foundation
1999	CFB VI	Würzburg, Germany	Werther	DECHEMA
2001	Fluidization X	Beijing, China	Kwauk, Li, Yang	United Engineering Foundation

2002	CFB VII	Niagara Falls, Canada	Grace, Zhu, de Lasa	Canadian Society for Chemical Engineering
2004	Fluidization XI	Ischia, Italy	Arena, Chirone, Miccio, Salatino	Engineering Conferences International
2005	CFB VIII	Hangzhou, China	Cen	International Academic Publishers
2007	Fluidization XII	Harrison, Canada	Bi, Berruti, Pugsley	Engineering Conferences International
2008	CFB IX	Hamburg, Germany	Werther, Nowak, Wirth, Hartge	TuTech Innovation
2010	Fluidization XIII	Gyeong-ju, Korea	Kim, Kang, Lee, Seo	Engineering Conferences International
2011	CFB 10	Sunriver, Oregon, USA	Knowlton	Engineering Conferences International
2013	Fluidization XIV	Noordwijkerhout, Netherlands	Kuipers, Mudde, van Ommen, Deen	Engineering Conferences International
2014	CFB 11	Beijing, China	Li, Wei, Bao, Wang	Chemical Industry Press
2016	Fluidization XV	Montebello, Canada	Chaouki and Shabanian	Vol. 316 of Powder Technology, Elsevier
2017	CFB 12	Krakow, Poland	Nowak, Sciazko, Mirek	Journal of Power Technologies and Archivum Combustionis
2019	Fluidization XVI	Guilin, China	Wang and Ge	American Institute of Chemical Engineering
2020	CFB 13	Vancouver, Canada	Bi, Briens, Ellis, Wormsbecker	GLAB

- They are inherently fascinating to observe, even finding their way into kinetic art.
- Due to their complex flow patterns and the many factors involved, fluidized beds are challenging and difficult to model, with some surprising features.
- They may be related to some natural phenomena, in particular avalanches, pyroclastic flows associated with volcanic eruptions and atmospheric convection of water drops, snowflakes, and hailstones [15, 16]. There has even been speculation that some craters on the surface of the moon may be related to eruption of fluidization bubbles.

1.5 Sources of Information on Fluidization

Thousands of papers have been published in the scientific and engineering literature (journals and books) on fluidization fundamentals and applications. Due to length restrictions and its scope, this book cites only a small fraction of these articles. In addition to the many research articles that appear in journals like *Powder Technology*, *Particuology*, *Advanced Powder Technology*, and *the International Journal of Multiphase Flow*, many relevant papers appear in the major chemical engineering journals such as *Chemical Engineering Science*, *Industrial and Engineering Chemistry Research*, and *American Institute of Chemical Engineers (AIChE) Journal*, as well as a wide variety of other engineering- and physics-related journals. In addition, there are many published proceedings of conferences and symposia on fluidization. The most useful of these for those interested in fundamentals of fluidized beds have appeared in refereed proceedings of tri-annual Fluidization conferences, coordinated for many years by the Engineering Foundation and then by Engineering Conferences International, and tri-annual CFB conferences (recently renamed “International Conference on Fluidized Bed Technology.”) Information on these proceedings is summarized in Table 1.3. Less rigorously refereed proceedings of fluidized bed combustion, originally coordinated and published by the American Society of Mechanical Engineers at two-year intervals, and more recently every three years, also contain many applied and fundamental fluidization articles. Periodic China–Japan Conferences on Fluidization have also led to a series of well-edited volumes.

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Problems

1.1 Gullichsen and Harkonen [17] applied the term "fluidization" to the creation of a fluid-like state in pulp fibre aqueous suspensions due to rapid centrifugal mechanical mixing. Is this use of the term consistent with the definition of fluidization given in this chapter?

1.2 Imagine a reactor of cross-sectional area 100 m^2 containing catalyst particles of diameter 60 μm and density 1600 kg/m^3. The void fraction of the static material is 0.52. How many particles are needed to fill the reactor to a static bed depth of 6 m? What is the total mass of these particles?