Fluidized Bed Technology

Principles and Applications

J R HOWARD

Adam Hilger

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Preface

The primary objective of this book is to help beginners and students gain sufficient insight into the subject of fluidized bed technology, from which they can form their own appreciation of the capabilities and limitations of the technology and proceed, if necessary, to greater expertise. The fluid used for fluidization of a bed of solid particles can be either a liquid or a gas, but this book concentrates entirely upon beds of particles fluidized by gases, for reasons of space.

Accordingly, the early part of the book begins with the fundamental subject matter, describing how a bed of solid particles may behave when a gas is passed upwards through the bed at a sufficiently high rate of flow for the bed to assume fluid-like properties. The book then develops, sometimes using worked examples, to illustrate the considerations involved in the design of equipment based on fluidized bed technology.

The treatment is pitched at a modest level such that anyone with a basic understanding of engineering and science should be able to comprehend. It is also hoped that the book will be valuable to experienced engineers, particularly if they are having to train staff, teachers in engineering departments of colleges, universities and polytechnics and also managers or consultants who may need to gain a rapid appreciation of the technology.

The quantity of literature devoted to fluidized beds, especially research and development papers, is vast and the degree of expertise and knowledge required to design, construct and operate modern fluidized bed systems successfully requires a large investment of time and effort. Experience has shown that anyone without prior knowledge, who desires to gain an appreciation of any particular technology, is likely to have difficulty in knowing where to start. It is hoped that this book will help readers to make such a start with fluidized bed technology. In addition to the instructional aspects of this book, a selection of literature references has been included from which the reader may obtain further guidance.

I am extremely grateful to many friends and colleagues with whom I have discussed various topics over the years and from whom I have

received invaluable criticism and advice as the work of writing progressed. My thanks are especially due to Dr John Botterill, Mr Derek Hickson, Dr Bernie Gibbs, Mr David Reay and the referees appointed by the publishers. Finally, I shall always owe a debt of gratitude to my former colleague, the late Professor Douglas Elliott, who first stimulated my interest in fluidized beds and who has been justly described† as one of the real heroes of the story.

J R Howard

† Ehrlich S 1976 in *Proc. 4th Int. Conf. Fluidized Bed Combustion, 1975* (McLean, Virginia: MITRE Corporation) pp 15–20.

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Contents

1 Introduction

1.1 Processes Involving Contact Between Solid Particles and a Fluid

A great many industrial processes involve contact and interaction between solids and fluids (i.e. gases or liquids). Examples include combustion, gasification of solid fuels, shales or solid wastes, drying of particles, calcining, particle heating, regenerative heat exchangers, oxidation or reduction of ores, metal surface treatments and catalytic and thermal cracking.

It may be helpful to distinguish roughly between the functions of fluids and solids and give examples of practical plant. This is done in table 1.1.

Table 1.1 The functions of fluids and solids and some examples of associated plants.

Fluid function	Solid function	Examples of plant
Heat carrier	Non-reactive feedstock	Solid heaters, regenerative heat exchangers, foundry sand reclaimers, dryers
Mass carrier	Non-reactive feedstock	Pneumatic or hydraulic solids transporters
Heat and mass carrier	Non-reactive feedstock	Dryers
Chemical reactant	Chemical reactant	Combustors, gasifiers, catalytic cracking, catalyst regeneration, ore reduction or oxidation plant
	Active particles for chemical reaction, inert particles as heat transfer	Combustors, metallurgical surface treatment and heat treatment furnaces
Agitation only	Non-reactive	Mixers, classifiers

It will be seen from table 1.1 that several combinations of the functions of solids and fluids can arise in practical plant. Thus, when considering processes or plants it is necessary to be clear as to the particular purpose served by the fluids and the solids. Heating and drying of solids, for example, involve heat and mass transfer only, whereas combustors, gasifiers etc have the additional complication of chemical reactions which have to be carried out simultaneously with heat and mass transfer. However, with both categories it is sufficient at this stage to say that, broadly speaking, the principles used to bring fluids and solids into contact are similar.

Conceptually, the easiest way to perform such processes is to arrange for the fluid to flow through a bed of the solid particles, percolating through the interstices between the particles, as shown in figure 1.1. The simple 'packed bed' of particles shown in figure 1.1 comprises a containing vessel with a porous base through which fluid can flow upwards or downwards among the particles. (Frequently, the fluid is made to flow downwards rather than upwards because when flowing upwards the fluid velocity is limited to that which is the smaller of (i) that for incipient fluidization of the bed (see §1.3.2) or (ii) that resulting in an excessive amount of the finer particles being blown out of the system. With downward flowing fluid, the limit to fluid velocity is set by the allowable functional pressure drop across the bed.) In either case the fluid makes contact with the surface of the particles and continuous fluid flow ensures exposure of the particle surface to a fresh fluid continuously. The nature of the fluid flow (e.g. laminar, turbulent, transitional) at the particle/fluid interface influences the *rate* of interaction between fluid and particle, for example the heat or mass transfer rate or the chemical reaction rate at the interface.

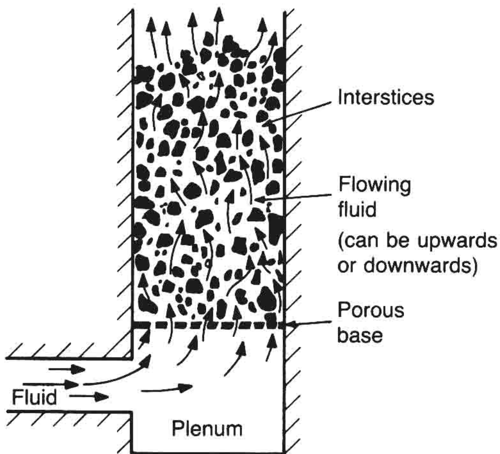

Figure 1.1 A packed bed.

Other ways of bringing a fluid into contact with the surface of particles include the dropping of particles down a vertical duct containing the fluid, as shown in figure 1.2; mechanical stirring or agitation (see figure 1.3); the use of a 'spouted bed', as shown in figure 1.4, in which a jet of fluid at high velocity pierces through the bed, entraining and agitating the particles; or the use of a moving bed (see figure 1.5). Each of these ways of bringing fluid into contact with the surface of particles has its merits and its deficiencies. Deciding which of them is the most

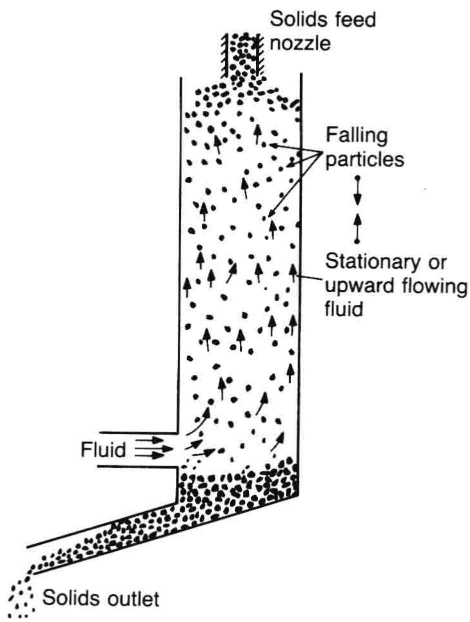

Figure 1.2 A 'falling cloud' duct.

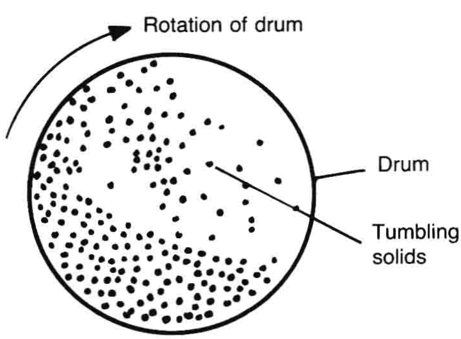

Figure 1.3 The agitation of solids by a rotating drum.

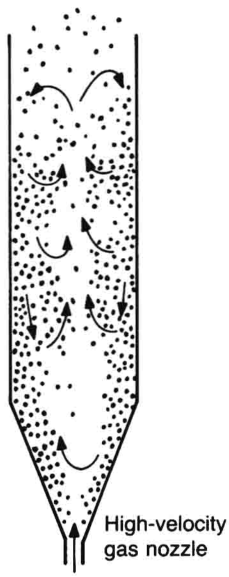

Figure 1.4 A spouted bed.

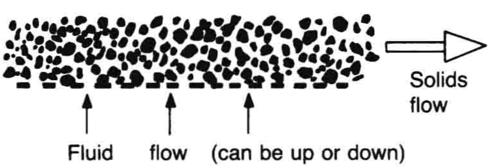

Figure 1.5 A flowing packed bed.

suitable for a prescribed task is not always easy and depends upon the constraints (including economics and convenience) within which the process has to be accomplished. Indeed, two different designers faced with the same task of bringing fluid into contact with particles may have differing opinions and select different ways of performing the process. The procedure for selection will not be discussed here, however, but table 1.2 outlines the advantages and disadvantages of alternative methods.

1.2 Packed (or Fixed) Beds

A packed (or fixed) bed (figure 1.1) suffices in principle for processing solids a batch at a time. If a continuous process is required, the unprocessed solids must flow into the container and the processed solids be removed at the desired rate. Such a system becomes a flowing packed bed. Static packed beds are unsuitable for continuous processes because of the difficulty of transporting solids into and out of the system easily.

There are other difficulties with packed beds such as the existence of temperature gradients within the bed if the fluid/solid or gas/solid reaction is exothermic; this can result in sintering of the particles. Heat transfer to and from the bed is relatively poor, requiring a large surface area to effect it. Further, if the fluid velocity has to be high (to satisfy the requirement of high throughput), then only large particles can be processed because the smaller ones may be transported out of the bed by entrainment in the gas. On the other hand, the pressure drop across the bed is relatively small.

Fluid flowing through the spaces between the particles (interstices) exerts a drag force on the particles and this force may be large enough to disturb the arrangement of the particles within the bed. If the upward velocity of the fluid through the bed is raised progressively, a situation will eventually arise where the fluid drag exerted on the bed of particles is sufficient to support its entire weight. The bed is then said to be 'incipiently fluidized' and it exhibits fluid-like properties. The bed will flow under a hydrostatic head, the free surface will remain horizontal if the containment is tilted and low-density objects will float (see figure 1.6(*a*), (*b*), (*c*) for illustration). This leads naturally to the exploitation of the phenomenon of fluidization to, for example, the transport of solids and to the examination of what happens when fluid flow is increased beyond that required for incipient fluidization.

1.3 Fluidized Beds

1.3.1 Components

From the discussion in §1.2 it will be seen that the most easily perceived parameter dictating whether a bed is fluidized or packed is the velocity at which the fluid passes upwards through an unrestrained bed of particles. Both types of bed require a containing vessel with a porous base through which the fluid can be introduced to the bed. The exact form of the porous base is a matter of design choice, ranging from a plate with a large number of small holes drilled in it to a block of sintered ceramic, powder metal, stand pipes or bubble caps. Whatever the construction, the most important function of the porous base is that it distributes the fluid across the base of the bed uniformly. The porous base is therefore almost universally called a 'distributor'.

Table 1.2 A comparison of alternative gas–solid contacting methods.

Method	Advantages	Disadvantages
Packed beds (figure 1.1)	High conversion provided that control of gas distribution and temperature is good (not easy) Long gas residence time High flow rates through constrained bed at expense of higher pressure drop	Low gas velocity—large reactor size Only large particles Steep temperature gradients and large heat transfer areas required with exothermic reactions Danger of particle sintering and blockage of reactor Suitable only for batch processes Non-uniformity of product
Fluidized beds (figure 1.7) bubbling regime	Good gas–solid contact Good particle mixing Uniform temperature and control of process giving uniform quality of products High bed-to-surface heat transfer coefficients Can use wider particle size range Ease of transport of solids into and out of reactor	Lower conversion Pressure drop and necessary pumping power increase with deep beds Erosion of vessel and pipes and production of fines by attrition Elutriation of fines can limit performance Gas by-pass can be excessive Size range of particle to be used is limited Segregation of particles
Falling cloud (figure 1.2)	Simplicity of construction Low pumping power Can operate with dirty gases	Dependent upon reliable means of dispersing particles across duct section Non-uniform particle residence time across duct section Gas velocity distribution non-uniform Close particle size range required Large vessel per unit mass flow of solids or per unit heat rate

Table 1.2 (*cont*)

Method	Advantages	Disadvantages
Flowing packed bed (figure 1.5)	Small cross sectional area of duct for solids transport Uniform temperature distribution Relatively little elutriation Large thermal capacity for transporting heat High conversion	Particle segregation Maximum gas velocity limited to minimum fluidizing velocity of solids Heat transfer coefficients low Close particle size range required
Spouted bed (figure 1.4)	Good agitation of particles which are too coarse or non-uniform for good fluidization Interparticle collisions inhibit agglomeration of particles or expose fresh surface of particles Regular cyclic motion of solids Spouts can be used to prevent local defluidization Spouted bed dryers—cheap—mechanically simple	High pressure drop, particularly on starting Particle attrition if particle residence times are long or particles are fragile Limited to relatively large particles Possibility of erosion