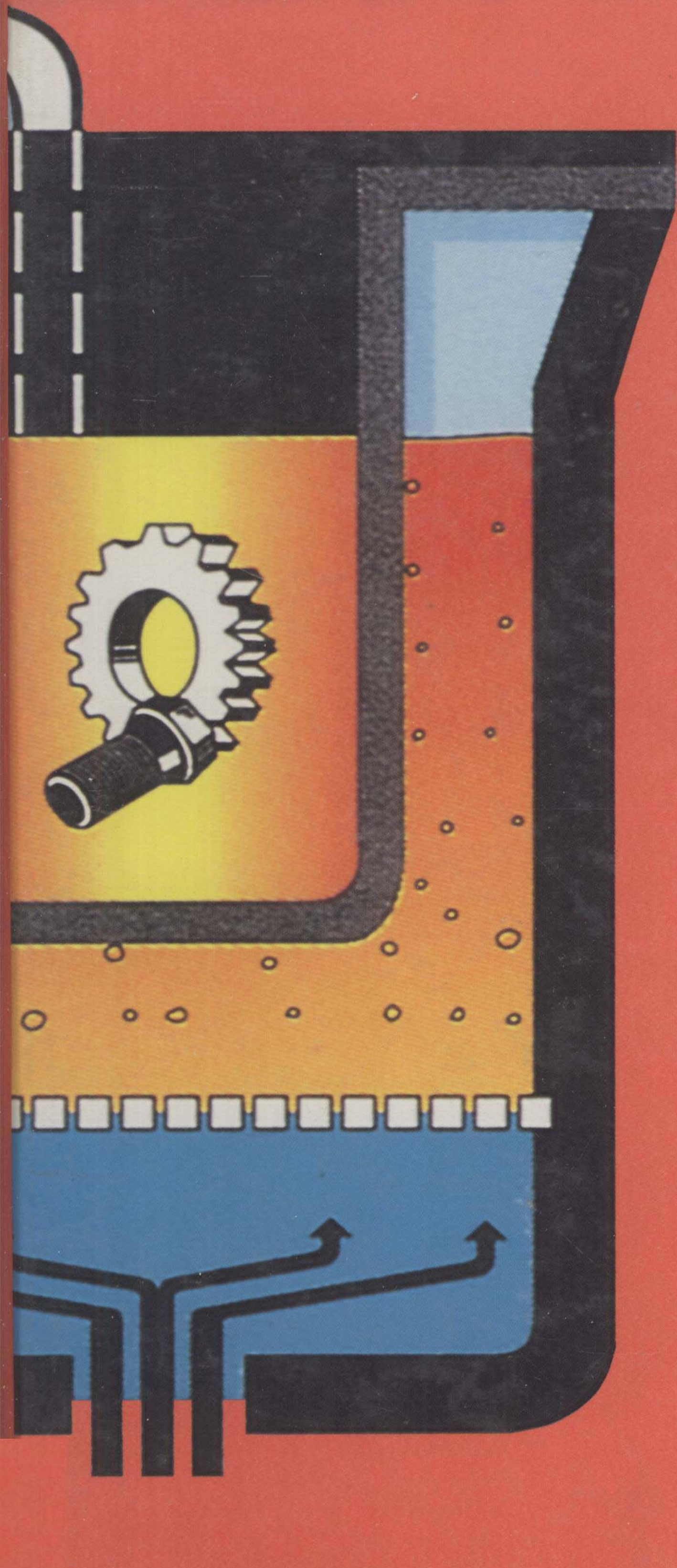

# Heat Treatment in Fluidized Bed Furnaces

R.W. Reynoldson

ASM INTERNATIONAL
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# HEAT TREATMENT IN FLUIDIZED BED FURNACES

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# Foreword

This book has been written for users of fluidized beds involved in the heat treatment of metals. It combines theory with practical solutions to many of the questions that arise with this relatively new technology. In addition, it includes a bibliography of relevant published papers and reference books for further reference.

# Acknowledgments

I would like to acknowledge the help I have received from my friends and colleagues in the preparation of this book. I also acknowledge the permission of Associated Swedish Steels (ASSAB) to incorporate extracts of their published work on the heat treatment of tools and dies.

In addition, I thank the Wolfson Heat Treatment Centre, Birmingham, UK, and ASM International, Materials Park, Ohio, USA, for permission to include illustrations from *Heat Treatment of Metals,* the Wolfson quarterly journal, and the *ASM Handbook, Volume 4, Heat Treating.* I also wish to acknowledge the information and feedback received from the users of the 250 fluidized-bed installations I have been associated with during the last 15 years. Additional thanks are in order for those who reviewed the manuscript, including special acknowledgement of the helpful advice and comments provided by Stig Samuelson and Associate Prof. John Hensler, of the Royal Melbourne Institute of Technology.

Finally, my grateful thanks to my wife, who typed most of my original papers and patiently prepared the manuscript for this book.

**Ray Reynoldson, January 1993**
Bayswater, Victoria, Australia

# Contents

CHAPTER 1

# Introduction

Today's more exacting metallurgical specifications call for increasingly greater precision in heat treatment operations. Modern processes require closer control of the atmosphere and temperature level and their uniformity, while at the same time complying with the operator's need for reduced costs and acceptable environmental effects. The use of fluidized beds in heat treatment shows increasing capability to meet such demands and to fulfill the inherent advantages that have been recognized for some time: high heat transfer and freedom from contamination of either the workpiece or the atmosphere.

In reviewing the published literature on fluidized beds for heat treatment, it is clear that over the last 25 years these potential benefits have aroused considerable interest among metallurgists and prompted publication of a number of assessment papers on this type of furnace. From these it is apparent that the historical development of fluidized bed furnaces has taken a similar path to a number of other technological innovations. A paper by Sinclair *et al.* published in 1965, listed in the bibliography for Chapter 2, expressed the opinion that the limitations of the process were such that there were no applications for fluidization in any of the main fields of steel heat treatment. However, with development of the technology, applications of fluidized bed furnaces for the treatment of tools and annealing of wire were reported as early as 1969.

The present position is described in this book, which reviews the principles, development, and applications of fluidized beds for the heat treatment of metals. A basic understanding of the principles of heat treatment is assumed. A good account of these principles is presented by K.E. Thelning in his book *Steel and its Heat Treatment,* listed in the bibliography of Chapter 8.

A short list of relevant published papers and reference books is included at the end of each chapter, to provide references for further reading in the topic area of each chapter. A brief list of general references is included at the end of this first, introductory chapter. These bibliographies are not intended to be comprehensive surveys of all published articles, technical documentation, press releases, or internal reports issued on heat treatment in fluidized beds, but instead lists of useful references for further reading.

## Selected References


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CHAPTER 2

# Theory and Principles

## The Fluidized Bed Phenomenon

Various systems of fluidized solid particles, such as quicksand, occur in nature, and there are old, established practical applications, including potter's clay and miner's hydraulic slurries. Fluidization is not a new technique; an American patent of 1879 describes the roasting of minerals under fluidized bed conditions and draws attention to the outstanding uniformity of temperature it affords.

Fluidization involves making a bed of dry, finely-divided particles (typically aluminum oxide, in the current context) behave remarkably like a liquid when its individual particles become microscopically separated from each other by a moving gas fed up through the bed. A gas-fluidized bed is considered to be dense-phase fluidized as long as it exhibits a clearly-defined upper limit or surface. However, at a sufficiently high fluid-flow rate, terminal velocity of the solids is exceeded, the upper surface of the bed disappears, entrainment becomes appreciable, and solids are carried out of the bed with the fluid stream. This stage constitutes a disperse, dilute, or lean-phase fluidized bed with pneumatic transport of solids. Figure 2.1 shows the general types of fluidized beds. The majority of beds used for heat treatment are of the aggregative or bubbling bed type.

Although the properties of solids and fluids alone will determine the quality of fluidization (i.e., whether smooth or bubbling fluidization occurs), many factors influence the rate of solid mixing, the size of the bubbles, and the extent of heterogeneity in the bed. These factors include bed geometry, gas flow rate, type of gas distributor, and internal vessel features such as screens, baffles, and heat exchangers.

In determining the quality of fluidization, a diagram of pressure drop ($\Delta_p$) vs velocity ($\mu$) is useful as a rough indication when visual observation is not possible. A well-fluidized bed will behave as in the diagram in Fig 2.2, which has two distinct zones. In the first, at relatively low flow rates in a

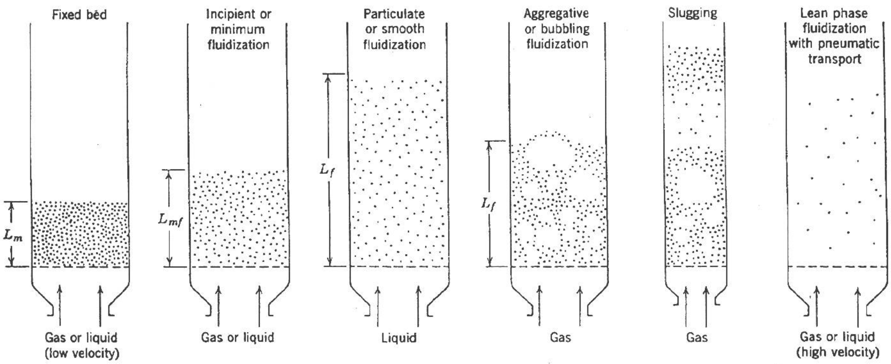


**Fig 2.1** Various types of contact in fluidized beds

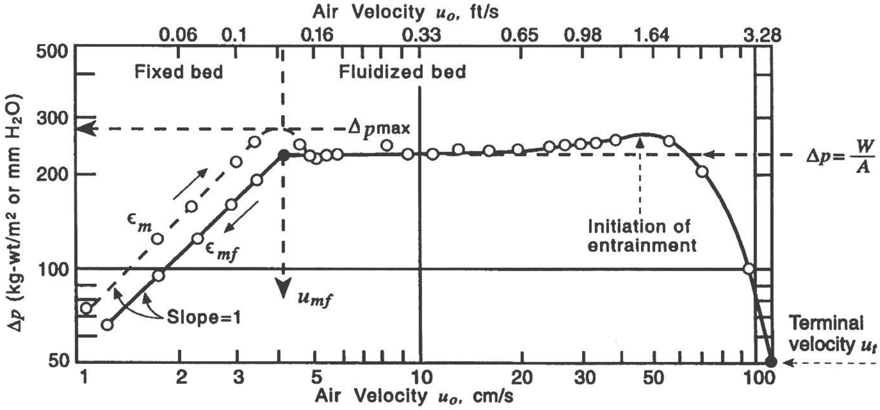


**Fig 2.2** Pressure drop vs gas velocity for a bed of uniformly-sized particles (measured by Shirai)

packed bed, the pressure drop is approximately proportional to the gas velocity, usually reaching a maximum value, $\Delta_{pmax}$, slightly higher than the static pressure of the bed. With a further increase in gas velocity, the packed bed suddenly "unlocks"; in other words, the voidage* increases from $\varepsilon_m$ to $\varepsilon_{mf}$, resulting in a decrease in pressure drop to the static pressure of the bed. With gas velocities beyond minimum fluidization ($\mu_{mf}$) the bed expands, and gas bubbles are seen to rise, resulting in a heterogeneous bed. This is the second zone in which, despite a rise in gas flow, the pressure drop remains practically unchanged.

In order to understand this constancy in pressure drop, note that the dense gas-solid phase is well-aerated and can deform easily without appreciable resistance. In its hydrodynamic behavior, the dense phase can be likened to a liquid. If a gas is introduced into the bottom of a tank containing a liquid of low viscosity, the pressure required for injection is roughly the static pressure of the liquid and is independent of the flow rate of gas. The constancy in pressure drop in the two situations, the bubbling liquid and the bubbling fluidized bed, may be taken intuitively to be analogous.

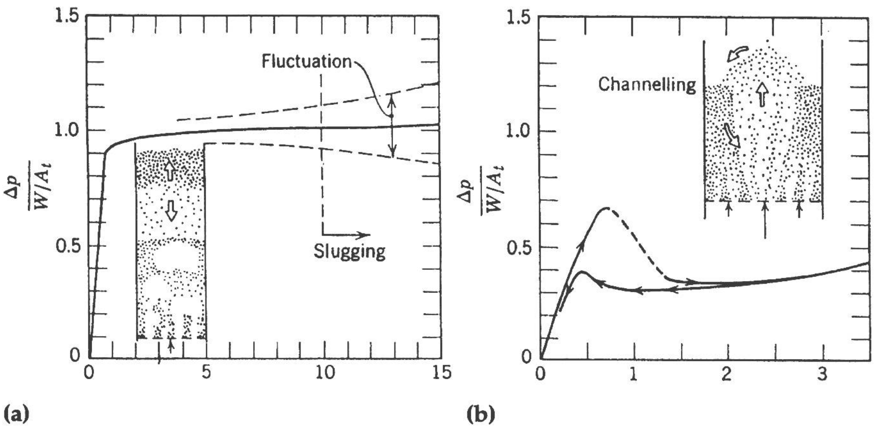


**Fig 2.3** Pressure drop for poorly fluidized beds (measured by Hiraki)

* $\varepsilon_m$= fraction of voids in a fixed bed of particles
$\varepsilon_{mf}$ = fraction of voids at minimum fluidization

The diagrams in Fig 2.3 are representative of poorly fluidized beds. The large pressure fluctuations in Fig 2.3(a) suggest a slugging bed, whereas an absence of the characteristic sharp change in slope at minimum fluidization and the abnormally low pressure drop in Fig 2.3(b) suggests incomplete contact with particles only partly fluidized. As mentioned earlier, a number of factors influence the quality of fluidization and one of the most important of these is the type of distributor employed. Figure 2.4 illustrates this schematically.

## *Analogy between Fluidized Beds and Liquids*

Whatever the upper surface contour of a fixed bed may be when it is brought to fluidization, it becomes level and flat when this occurs, in agreement with the behavior of a liquid. When fluidization occurs in a container divided into several interconnected compartments filled with an unequal number of particles, the surfaces in the different compartments even out and attain the same levels as soon as the whole system is fluidized. This follows the principle of communicating vessels for liquids. A hand plunged into a

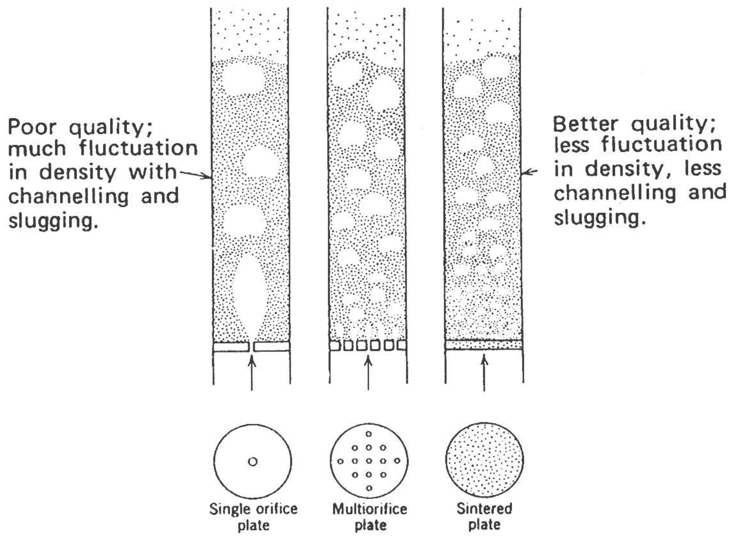


**Fig 2.4** Quality of fluidization as influenced by type of gas distributor

fluidized medium experiences similar sensations as in a liquid, and light objects float on the surface. Figure 2.5 illustrates this behavior.

These analogies naturally encourage examination of existing knowledge of liquid behavior as a basis for the study of fluidized beds and their applications. The use of submerged combustion in heating fluidized beds, described later, is a case in point.

## Minimum Fluidization Velocity and Temperature

One of the most important parameters of a fluidized bed is the minimum fluidization velocity, for which a number of complex formulas have been proposed. However, in simplified terms, minimum fluidization velocity ($\mu_{mf}$) approximates a function of the square of the particle diameter (d) and a linear function of particle mass (p) as follows:

$$\mu_{mf} \approx d^2 p$$

In the design of heat treatment furnaces the effect of temperature must be taken into consideration; Fig 2.6 shows how the flow of gas required for fluidization decreases very rapidly with temperature.

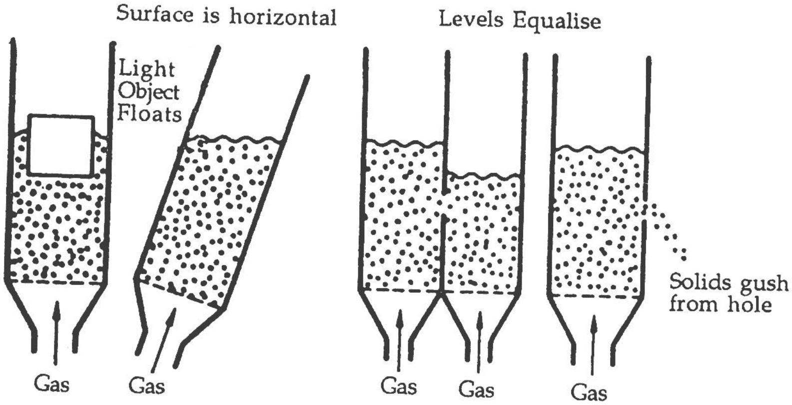


**Fig 2.5** Liquid-like behavior of gas fluidized beds

## Heat Transfer

The high heat transfer coefficient of a fluidized bed, typically between 120 and 1200 $W/m^2$ °C (21 and 211 Btu/$ft^2$·hr·°F), is one of its most important properties. It enables work pieces in it to be heated or cooled at speeds very close to those obtained in conventional salt or lead bath equipment. The turbulent motion and rapid circulation rate of the particles and the extremely high solid-gas interfacial area account for this feature. In work performed by Kovacs *et al.*, it was established that the following factors are important in heat transfer:

### *Particle Diameter*

Of all the parameters affecting the heat transfer coefficient in fluidized beds, the particle diameter has the greatest influence. The tests indicated that particle diameter should be as small as possible, but that below a certain size, electrostatic effects could cause problems. In practice, the optimum particle size is 100 μm (3940 μin.).

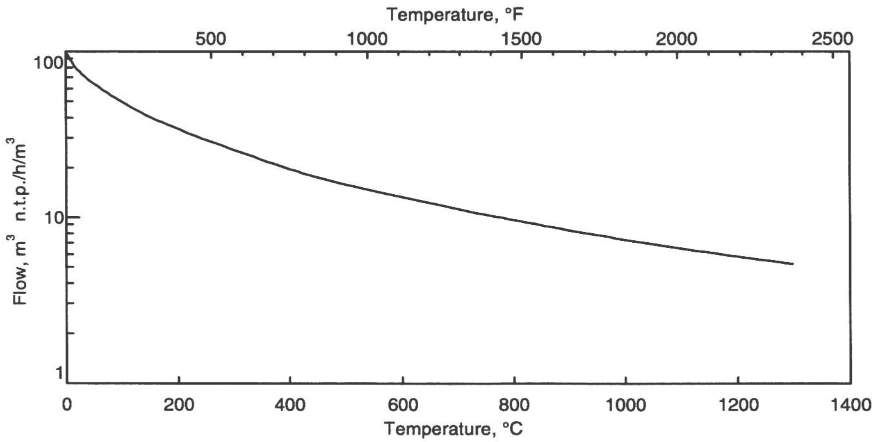


**Fig 2.6** Effect of temperature on flow corresponding to minimum fluidization for 0.1 mm (0.004 in.) diam particles with an apparent density of 2

### *Bed Material Density*

It was concluded that the governing physical property of the bed material is its density. There appears to be an optimum density for bed materials of around 1280 to 1600 kg/m$^3$ (80 to 100 lb/ft$^3$). Denser materials tend to produce lower heat transfer coefficients and also require more power for fluidization, while problems with electrostatic effects occur with low-density materials. Other properties such as thermal conductivity and specific heat are relatively unimportant.

### *Fluidization Velocity of Gas*

It is essential that an optimum flow rate be used that provides maximum heat transfer for a particular particle density and diameter. Generally this optimum flow rate is between two and three times the minimum fluidization velocity. Too high a velocity leads to particle entrainment, high consumption of fluidizing gas, and poor heat transfer, while too low a velocity leads to poor heat transfer and lack of uniformity in processing. This is discussed in more detail in Chapter 4.

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CHAPTER 3

# Basic Design Types

The most widely used fluidized bed for heat treatment is the dense-phase type, although units have been constructed based on the dispersed-phase bed type, with particle circulation for heat treatment of long, thin metal parts, such as shafts and plate. In a typical dense-phase fluidized bed, the parts to be treated are submerged in a bed of fine, solid particles held in suspension, without any significant particle entrainment, by an upward flow of gas.

A major problem in adapting fluidized beds for metal processing has been liberating adequate quantities of heat within them. The first problem is to transfer suitable quantities of heat to the fluidizing medium, because the heat transfer characteristics of the bed itself are usually much more efficient than heat transfer to the fluidizing gas from the heat source. In addition, the major component of heat loss from any practical fluidized system is the heat content of the spent fluidizing gas. In instances where thermal efficiency is unduly influenced by this factor, recirculation of the fluidizing gas or installation of a recuperative system may be justified, and both have been used in practical applications.

In the past, the heating means for fluidized beds was one of the major disadvantages in adapting them to heat-treatment use. However, over the last twenty years a variety of approaches have been developed to improve the efficiency of heat transfer from the heat source to the fluidized bed. The various types of heat sources are summarized as follows: