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Fluidized-Bed Heat Treating Equipment*

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FLUIDIZED-BED TECHNIQUES are not new to the metalworking industry. They were first developed in the 1960s to 1970s for the treatment of metals. As the understanding of fluidization fundamentals improves, several major technological innovations have occurred since then:

- The use of smaller particles greatly reduces the volume of fluidizing gas consumed and in turn the operating cost.
- A variety of approaches to bed heating have been developed to improve the efficiency of heat transfer from the heat source to the fluidized bed.
- The internal combustion heating design replaced early gas-fired heating designs that ignite and combust a premixed gas-air mixture at the base of the container. This eliminated the danger of explosion at the point of entry and reduced the requirements for distributors to comply with high temperature.
- External heating techniques made the fluidized-bed furnaces more flexible in temperature control, selection of fluidizing gas, and heat treatment atmosphere.
- The temperature limitations of early fluidized beds have been widened to include higher temperature ranges, resulting in the technique being applicable for most common heat treatments and thermochemical diffusion treatments.
- Chemical vapor deposition techniques led to the development of thermoreactive deposition/diffusion processes with fluidized beds.
- Fluidizing gas recirculation and heat recovery made the fluidized-bed furnaces efficient in energy consumption and in the use of fluidizing gases.

Today (2013), fluidized-bed furnaces are widely accepted for heat treating ferrous and nonferrous metals and alloys.

Principles of Fluidized-Bed Heat Treatment

Fluidized beds are formed by blowing a gas upward through a layer of fine solid particles, typically aluminum oxide in the heat treating context, into a chamber with a grid bottom. The flow rate is such that the pressure drop of the gas in the layer equals the weight of the material per unit grid area. The particles are then separated from each other and able to move relative to one another. The layer of particles behaves like a liquid or fluid, and the continuous supply of gas keeps the bed in continuous motion (Ref 1, 2).

Gas-Fluidized Beds

A gas-fluidized bed is considered a dense-phase fluidized bed when it exhibits a clearly defined upper limit or surface. At a sufficiently high fluid-flow rate, however, the terminal velocity of the solids is exceeded, the bed goes into motion, and the upper surface of the bed disappears. This state constitutes a disperse, dilute, or lean-phase fluidized bed with pneumatic transport of solids. The general phases or stages of fluidization are shown in Fig. 1. Usually, the aggregative or bubbling-type stage is used for heat treatment processes.

In determining the quality of fluidization, a diagram of pressure drop ($\Delta p$) versus velocity ($v$) is useful as a rough indication when visual observation is not possible. A well-fluidized bed will behave as shown in Fig. 2, which has two distinct zones. In the first zone, at relatively low flow rates in a packed bed, the pressure drop is approximately proportional to the gas velocity and usually reaches a maximum value ($\Delta p_{\text{max}}$) slightly higher than the static pressure of the bed. With an increase in gas velocity, the packed bed suddenly "unlocks" and becomes fluidlike. The gas velocity corresponding to the beginning of fluidization is known as the minimum fluidization velocity ($U_{\text{mf}}$).

When gas velocity increases beyond the minimum fluidization, the bed expands and gas bubbles 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. The dense gas-solid phase is well aerated and can deform easily without appreciable resistance. The excess amount of the gas, or at least a part of it, gets through the bed in the form of bubbles, resembling the boiling of a liquid. In its hydrodynamic behavior, the dense phase can be likened to a liquid. The upward flow of the bubbles draws the particles to the surface of the bed and causes the intense mixing of the entire particulate material.

Minimum fluidizing velocity ($U_{\text{mf}}$) is one of the most important hydrodynamic parameters of a fluidized bed. It has been routinely determined by theoretically analyzing or experimentally measuring the bed pressure drop as a function of the gas velocity (Fig. 2), which is

![Fig. 1 Various types of contacting in fluidized beds](image)
term the superficial fluidizing velocity at specified values of temperature and pressure. The minimum fluidizing velocity increases with an increase in the density and diameter of the particles and is dependent on the density and viscosity of the gas. Figure 3 plots the dependence of minimum fluidizing velocity on these parameters. For 120-mesh alumina particles with a density of 3890 kg/m³ (240 lb/ft³), their minimum fluidizing velocity by air at room temperature is approximately 0.02 m/s (0.07 ft/s).

In a bed of fine particles (dp < 0.5 mm, or 0.02 in.), the minimum fluidizing velocity decreases when bed temperature increases. Figure 4 shows an example of the flow of gas required for fluidization. The effect of temperature on the minimum fluidization velocity is mainly attributed to the decrease of the gas density, the increase of the gas viscosity, and the variation in the voidage of the dense phase.

**Regions in Fluidized Beds for Heat Treatment**

The entire space occupied by a fluidized bed can be divided into three zones: grid zone, main zone, and above-bed zone.

**Grid Zone.** It is also named the zone near the distributor. The nucleation and growth of gas bubbles take place, and, in some cases, the combustion of fuel for heating the bed or chemical reactions for generating the furnace atmosphere also take place in this zone. The height of the grid zone greatly depends on the distributor; for instance, it is tens of millimeters for the small-hole perforated plate and porous plate gas distributors. Because of the nonuniformities of temperature and atmosphere in the grid zone, the parts to be treated are commonly not placed in this zone.

**Main Zone and Particle Circulation.** The part-loading zone is the main zone above the grid zone and can extend to the upper boundary of the initial immobile layer (Ref 5). In the main zone, the gas bubbles rise in the bed, grow in size, coalesce, and split. In the fluidized beds without load, the rising bubbles intensively stir the fine particulate material and draw a portion of it to the surface of the bed. They also tend to leave the vertical walls and concentrate in the center of the bed. This effect is especially noticeable in a high bed. As a result, the intensive mixing of fine particles in the bulk of the bed is accompanied by the circulation of particles, downward at the sides and upward in the middle. The treated parts loaded in the main zone greatly change these behaviors of bubbles and particles.

**Above-Bed Zone.** When the bubbles reach the bed surface, they burst and eruptively eject particles into the space above the bed. Some smaller particles are carried away from the bed by the flowing gas, but most of the particles return into the bed (fall back). As a result, the third zone above the free surface of the bed is formed, in which the particle concentration is much lower than that in the main zone.

**Heat Transfer**

Heat transfer in fluidized beds includes conduction, convection, and/or radiation from gas-to-particles, particles-to-particles, and bed-to-surfaces of the chamber and the immersed parts. The heat transfer between the bed and a part or chamber surface can be described as a sequence of intermittent events of either a dense gas-particle phase or a gas bubble coming close to the surface and exchanging energy with it (Ref 4, 6). For heating fluidized beds, solid particles release heat by thermal conduction at the part surface. As they transport to the bulk region of the hot bed, they gain heat again from other particles and gas.

The particle circulation induced by bubbles is the primary cause of high-efficiency heat transfer in fluidized-bed heat treatment furnaces. The heat transfer between gas bubbles and solid surfaces is by convection. Radiative heat transfer occurs between fluidized particles and chamber walls and part surfaces at high temperatures.

**Heating Rate**

An important characteristic of fluidized beds is high-efficiency heat transfer. The turbulent movement and rapid circulation of the particles in the fluid furnace provide a uniform temperature distribution in the bed and a high heat-transfer efficiency comparable to that of conventional salt bath or lead bath. The heat-transfer coefficient of a fluidized bed is typically between 120 and 1200 W/m²·°C (21 and 210 Btu/ft²·h·°F). Using high-thermal-conductivity gases, such as
hydrogen and helium, as the fluidizing medium can give high rates of heat transfer.

A comparison of heating rates for heating a 16 mm (0.6 in.) steel bar in a salt bath, a lead bath, a fluidized-bed, and a conventional furnace is illustrated in Fig. 5. Figure 6 shows heating and recovery rates for a fluidized bed. Results of both hardening and isothermal quenching of type D3 tool steel with salt baths and with fluidized beds are given in Table 1. The difference between the two installations in total time for final heating and holding is the result of a difference in preheating conditions.

**Design of Fluidized-Bed Furnaces**

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

The quality of fluidization is determined by the properties of solid and fluid, bed geometry, gas-flow type, type of gas distributor, and internal vessel features, such as screens, baffles, and heat exchangers.

**Fluidized Material**. The capability of solid particle media to be fluidized by gases is based on their position in the Geldart chart (Ref 7), closely depending on their mean size and density. Four powder groups (A, B, C, and D) were suggested to distinguish broad types of behavior. The four groups are frequently referred to in the literature. The greatest heat-transfer rates occur with type B media, such as 100 to 800 μm sand particles. There appears to be an optimum density for bed materials: approximately 1280 to 1600 kg/m³ (80 to 100 lb/ft³). Of these media, the best material is aluminum oxide due to its strength, low mechanical wear, stability of size fractions, safety of its dust, and its best heat-transfer capacity, thermal stability, and uniformity. High-density materials tend to produce lower heat-transfer coefficients and also require more power for fluidization. Carry-out problems occur with low-density materials.

The thermal properties of the solid particles, such as thermal conductivity and specific heat, have a relatively small effect on heat transfer. The fluidized particles in general are chemically inert, have a high melting point, and do not react with metal parts. The exception to the selection of inert particles for the fluidized media is where the particles also act as the source of the precursor vapors in the thermochemical treatment. The selection is based on the desired coating and its reaction with the fluidizing gas. The fluidized media could be a combination of inert particles with reactive powders, inert particles coated with the element to be diffused into parts, or only composed of reactive powders. For example, 1 to 40% mass ferrovanadium particles mixed with aluminum oxide are used in the hard surface or vanadium carbide coating of ferrous metals.

**Particle Diameter**. Of all the parameters that affect the heat-transfer coefficient in fluidized beds, particle diameter plays the most important role. Small particles can be fluidized with an economical use of gas and provide a high heat-transfer coefficient. However, when the particle size is less than 100 μm, the uniformity of fluidizing deteriorates and high entrainment or carry-out occurs. Normally, particles in the range of 100 to 125 μm are used (Ref 8).

**Fluidization Velocity of Gas**. The general nature of fluidized-bed heat transfer is illustrated in Fig. 7. It is essential to use the optimum flow rate, that is, one that provides the maximum heat-transfer rate for a particular particle density and diameter. Generally, this flow rate is considered to be 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; too low a velocity results in poor heat transfer and lack of uniformity in processing.

The volume of gas used is dictated by particle size, temperature of operation, and optimum fluidization velocity.

**Fluidizing Gas Distributor**. The gas distributor, also called a grid, controls the fluidization quality and the temperature uniformity across the entire bed cross section, especially for the state of the fluidized bed in the near-grid zone. Figure 8 illustrates this schematically. The design of the distributor is intended to produce a uniform gas across a wide cross-sectional distance at a low pressure loss over the plate, operate for long service lives without plugging or breaking at high temperatures, and support the weight of the bed material without gravitating into the plenum beneath the grid during shutdown. A wide variety of distributors can be used, including perforated metal plates, nozzles, bubble caps, and ceramic filters.

The retort is designed to transfer heat from the outside to the particles contained in it. It is generally fabricated from a high-melting-point metal alloy, which therefore limits the operating temperatures of the bed, that is, safe working temperatures. For some heating methods, for example, internal gas combustion, refractory containers are often used.

**Elimination of Defluidization**. The main advantages of fluidized-bed furnaces, that is, the high rate and high uniformity of heating or cooling, are remarkable for small parts with simple geometry. When treating large parts with horizontal surfaces that remain stationary in the bed, or a bank of several parts, the states of fluidization around the parts are different, and the particle stagnation zones appear on the upper surfaces of the parts and in the cavities and holes and even in the bed, forming a thermal screen, which will markedly degrade the uniformity of heat transfer. Various methods can be used to overcome this apparent disadvantage, and these have been incorporated into the design of most fluidized beds. These methods are:

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![Figure 5](image_url)  
**Fig. 5** Relative heat-transfer rates. Heating rates for 16 mm (0.6 in.) diameter steel bars in lead, in salt, in a fluidized-bed furnace, and in a conventional furnace. Source: Ref 1

![Figure 6](image_url)  
**Fig. 6** Recovery rates for 25 mm (1 in.) diameter steel parts in a 0.3 m³ (10 ft³) fluidized-bed furnace

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**Table 1** Comparison of the effects of hardening and isothermal quenching of type D3 tool steel in salt baths and in fluidized beds

<table>
<thead>
<tr>
<th>Heating or cooling medium</th>
<th>Diameter of testpieces (mm)</th>
<th>Preheating temperature (°C)</th>
<th>Total time for final heating and holding at 960 °C (1760 °F), min</th>
<th>Hardness, HRC</th>
<th>Oxide or carry-out</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salt bath</td>
<td>80</td>
<td>3.2</td>
<td>500</td>
<td>44</td>
<td>65.5</td>
</tr>
<tr>
<td>Fluidized bed(a)</td>
<td>80</td>
<td>3.2</td>
<td>490</td>
<td>51</td>
<td>65</td>
</tr>
<tr>
<td>Salt bath</td>
<td>40</td>
<td>1.6</td>
<td>540</td>
<td>51</td>
<td>64.5</td>
</tr>
<tr>
<td>Fluidized bed</td>
<td>40</td>
<td>1.6</td>
<td>500</td>
<td>41</td>
<td>64.5</td>
</tr>
</tbody>
</table>

(a) Small parts of the same steel but with a diameter of 8 mm (0.3 in.) were treated at the same time; hardness of these parts was 66 HRC.
Atmosphere
Fluidizing Gas and Treatment

- Movement of the parts being treated
- Inducing particle circulation in potential stagnation zones by the use of flow-deflector grids
- Introduction of additional agitation in the fluidization zone around the parts, either by localized injection of fluidizing gas or by careful design of the outline of the basket that holds the parts
- Increased fluidizing velocity
- A pulsed gas flow
- A more favorable arrangement of parts and orientation of each part

Fluidizing Gas and Treatment Atmosphere

A full range of atmospheres can be generated within the work zones of fluidized beds by selecting fluidizing gas. Any atmosphere that is used in a convectional heat treatment process can be used to fluidize beds. The choice of gas type depends on the heat treatment process, composition of the alloys to be treated, the heat-transfer rate required, heating means used in the fluidized bed, and the cost of gas. With careful design and the use of low-cost carrying gases, such as nitrogen, even low-temperature surface treatments can be both effective and economical. In fluidized beds, various types of atmospheres can be obtained.

Oxidizing and Decarburezing Atmosphere. Air atmosphere is generally used for most tempering operations and sometimes for hardening at high temperatures, but the oxidizing atmosphere will cause decarburization of steel surfaces. When using hydrocarbon gas-air mixtures as a fluidizing medium and heat source, the carbon potential of atmosphere is related to the gas-air ratio, as shown in Fig. 9. Either gas-rich (low-carbon-potential atmosphere) or air-rich (oxidizing) causes some decarburization or oxidation reactions in the materials being processed. However, these are time-dependent reactions, and, because of the high heating rates of the parts being processed and the subsequent short immersion time required to obtain correct structure and throughout hardness, little surface effect other than discoloration and slight scaling is exhibited in section sizes up to 25 mm (1 in.). For components of larger size, the user must be aware of surface reactions that can occur, particularly as the processing temperature increases. Figure 10 shows the relative decarburization bands for steels held in a fluidized bed.

Neutral or Inert Gases. Atmospheres for the neutral hardening of tool steels can be used for bed fluidization. This practice allows oxygen-free heating of tool steels. However, care must be taken during the transport of articles to the quench tank to prevent decarburization or oxidation.

Nitrocarburizing and Nitriding. Fluidized beds, using atmospheres composed of ammonia, natural gas (or methane), nitrogen, and air, or similar combinations, are capable of performing low-temperature nitriding and nitrocarburizing treatments equivalent to conventional salt bath processes or other atmosphere processes. Many grades of steel can be effectively treated using fluidized beds, including all stainless steels, which require good gas-flow control and the appropriate gas dissociation. High-speed steel tools oxynitrided in a fluidized bed are comparable to similar tools treated by the more conventional gaseous processes. The principles and controls for convective atmosphere processes can be applied to fluidized beds. The diffusion rate of nascent nitrogen into the steel surface in fluidized beds is the same as in ammonia gas nitriding.

Carburizing and Carbonitriding. The more conventional carburizing and carbonitriding atmospheres can be used in fluidized beds and can yield similar results to conventional atmosphere furnaces. The atmospheres can be both the carbon and heat source in one (e.g., mixtures of either propane or natural gas and air and/or nitrogen). Mixtures of propane and air produce the results shown in Fig. 11, which compares the case depths obtained on SAE 8620 steel bearing rings carburized in a fluidized bed and by the conventional atmosphere process. An effective case depth of 1 mm (0.04 in.) is achieved in 1.5 h using the fluidized-bed technique.

The essential advantage of fluidized-bed carburizing and carbonitriding, but in particular of the carburizing process, is the increased rate of carbon penetration from the gaseous phase to the steel surface. The carbon-transfer coefficient at the steel surface is 2 to 5 times that in conventional carburizing furnaces. With increased carburizing temperatures, the carbon transfer in the fluidized bed can be equivalent to that in plasma carburizing.

In conventional propane-enriched-atmosphere furnaces, carburizing occurs through the catalytic decomposition of CO according to:

\[ CO + H_2 \rightarrow C_2 + H_2O \]  

(Eq 1)
Propane enrichment aids this reaction according to:

\[
\text{C}_3\text{H}_8 + 3\text{CO}_2 \rightarrow 6\text{CO} + 4\text{H}_2 \quad \text{(Eq 2a)}
\]

and

\[
\text{C}_3\text{H}_8 + 3\text{H}_2\text{O} \rightarrow 3\text{CO} + 7\text{H}_2 \quad \text{(Eq 2b)}
\]

During fluidized-bed carburizing, the relatively large volumes of propane consumed, together with high gas velocities, favor carburization by the thermal decomposition of propane to precipitate carbon in accordance with:

\[
\text{C}_3\text{H}_8 \rightarrow \text{C} + 3\text{CH}_4 \quad \text{(Eq 3)}
\]

The amount of carbon precipitated is proportional to the number of carbon atoms in the hydrocarbon fuel gas; that is, propane forms more carbon than methane does. In addition, the purity of propane is important, especially with respect to unsaturated hydrocarbon content, which increases its carbon-forming capability. The precipitated carbon reacts instantaneously with the oxidizing products of combustion:

\[
\text{C}_3\text{H}_8 + 5\text{O}_2 \rightarrow 3\text{CO}_2 + 4\text{H}_2\text{O} \quad \text{(Eq 4)}
\]

to form carbon monoxide and hydrogen:

\[
\text{C} + \text{H}_2\text{O} \rightarrow \text{CO} + \text{H}_2 \quad \text{(Eq 5a)}
\]

and

\[
\text{C} + \text{CO}_2 \rightarrow 2\text{CO} \quad \text{(Eq 5b)}
\]

Carburization then proceeds by the catalytic decomposition of CO by H\(_2\), as in conventional carburizing. It is possible that carburization is further complemented by thermal dissociation of the methane formed during carbon precipitation:

\[
\text{CH}_4 \rightarrow \text{C} + 2\text{H}_2 \quad \text{(Eq 6)}
\]

The carbon potential of the atmosphere varies with the air-to-gas ratio, as shown in Fig. 9. For each type of hydrocarbon gas (typically methane, propane, natural gas, or vaporized methanol), a relationship can be established among air-to-gas ratio, temperature, and carbon potential. Control of the reaction and carbon potential of the atmosphere by conventional gas analysis is possible, and fluidized-bed furnaces are equipped with sample ports and probes so that suitable measurements can be taken.

### Chemical Vapor Deposition Atmosphere

The coating precursors are either directly injected into fluidized beds (mixing with the fluidizing gas prior to the injection to the bed) or, more generally and effectively, produced in fluidized beds through reaction between reactive gas and treating agent. By choosing treating agent and reactive gas, metallic and ceramic coatings can be formed on metallic and ceramic substrates. The treating agent may be composed of a refractory powder of alumina (such as Al\(_2\)O\(_3\)) or the like and a powder of a metal or an alloy that serves as the donor of the element or elements to be coated. In addition to the quality of fluidization, the inert oxide also avoids the sintering of the metallic powder. A halide, such as HCl and HBr, is generally used as an activator and is continuously or periodically introduced by inert fluidizing gas (argon) into fluidized beds.

### Heating Systems of Fluidized-Bed Furnaces

Liberation of adequate quantities of heat within fluidized beds is a prime consideration in adapting them for metal processing. Because the transfer of heat from the bed to workpiece is usually much more efficient than the transfer of heat from heat source to fluidizing medium, the greatest difficulty is encountered in transferring a suitable quantity of heat to the fluidizing medium.

In addition, the major part of heat loss from any practical fluidized system is the heat content of the spent fluidizing gas. In instances in which thermal efficiency is unduly influenced by this factor, recirculation of the fluidizing gas or installation of a recuperative system may be justified. Each has been used in practical applications.

Heat input to a fluidized bed can be achieved by several different methods. The most accepted are described in the following sections.

#### External Resistance Heating

A fluidized bed contained in a heat-resisting pot can also be heated by external gas firing (Fig. 13). The retort is made from the same heat-resisting material as the electrical heating system, contained within the furnace combustion chamber, which in turn is surrounded by heat resistance and thermal insulation materials and the furnace casing. A fuel-air mixture is introduced through a combustion burner. Many different types of burners can be used, including recuperator type. The burner can be controlled very accurately down to low temperatures for low-temperature tempering. Controlling the flow of combustion products in the chamber to increase convective heat transfer to the retort, recovering the heat of discharge gas, and pre-heating the combustion air can be used to reduce fuel consumption.

#### Internal Resistance Heating

The gas and particles are heated by suitably sheathed internal resistance-heated elements. This heating method is very similar to that of the immersed electrodes in a salt bath, except for the sheath of the heating elements. The submerged-element heating method provides good heat transfer between the heat elements and the gas and particles. However, the elements and workload will make contact if insufficient care is taken, which limits its application.

#### Direct Resistance Heating

This method uses an electrically conducting material as fluidized media, directly applying power to the bed by means of electrodes to generate Joule heat by the particle-electrode contact resistance, the interparticle contact resistance, and the resistance across each particle. The electrothermal materials usually used include graphite, coke, and silicon carbide. Current distribution within the bed can be controlled by the configuration of electrodes. For example, a working zone with a zero electrical potential can be formed by locating electrodes within the fluidized space between a well-grounded electric screen and the retort, as shown in Fig. 14. When air is used as the fluidizing gas, the chemical reaction of carbon materials with air also provides heat to the bed. Heat-up time from ambient to a temperature of 900 °C (1650 °F) typically takes 1 to 2 h.

#### Submerged Combustion Heating

The technique of submerged combustion consists of passing the combustion products directly through the mass to be heated. This method provides an excellent rate of heat transfer and is now well established for a wide range of liquid-heating applications, including heating.
swimming pools and the concentration of acid solutions. The application of this method of heating a fluidized bed requires that the burner be used such that it provides strong agitation of the suspended particles, thereby achieving the desired properties of excellent heat transfer and uniformity of bed temperature.

Equipment developed for this purpose consists essentially of a burner, two concentric tubes, and a particle separator. A suitable gas mixture is fed through the burner into the central tube, where it is ignited. The flame develops in the tube, and the combustion products escape at its lower end, where they impart heat to the suspended particles before moving up through the annular space between the two tubes. As they rise, a quantity of particles is entrained. These are separated from the gas stream by the deflector plate and fall back into the bed by virtue of gravity. The particle-free gases can be rerouted to fluidize the bed itself to reduce fuel consumption. Figure 15 shows a system that incorporates submerged combustion with a controlled atmosphere for the low-temperature treatment of metals.

Internal Combustion Heating. When an air-gas mixture is used for fluidization and ignited in the bed, combustion occurs in the bed. The advantage of this system is that the heat is generated within the bed, resulting in significant increases in heating-energy use. A typical furnace design incorporating this technique is shown in Fig. 16.

In gas-fired fluidized beds, the supporting gas or fluidizing medium is a near-stoichiometric mixture of gas and air. For a combustible mixture, there is a critical bed temperature ranging between 650 and 860 °C (1200 and 1580 °F), beyond which the gas mixture burns inside the bed. To approach a stable combustion above the distributor and a uniform temperature in the working zone, the bed is required to operate at a high temperature, for instance, above 860 °C (1580 °F) for a natural gas-air mixture. For a bed with an initial temperature of less than the critical value, the gas mixture is ignited above the bed and quickly imparts its heat to the particles, which in turn heats the incoming gas further down the bed. After a period, combustion takes place spontaneously within the bed and is complete within the first 25 to 30 mm (1 to 1.2 in.) of the diffuser once the spontaneous combustion temperature for the gas being used is reached. If the vessel is well insulated, the bed temperature can rise to a theoretical combustion temperature, and heat-up time from cold to 850 °C (1560 °F) is typically between 1 and 1½ h.

An inherent problem to the basic technique is that the bed is fluidized by burning gases. A careful design is essential to approach an optimum fluidization at the desired temperature for a certain heat treatment process. To obtain good temperature control and optimum fluidizing conditions, it is desirable that the heat input rate and fluidizing velocity be independently variable, which makes this technique more difficult to use than external heating. Practical ways to solve this problem include combining with other heating methods, such as external resistance heating and two-stage combustion technology by the use of second air.

Very high temperatures can occur in the immediate vicinity of the distributor/diffuser tile. When the bed is incorrectly fluidized so that this heat cannot be removed from the top of the distributor, theoretical flame temperatures are achieved with consequent deterioration of the distributor. The thermal stresses of expansion and contraction on the distributor tile at these high temperatures tend, even with the best fixing techniques available, to cause failure of joints. In practice, this problem can be overcome by adopting coarse refractory...
The heating-zone atmosphere can be controlled for uniform properties over the cross section of the part. Every part loaded in a bed is affected by the atmosphere and the choice of fluidizing gas, which can be adjusted in a broad range, depending on bed particle size, type of fluidizing gas, fluidizing gas velocity, and bed temperature. The heating rate (time) is close to those in convection furnaces, and they have low operating costs under service conditions because of high thermal efficiency and low fuel consumption.

Applications of Fluidized-Bed Furnaces

The fluidized-bed furnaces can be accepted as a viable alternative to more established techniques, such as salt and lead baths and atmosphere and vacuum furnaces, used for isothermal and thermochemical processes of many types of materials. Figure 17 specifies those applications in which fluidized beds can compete with conventional furnaces. The popularity of fluidized-bed furnaces in heat treating is growing considerably due to the natural characteristics of the fluidized-bed technology.

Advantages of Fluidized-Bed Heat Treatment

The major advantages of fluidized-bed heat treatment include:

- The heating rate (time) is close to those in liquid salt and lead baths, as shown in Fig. 5, and it can be adjusted in a broad range, which depends on bed particle size, type of fluidizing gas, fluidizing gas velocity, and bed temperature.
- Every part loaded in a bed is affected by the same heating and atmosphere, which is responsible for uniform properties over the cross section in volume heat treatment and for the same case depth in surface heat treatment.
- The heating-zone atmosphere can be adjusted immediately to suit the treatment requirements, and the purity of the atmosphere is equivalent to that of the gas supply.

This makes it possible to change charges in several minutes and easily change from one process system to another (e.g., from nitriding to ferritic nitrocarburizing, or from carburizing to carbonitriding).

- The furnace heat-up time is relatively short compared to that of salt baths, due to the elimination of the latent heat for melting the salt. This means the bed can be shut down overnight without lost production time the following day.
- Fluidized media are nonabrasive and noncorrosive, and they do not wet immersed articles.
- They operate without contaminating the environment. The fluidized material is nonreactive and nontoxic, the process gases can be fully burnt without emission of harmful substances, and there is no solid waste for disposal.
- Expensive gases need not be consumed while there is no work in the bed.
- The capital cost per unit volume of a charge is approximately half that of convection furnaces, and they have low operating costs under service conditions because of high thermal efficiency and low fuel consumption.

Hardening and Tempering of Tool Steels and Components

Applications of fluidized-bed furnaces to the heat treatment of metals include continuous units for all types of wire and strip processing (patenting, austenitizing, annealing, tempering, quenching, and so on) and all configurations of batch-type units for general heat treating applications. An example of using fluidized beds to replace salt and lead baths is the patenting process for steel wire, where three successive fluidized beds were installed: one for heating, another for rapid cooling, and a third for holding at patenting temperatures. With the use of fluidizing gases, such as argon and nitrogen, it is possible to perform conventional neutral hardening processes of all ferrous and nonferrous alloys at a short cycle time. The fluidizing gas can protect the treated surface from decarburization and oxidation at a heating rate comparable with that in a salt bath at temperature uniformity in the operating space of better than $5^\circ \text{C} (9^\circ \text{F})$.

Carburizing, Nitriding, and Carbonitriding

The fluidized bed has thoroughly demonstrated itself to be a practical tool for general thermochemical surface treatments, such as carburizing, carbonitriding, nitriding, and nitrocarburizing. Gas-fired internal combustion units or submerged combustion units have been used successfully to provide both heat source and fluidizing/Carburizing medium. The use of externally heated fluidized beds showed that they are more flexible in the control of the carburizing process as a result of separate heating and fluidizing functions (Ref 9).

Through control and regulation of the carburizing media, fluidized beds show extremely well in the performance of boost/diffuse carburizing because of rapid change in atmosphere between the boost and diffusion cycles. During the boost period, enriching hydrocarbon gas in excess of the desired carbon potential is passed through the bed to produce a buildup of carbon on parts. In the diffuse period, either nitrogen or the gas with lower carbon potential is
present, and the absorbed carbon diffuses toward the core of the material. By altering the carburizing cycle, an optimum carbon profile can be produced, and the final properties of a case-hardened component can be significantly improved.

High carbon levels in the case of the steel can be produced, and dispersed carbides can be deliberately introduced into the microstructure of a case-hardened component to increase both the hardness and wear resistance. Carbide-dispersed carburizing, which cannot be performed in other atmosphere-based furnaces, can improve the performance for such applications as highly stressed gears and molds for concrete and brickmaking applications.

The advantages of fluidized-bed carburizing are reduced cycle time because of faster temperature recovery, and reduced treatment time because it permits use of a higher treatment temperature, which in turn provides rapid carburizing. Nitriding in fluidized beds is not faster than that in conventional furnaces. The major distinction of fluidized-bed nitriding from the conventional method is reduced cycle time because of faster recovery time and rapid change of atmosphere composition when needed.

The principal disadvantage of the fluidized bed is the amount of atmosphere gas it uses. For carburizing, the gas usage for comparable volumes is approximately 1:3 in favor of conventional furnaces. It is possible to reduce the gas consumption by using the boost/diffuse technology and increasing the carburizing temperature without significantly increasing the soaking time. For nitriding and nitrocarburizing, the consumption of reactive gas required to fluidize the bed can increase as much as ten times compared to sealed quench units. Because the fluidized bed does not increase the rate of diffusion over the best achieved in convection equipment, the only possibilities of improving its operating costs, with respect to the treating process, are to increase the depth of the bed, thus increasing the volume of charge, or to reduce the gas flow. The recirculation of atmosphere gases is very efficient to reduce this high characteristic consumption of fluidized beds.

**Hard Surface Coating**

Fluidized-bed reactors (FBRs) have proven themselves to be effective in carrying out chemical vapor deposition (CVD) processes and thermoreactive diffusion treatments. The CVD-FBR has been used successfully to coat coatings, such as boron, chromium, aluminum, silicon, zirconium, vanadium, and titanium, on such metal substrates as copper, steel, and alloy. It has been shown that the materials coated in fluidized beds are equivalent to those deposited by CVD or the salt bath method. Because the part to be coated is in close contact with the treating agent, even very unstable, short-lived species of the chemical reaction between the donor and the activator can contribute significantly to the coating. The deposition is then achieved at lower temperatures than with conventional CVD.

Coating a metallic element and/or elements on the surface of the substrates that have been treated, such as nitrocarburized, allows diffusion to occur between the substrate and the active elements deposited and, in turn, results in the deposition of hard carbide, nitride, and carbonitride layers. The range of applications appropriate for fluidized-bed hard-coating processes is the same as for the conventional thermoreactive diffusion processes (Ref 10).

**Quenching**

A fluidized bed can also be used for cooling or quenching metal parts. A broad range of cooling rates can be approached from gas and oil quenching to those attainable in salt and lead baths, depending on temperature and choice of gas.

Fluidized-bed quenching can be operated together with heating. There are a number of configurations. One design can be likened to a pit furnace, where an upper hot chamber is for heating and a bottom fluidized bed is for quenching. The parts are first loaded into the hot zone above the slumped (static) bed with quenching media similar to normal quenching particles. The slumped particles at the surface of the packed bed act as an insulator. After the end of the heat cycle, the bottom vessel is turned and fluidized with cold gas, and the parts are lowered into the fluidized bed for quenching. Another modus is that the fluidized beds for heating and quenching are structurally...
The steel directly travels from the heating zone to the quenching zone. This is most suitable for the general heat treatment of wire and strip. Another configuration links batch heating fluidized beds to quench tanks with a traveling hood. The hood is purged links batch heating fluidized beds to quench with a protective atmosphere, such as nitrogen, during the sealed quenching.

**Operation of Fluidized-Bed Furnaces**

In practice, general-purpose baskets are used for batch processing, and racks are used only for large tools and dies or shafts. The design of baskets, grids, racks, jigs, and fixtures should minimize any tendency to deteriorate fluidization of the particles, affect particle circulation in the retort, and even retain particles. Adequate support at high temperature is also required. The sides of the baskets should be made of mesh, and the grids should have a minimum of flat surfaces and preferably be made from round material.

**Loading of Parts**

The parts or articles loaded into a fluidized bed should stand individually, independent of each other, rather than stacked in a basket. Normal procedure in handling large parts, such as tools and dies, is to rest them on their vertical axes. Long, slender parts that are likely to distort are wired to the side of the basket, and parts that require vertical jiggling are loaded with inner liners or suitable spacers. The parts should be spaced sufficiently far apart to allow drainage of the particles and to allow adequate gas flow over all surfaces. Wherever possible, the parts should be jigged on their vertical axes. If the parts are to be carburized or nitrided and internal holes are critical, they must be jigged face down. For small parts, two flat surfaces do not touch each other, and the fluidizing gas is allowed to pass over the parts being treated. Parts such as self-tapping screws, bearings, and so on can be placed in a basket in the same manner as in a conventional atmosphere furnace or salt bath.

The deposition of the bed material on the upper surface of treated parts and in cavities and holes adversely affects the uniformity of heating and cooling, as well as the transport of gaseous species to these particle-covered surfaces in the case of thermochemical treatment. Bed collapse can be turned to advantage for special heat treatments in which one area of the part must be hard and tough and the remainder must be soft and more ductile. In this case, after uniform heating, the part is removed from a hot fluidized bed and partially submerged in a fluidized quenching bed, with the part to be hardened facing down. The top horizontal surface becomes covered with a cap of particles that form a thermal screen, which retards the vigorous cooling caused by the fluidized bed.

**Cleaning Operations**

Fluidized solids are nonabrasive and noncorrosive and do not wet immersed objects. There is some dragout loss of the aluminum oxide, however, because some particles accumulate on flat surfaces as workloads are removed from the fluidized bed. These particles can be removed in part by agitating, bouncing, or blowing with an air pipe. Particles can be reused after being dried, sieved, and returned to the bed. When parts already scaled or preoxidized are placed in a fluidized bed, particles tend to adhere to the scale to a greater degree than if the workpieces were clean. These particles can be removed by water spraying.

Alternative cleaning techniques include compressed air or high-pressure water spraying; abrasive blasting that uses compressed air to propel light abrasive particles, for example, glass beads, at a high velocity to impact and clean the surface; and vacuum suction. Cleaner can be added into the spraying media. The blasting can be operated by cycling on and off, instead of continuous spraying. These techniques can be incorporated into mechanical handling systems, and all can clean as well as provide a suitable finish for subsequent operations. For a plant processing a large variety of parts, a compressed air or high-pressure water jet cabin with portable hand guns turned on and off by pedal- or handle-operated valves is the most suitable system.

**Safety**

As with all forms of gas heating, normally accepted safety devices are incorporated into the majority of beds presently manufactured. The flexible-tile concept ensures that any failure of joints does not influence the performance of the bed.

Parts carrying surface oil or moisture will not cause an explosion, and precleaning is not generally required except for certain surface treatments, because the contaminants simply vaporize and are removed with the waste gas, as in conventional furnaces. The heat-transfer medium (aluminum oxide) is nonhazardous and as such is not subject to disposal restrictions.

**REFERENCES**