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Fluidized-Bed Quenching

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FLUIDIZATION occurs when fine-grained materials such as quartz sand are filled into a tank with a gas-penetrable bottom, and a gas, such as air, is blown up through the bottom at such a rate that the buoyed weight of the particles is completely supported by the drag force imposed by the gas. The particles are then able to move relative to one another. During fluidization, the bed of particles gains the appearance and many properties of a true liquid. The fluidized bed provides a means for exchanging heat between a metal part, the solid particles, and the fluidizing gas and is viable for quenching.

The potential of using the properties of the fluidized particle bed for quenching metals was first outlined in the 1950s. Since then, the use of fluidized beds has been investigated for a wide range of quenching applications, from cast iron and tool steels to aluminum alloys, and their use in industrial production is still growing (Ref 1–3).

Design of Quenching Fluidized Beds

The basic design of a quenching fluidized bed is shown schematically in Fig. 1

The bed consists of a container or retort with lateral walls and a gas-penetrable bottom (the so-called gas distributor), in which fine-grinded materials, typically aluminum oxide particles, are fluidized by a passing gas introduced into the bed through the distributor. Parts to be heat treated are immersed in the fluidized bed, individually or loaded all together in a basket. Cooling of the bed to extract the heat removed from the load being quenched to maintain bed temperature is performed by external water jackets or internal tubing. This section briefly considers some of the important aspects of equipment design.

Gas Distributor. The gas distributor (also called a grid) induces a uniform and stable fluidization across the entire bed cross section. To ensure an even distribution of fluidizing gas, it is necessary to use distributors with dense gas-entry points, for instance, a sufficient number of holes in a perforated metal plate distributor, to have an adequate pressure drop through it. Otherwise, the bed will tend to fluctuate in density with channelling and slugging. This is more important for shallow beds, such as wire patenting beds, because once channels have formed, these may persist, so that gas mainly passes up through the void regions of the bed, while nonfluidization prevails in other regions. On the other hand, because an excessive pressure drop can contribute appreciably to the power cost, it is much more practical to keep this to a minimum, consistent with approaching an even gas distribution.

The other most important design variables for a gas distributor include that it should support the weight of the bed when the gas is shut off, not become blocked by particles and atmospheric dust, not cause weepage of solids into the plenum beneath the distributor, and not cause the injected gas to directly impinge on the fixed surfaces, such as container walls or cooling tubes. More design tips and details are provided in major texts and information sources on fluidization (Ref 4).

It is practical to adopt a layer of coarse refractory particles to act as the distributor. The layer is located under the fine particle layer, and the size of its constituted particles is sufficiently large so as to remain unfluidized when the bed is operating.

Plenum. The plenum, or windbox, is the chamber immediately below the distributor. A good design of the plenum and of the connecting gas supply ducting should provide an even distribution of gas without relying solely on the pressure drop through the gas distributor. However, for the case where the ratio of the pressure drop through the distributor to the bed pressure drop is high enough, the plenum design will probably not be that important.

Container. The container is designed to fill a certain height of granules to form the fluidized bed. Refractory containers are generally used for the fluidized beds without an external cooling jacket, while retorts fabricated from a high-melting-point metal alloy are preferable for the fluidized beds with a surrounded cooling jacket to remove heat from the fluidized beds.

As with convection quenching tanks such as oil and water, the fluidized bed must be designed for a maximum temperature rise of no more than 20 to 40 °C (40 to 70 °F) during the quenching cycle. The basic calculations used to size the container are identical in principle to that of sizing other quench systems, and thus, the heat load is calculated and related to the physical characteristics of the bed. For a continuous process, a bed with as shallow a depth as possible is preferable, because this gives the lowest pressure drop and power consumption. Beds too-deep will lead to an increase in the pressure drop through both the particle bed and gas distributor plate.

Bed Cooling and Temperature Control. The quantity of heat that transfers to the bed from the hot parts must be carried off. For a continuous quenching fluidized bed, the rate of heat removal must be the same as the heat-release rate to maintain a constant quenching temperature. This can occur via the fluidizing gas that is blown in at a low temperature, takes the heat from the particles, and then leaves the bed at a higher temperature. By regulating the entrance temperature and the flow rate of the fluidizing gas, the temperature of the fluidized bed may be kept at a constant value. However, the primary cooling by the fluidizing gas is limited, because the velocity of the fluidizing gas through the bed cannot be forced up to more than the terminal velocity of the particles and is, generally, determined by approaching the cooling rate required by the heat treatment process for the parts. Such a fluidized bed is also limited in its production capacity per

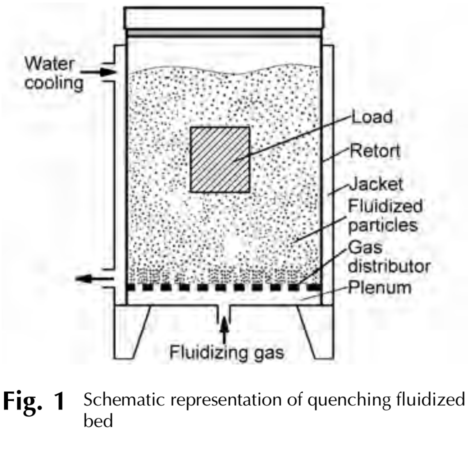

Fig. 1 Schematic representation of quenching fluidized bed

square meter of bed surface, so that a large fluidized bed must be designed to maintain the quenching temperature.

When the heat released from the hot treated parts largely exceeds the heat-removal capability of the quenching fluidized bed through only the fluidizing gas, it is necessary to use additional cooling systems and bed-temperature control means. These include a cooling container (Fig. 1), cooling pipes immersed in the bed, regular water spray, and air cooling of the bed surface (Fig. 2).

Cooling Retort. The retort is similar to that used in the external resistance-heated fluidized bed in terms of heat transfer. It is surrounded by a cooling jacket of a fluid, typically water, instead of a series of electrical elements. The amount of heat that can be removed by the cooling jacket is limited by the ratio of the area of retort surface to the bed volume. For wide, shallow beds, the cooling retort will probably be inefficient. The water jacket is preferably designed to have a higher heat-transfer rate from the retort to the cooling fluid than that from the fluidized bed to the retort. Various types of jackets can be used, such as conventional jackets with or without spiral baffles, dimple jackets, partial-pipe jackets (often called limpet jackets), and so on.

Immersed Cooling Pipes. The bed heat can be removed by cooling tubes immersed in the fluidized bed. This method provides a wide range of cooling rates, depending on the total length of the tubes, the configuration of the tubes in the bed, the cooling-fluid property, and the cooling-fluid flow rate. This cooling system with a controllable cooling-fluid flow rate provides a means to adjust and to maintain a constant temperature inside the quench bed for constant operation.

The cooling pipes can be in various shapes and configurations in fluidized beds. The heat-transfer surfaces or other fixed surfaces immersed into the beds should be either vertical or horizontal, not inclined, because oblique surfaces may cause the gas and particles to flow toward the higher end of the tubes.

When the cooling pipes are arranged along the inside wall of the container, the pipe surfaces should be separated sufficiently to avoid channelling upward in the gap, causing defluidization of the region and local gas bypass. For the cooling pipes horizontally crossing the fluidized bed, the density of the pipes per square meter bed surface should be controlled so as not to cause the bed to collapse and not to disturb the fluidization.

The heat-removal rate of the immersed cooling tube system is determined by the heat-transfer characteristics of the fluidized bed and forced convection flow through the tubes. When a fluidized bed at a temperature of T_{bed} is cooled by immersed thin tubes with a diameter of D, and the coolant inside the tubes has a temperature of T_{cf}, the rate of the heat that can be removed by per meter length of tubes can be approximated by:

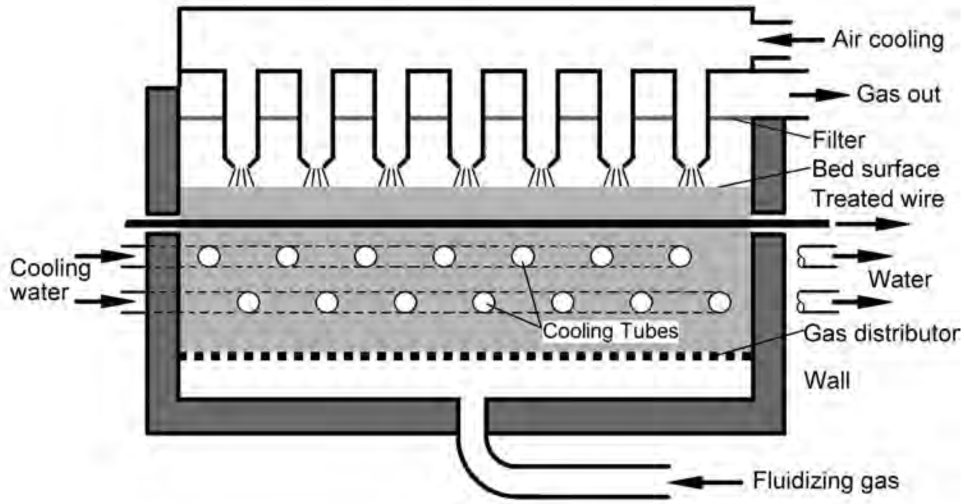

Fig. 2 Schematic representation of continuous-cooling fluidized bed with immersed cooling tubes and surface air spray cooling

$$q = \pi D \frac{h_{bed} h_{cf}}{h_{bed} + h_{cf}} (T_{bed} - T_{cf}) \quad \text{(Eq 1)}$$

The convective heat-transfer coefficient between the cooling tubes and the fluidized bed, h_{bed}, is usually of the order of 300 to 500 W/m^2 · K (50 to 90 Btu/h · ft^2 · °F), while on the coolant side the heat-transfer coefficient for laminar flow in the cooling tubes of a length L, h_{cf}, can be determined by:

$$Nu_D = 3.66 + \frac{0.065 Re_D Pr \frac{D}{L}}{1 + 0.04\left(Re_D Pr \frac{D}{L}\right)^{2/3}} \quad \text{(Eq 2)}$$

or by:

$$Nu_D = 0.023 Re_D^{0.8} Pr^{0.4} \quad \text{(Eq 3)}$$

for turbulent flow, where the Nusselt number $Nu_D = Dh_{cf}/k$; the Reynolds number $Re_D = \rho \upsilon D/\mu$; the Prandtl number $Pr = C_p \mu/k$; and ρ, C_p, k, μ, and υ are the density, specific heat, thermal conductivity, dynamic viscosity, and velocity of the cooling fluid, respectively. The transition from laminar to turbulent flow of the cooling fluid occurs at a Reynolds number of approximately 2300.

Water is typically used as the coolant. However, particle agglomeration may occur on the pipes, because the residual moistness in the fluidizing gas condenses against the cold cooling pipes. This leads to a particle-cake formation around the pipes, which reduces the heat transfer to the tubes and also causes the fluidized bed to rapidly block up or collapse. Therefore, it is preferable to regulate the water flow rate to control the cooling rate in order to keep the cooling-zone bed temperature above the saturation temperature of the fluidizing gas. An alternative is to use ambient air as the cooling fluid, although air has a smaller cooling capacity than water, or use a dry fluidizing gas to avoid the condensation.

Bed Surface Spray Cooling. Spray cooling occurs when ambient air is blown into the surface-particle layer above a fluidized bed. The air contacts with the particles erupted from the bed and the particles that constitute the upper surface of the bed, removing part of the energy of the particles due to the particle-gas convective heat-transfer effects. The cooled particles return into the bed, and hot particles are drawn up to the bed surface by the fluidizing gas and cooled there, so that a continuous heat removal is implemented by the bed-surface air spray. This cooling system generally consists of a ventilator, a regulator, and ducts to transport air to the air ejectors.

The advantages of this method are no disturbance in the bed, simple equipment, and very low cost for coolant. The main disadvantage is its small heat-removal capacity for deep beds, due to the low portion of surface particles being cooled relative to all bed particles when air is used above the bed. When the air is mixed up with atomized water, the cooling capacity is enhanced, due to the latent heat of evaporation in addition to substantial single-phase convection. However, care should be taken to avoid particle agglomeration in the upper surface of the bed.

Quenching Power

Heat-Transfer Characteristics

Cooling Rates. The cooling rate in a fluidized bed is higher compared to air cooling and approximately 10% lower than molten salt quenching. However, the fluidized bed can operate at lower temperatures without solidifying.

A comparison of the cooling curves of a fluidized bed to other common types of quenchants is given in Fig. 3. It is obvious that the fluidized-bed quench is slower than water and oil. The cooling rate in (°C/s) obtained in the fluidized bed is approximately 65% of that of the oil bath in this case. However, in high-temperature quenching, fluidized beds may provide a higher cooling rate than oil or water because there is no boiling in the fluidized beds.

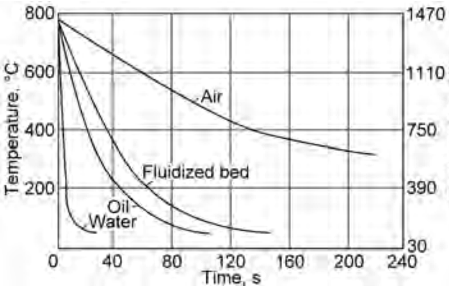

Fig. 3 Comparison of cooling curves for 16 mm (0.6 in.) diameter steel bars cooled in various quenching media from approximately 780 °C (1440 °F) to room temperature. Source Ref 3

Heat-Transfer Coefficients. The heat-transfer coefficient is a useful and comparable quantitative measure for assessing the quenching power of a medium. With the help of computational modeling, cooling rate and temperature change at any position in a specific part, such as at the surface and in the center, in a quenching medium can be reasonably predicted by the heat-transfer coefficient to obtain a general opinion on the possible application of the quenchant medium for the part, without the need of practical data or performing physical measurement for the quenching of the part to be treated.

The value of the heat-transfer coefficient of a fluidized bed depends on many technological factors and can vary between wide limits. Values of some fluidized beds are given in Fig. 4 and compared with other quench media.

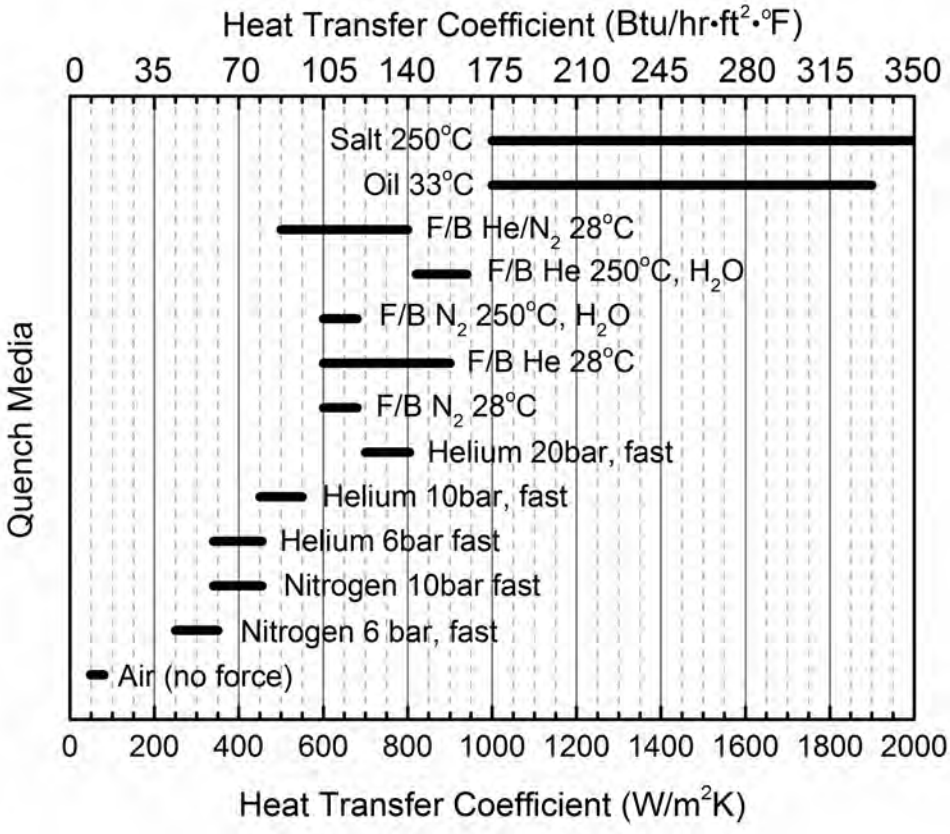

Fig. 4 Guide to the range of heat-transfer coefficients for various quench media against fluidized-bed quenching. Source: Ref 2

Table 1 Effect of grain diameter and density of fluidized bed (quartz sand) on the heat-transfer coefficient, W/m^2 · K (Btu/h · ft^2 · °F)

Density		Diameter, µm (mils)			
kg/m^3	lb/ft^3	50 (2.0)	100 (4.0)	200 (8.0)	400 (16.0)
1300	80	700 (125)	570 (100)	400 (70)	240 (40)
650	40	540 (95)	390 (70)	260 (45)	160 (30)
325	20	410 (70)	280 (50)	200 (35)	100 (20)

Source: Ref 6

Fundamental Factors Affecting Quenching Power

The quenching power of fluidized beds mainly depends on particle size, particle material, fluidizing gas composition, fluidizing gas flow rate, bed temperature, and the arrangement of quenched parts with respect to one another and to the bed.

Fluidized Particles. Desirable properties of particles intended for quenching fluidized beds include appropriate particle size, density and shape, good attrition resistance, appropriate hardness, no surface stickiness, inert to high temperatures of 1500 °C (2730 °F) and above, good resistance to thermal shock, no chemical reactivity with the fluidizing gases, and no toxicity. They should also be readily available and inexpensive. The size, density, and shape determine the fluidization quality and cooling rate. The particle classification of Geldart depending on the particle diameter and the relative density difference between the fluid phase and the solid particles (Ref 5) can be used to choose the particles in regard to the fluidization quality. Rounded particles provide a good fluidization and cause less surface wear than particles with sharp corners and edges.

Particle size has the greatest influence on heat transfer in fluidized beds (Table 1). Figure 5 also illustrates changes in the cooling rate with different particle sizes. The optimum particle size is in the range of 100 to 150 µm (4 to 6 mils). Small grains show a tendency to agglomerate, an irregular fluidization, and excessive dust from the bed. The heat transfer is also considerably affected by the bed density, which, in turn, depends on the density of the particle material themselves and on the degree of their loosening. The most commonly used materials are aluminum oxide (Al_2O_3) and silicon carbide

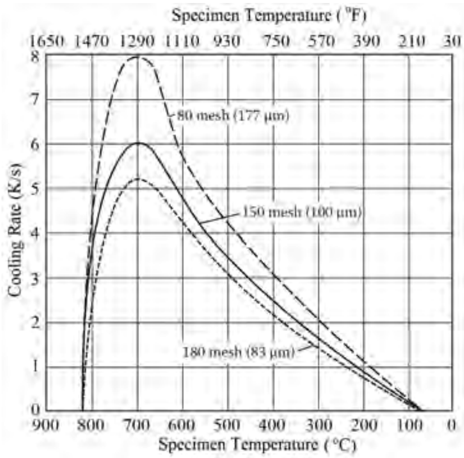

Fig. 5 Effect of alumina grain size on cooling rates for 50 mm (2 in.) diameter and 100 mm (4 in.) length steel samples quenched in an ambient-temperature fluidized bed. Source: Ref 1

(SiC) particles operated at a bed density of approximately 1761 kg/cm^3 (110 lb/ft^3). The thermal conductivity of the particles has little or no effect on the heat transfer.

Fluidizing Gas. The effect of the type of fluidizing gas on the quenching power is mainly attributed to its thermal conductivity. Higher conductivity provides a higher cooling rate, as shown in Fig. 6. Hydrogen and helium, which have thermal conductivities of 0.168 and 0.139 W/m · K (0.0975 and 0.0805 Btu/h · ft · °F), respectively, at room temperature, are high- thermal-conductivity gases, while nitrogen and air, which have a thermal conductivity of approximately 0.024 W/m · K (0.014 Btu/h · ft · °F), are low-thermal-conductivity gases by comparison. The thermal conductivity of argon is 0.0177 W/m · K (0.010 Btu/h · ft · °F) and that of steam is 0.045 W/m · K (0.026 Btu/h · ft · °F). Also, mixtures of low and high thermal- conductivity gases are used. The heat-transfer coefficients that these gases can provide are given in Fig. 4. Other considerations when choosing fluidizing gas include the cost and reaction (oxidation) with the treated parts.

Air and nitrogen are generally used as the supporting gas when lower heat-transfer coefficients are acceptable. Because of the safety issues of hydrogen, helium is the preferred fluidizing gas to obtain a high cooling rate. The high cost of helium, between 20 and 30 times the cost per cubic meter of nitrogen, is the major problem in changing over to it. The use of steam or water vaporization as an additive to the bed necessitates that the bed be operated well above the vaporizing temperature of water. A cheap and simple way to create a nonoxidizing bed atmosphere is to use cooled exhaust gas from a combustion furnace.

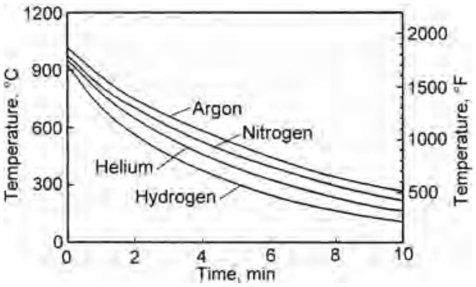

Fig. 6 Effect of gas composition on cooling rates for a 50 mm (2 in.) diameter cylinder. Source: Ref 3

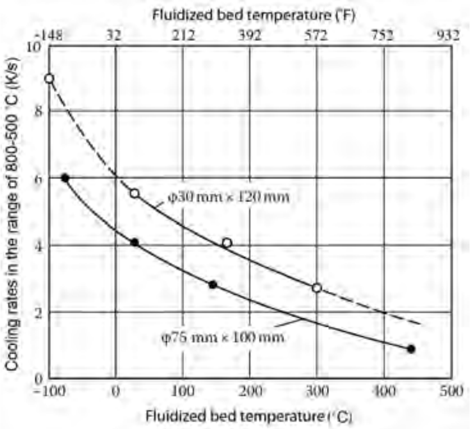

Fig. 7 Effect of fluidized-bed temperature on the center cooling rate between 800 and 500 °C (1470 and 930 °F) of steel specimens 30 × 120 mm (1.2 × 4.7 in.) and 75 × 100 mm (3 × 4 in.) in diameter. Source: Ref 1, 7, 8

Fluidization Velocity. As the flow rate of the fluidizing gas from the minimum fluidization velocity increases, the heat-transfer coefficient initially increases, reaches a maximum, and then decreases. The increased velocity is required for cooling as opposed to heating. The optimum heat transfer for cooling can be achieved when the fluidizing velocity is 3 to 4.5 times the minimum fluidizing velocity required for fluidization. Typical velocities, for example, range between 0.05 and 0.08 m/s (0.16 to 0.26 ft/s) for 100 μm (0.004 in.) corundum particles. The variation of fluidization velocity can be likened to the effect of agitation in oil and water quench tanks.

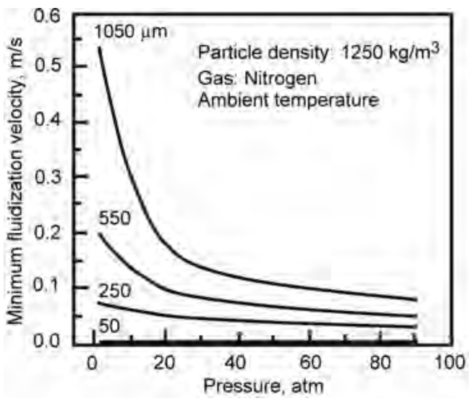

Fig. 8 Effect of pressure on minimum fluidization velocity. Source: Ref 9

Bed temperature influences the quenching capacity of a fluidized bed because of the heat-transfer coefficient at the cooled parts and the difference between the temperatures of the part and the cooling medium. The increase in heat-transfer coefficient with temperature is mainly because of the increase in thermal conductivity of the fluidizing gas around the part. A high temperature difference results in a high heat flux. Fig. 7 shows the variation of the cooling rate at specimen temperatures of 700 and 550 °C (1290 and 1020 °F) as a function of the bed temperature.

Bed Pressure. Because system pressure affects thermodynamic and transport properties of the fluidizing gas, a pressurized operation yields a lower minimum fluidization velocity and enhances the heat transfer. The convective heat transfer is higher under high-pressure operations than it is under ambient pressure, due to a higher gas density and an increase in the thermal conductivities of the gas phase and the dense gas-solid phase. The effect of system pressure on fluidization and heat transfer strongly depends on particle size. For particles greater than approximately 100 μm (4 mils), pressure effects are obvious (Fig. 8, 9). Materials of this size are essentially the particles used in quenching fluidized-bed and other powders of Geldart group B and D. For particles smaller than 100 μm (Geldart group A powders), change in

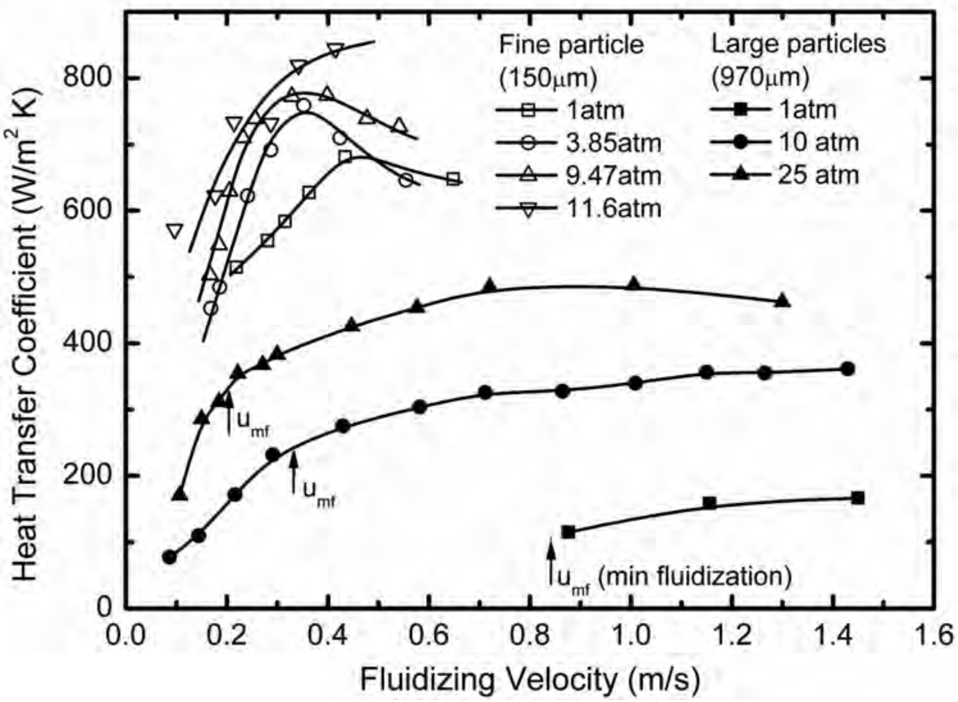

Fig. 9 Effect of system pressure on heat-transfer coefficient. Source: Ref 10 for large-particle data; Ref 11 for fine-particle data

pressure has no effect on minimum fluidization velocity (Fig. 8). High-pressure sealed quenching in a fluidized bed is capable of producing quench rates comparable to oil quenching.

Geometry of Parts and Their Configuration in a Bed. The effect of cooling rate on the shape of treated parts in fluidized beds is similar to that in other quenching media. The section size and the surface-area-to-volume ratio are essential as a single part is treated in a fluidized bed, whereas with loads comprised of several parts, the arrangement of the parts plays an important role, as shown in Fig. 10. In addition, a peculiar occurrence in quenching fluidized beds is the "shield" effect caused by deposition of the bed material on the upper surface of the treated parts and in cavities and holes (Fig. 10, 11), which adversely affects the uniformity of cooling and thus the uniformity of hardness developed. The particle shield acts like a thermal screen, hindering heat transfer. Fig. 12 shows the dependence of heat transfer on the orientation of the treated surface to the stream lines of gas and particles in a fluidized bed. To even out heat transfer between the sides and top face of a section, the workload should be continuously moved, rotated, or horizontally vibrated during cooling.

Application of Fluidized-Bed Quenching

Fluidized-bed quenching provides a number of advantages relative to quenching in molten metal and molten salt baths and oil quenching:

- There are no toxic vapors and gases, compared to salt baths, and no fire and smoke associated with quenching oil.
- The parts contain no salt residues and require no posttreatment as needed with salt baths.

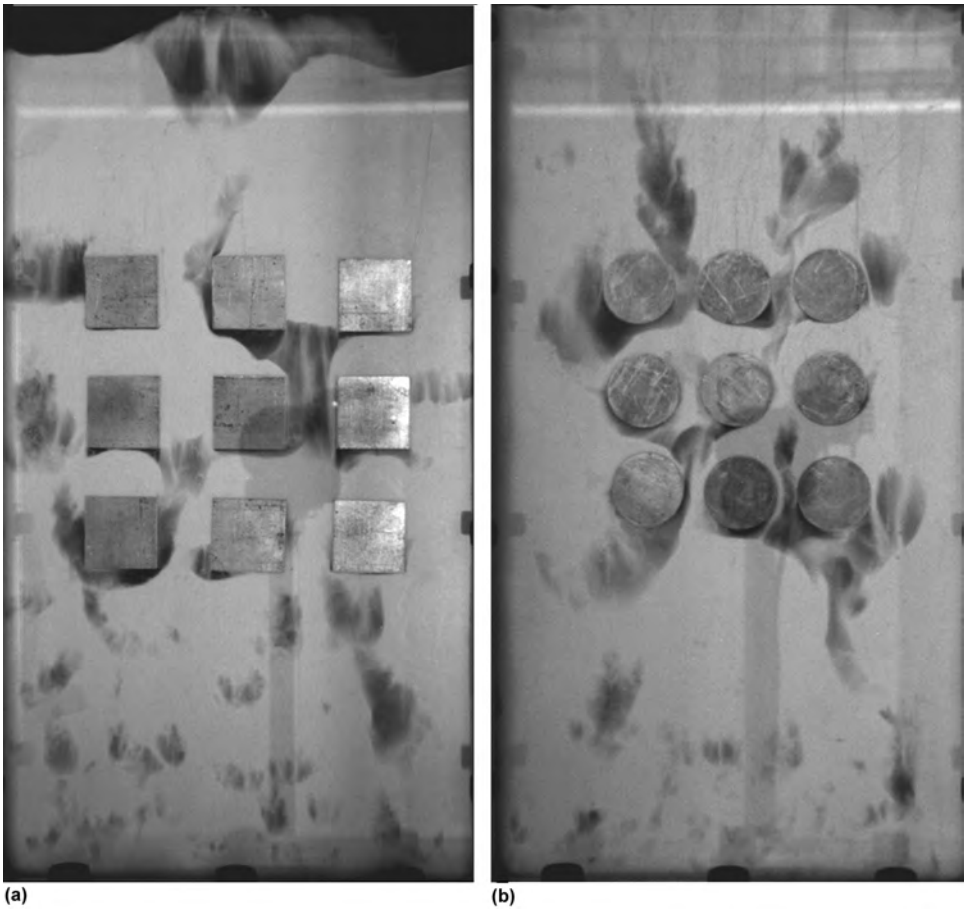

Fig. 10 Images of dense phase (light regions) and bubbles (dark regions) in Al_2O_3 fluidized beds with (a) 30 × 30 mm (1.2 × 1.2 in.) square-section parts and (b) 30 mm (1.2 in.) diameter cylinders at a fluidizing air velocity of 0.055 m/s (0.18 ft/s) (minimum fluidizing velocity = 0.021 m/s, or 0.069 ft/s)

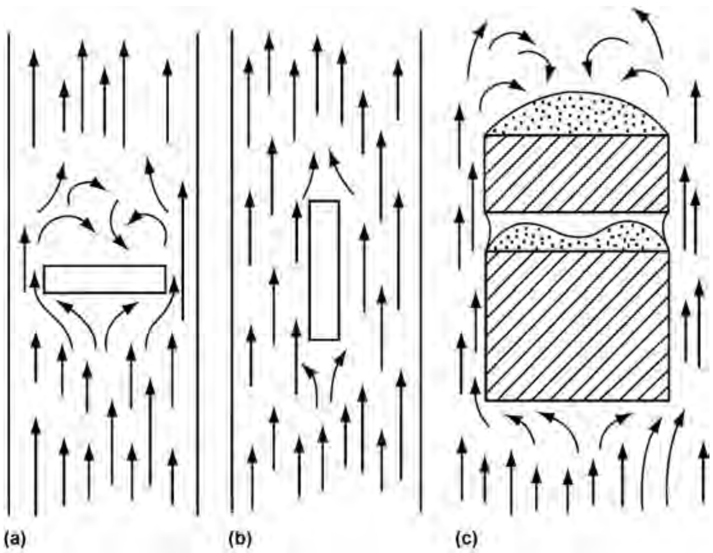

Fig. 11 Effect of part arrangement and shade phenomenon on cooling conditions. (a) Abnormal arrangement. (b) Correct arrangement. (c) Shade phenomenon. Source: Ref 12

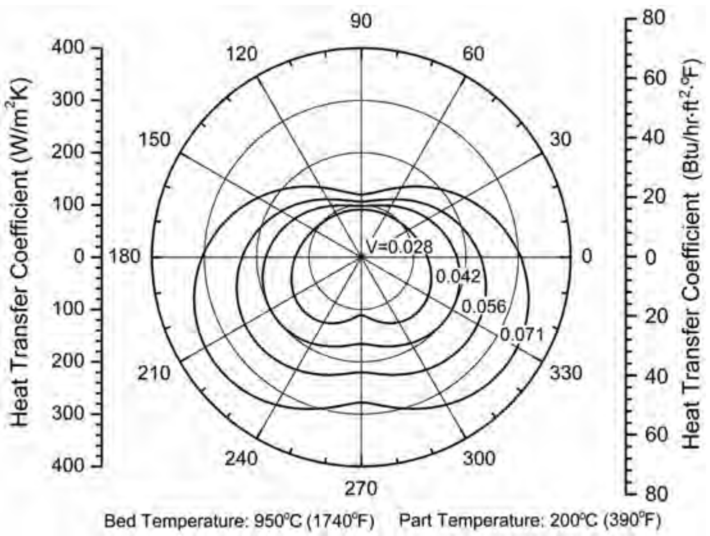

Fig. 12 Dependence of heat-transfer coefficient on the surface orientation of an 80 mm (3.2 in.) diameter by 30 mm (1.2 in.) long cylinder. Source: Ref 13

- The melting operation that is necessary with salt baths is not needed, so the fluidized bed is continuously ready for use, and energy consumption is reduced.
- Unlike vaporizable liquid quench media such as oil and water, where boiling limits the quenching rate and adversely affects uniform quenching and causes distortion, fluidized-bed quenching does not vary through the quenching process.

The major barrier to the use of fluidized beds in quenching is that they exhibit a lower quenching power than salt baths. This may rule out fluidized-bed quenching for some applications due to part geometry or alloy quench sensitivity. Cost is another significant disadvantage when expensive fluidizing gases such as helium are used and not recycled.

In addition to the aforementioned advantages, there are two important features that fluidized-bed quenching possesses. The heat-transfer coefficient can be adjusted over a wide range, because of the rapid change of gases and the flow rate of the gas within the bed. The fluidized bed can operate at any low temperature, and different-temperature quenching processes can work together. Therefore, in cases where hardness values in fluidized-bed quenching are slightly lower than those of the other quenchants, higher hardness can be obtained by slightly decreasing the fluidized-bed temperature. These, to some extent, compensate its major drawback of low cooling rate compared to salt baths.

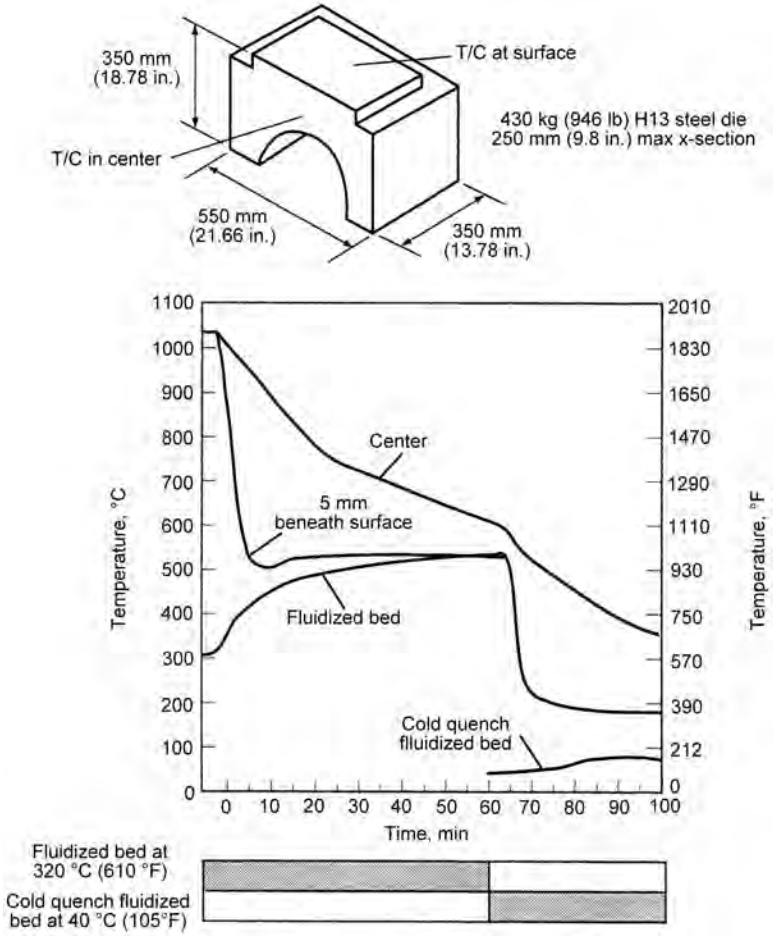

Fig. 13 Cooling curves for fluidized-bed quenching of a 430 kg (946 lb) H13 hot-work steel die casting tool. T/C, thermocouple. Source Ref 3

Fluidized-Bed Quenching Processes

Fluidized-bed quenching can be used for many grades of tool and alloy steels, and its potential for use in other applications continues to increase. It is possible for hydrogen or helium fluidized-bed cooling to replace oil quenching in a large number of applications. In heating operations and in marquenching and martempering, helium and hydrogen fluidized beds are good substitutes for salt baths in some situations. If correctly controlled, fluidized-bed quenching can replace high-pressure quenching in a vacuum furnace. Fluidized-bed quenching is also used to accelerate cooling after tempering or to heat treat aluminum alloys.

Fluidized beds can be operated in batch model for general quenching applications and in continuous model for various types of wire, tube, and strip quenching.

Conventional Batch Quenching. Fluidized-bed quenching is performed in a conventional manner, where one carrying gas is used and the treated parts stay in the fluidized bed through the cooling cycle. Low-temperature quenching of air-hardening tool steels, for example, is a typical application. The process requires that the quench rate must be severe enough to effect full metallurgical transformation of thick sections while not causing severe distortion or cracking. The quenching powers

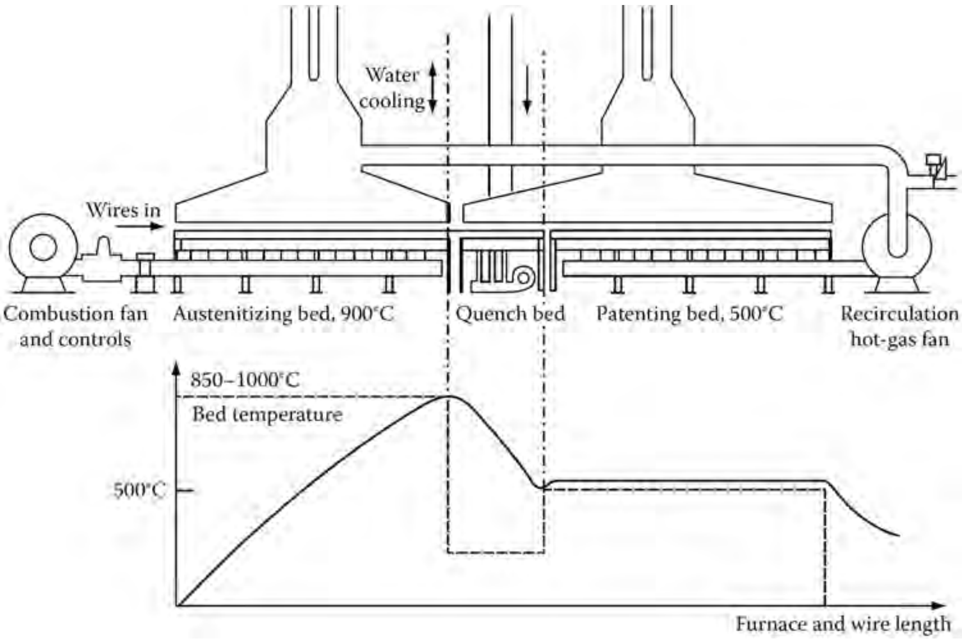

Fig. 14 Three-zone fluidized-bed arrangement and quench-temperature ranges. Source Ref 12

of various fluidized beds with respect to the carrying gas can be found in Fig. 4. With the use of hydrogen and helium, a fluidized bed affords a cooling rate similar to that of an unagitated salt bath. Using helium gas at 28 °C (82 °F), for example, the heat-transfer coefficient is in the range of 820 to 870 W/m^2 · K (144 to 153 Btu/h · ft^2 · °F), with a maximum cooling rate of 22 °C/s (40 °F/s). This cooling rate is fast enough to form satisfactory metallurgical properties in steels such as SAE 8620 (Ref 2). A fluidized bed that uses a water additive was designed to replace salt baths for austempering low-alloy steels (Ref 3).

Two-Step Batch Quenching. The conventional fluidized bed has insufficient heat-transfer characteristics to be used in the quenching of medium- and low-alloy steels because the critical stage of their cooling cycle is the first 10 s, where a high cooling rate is necessary to avoid precipitation of proeutectoid carbides at the grain boundaries. This limitation is overcome by a two-step process. In the first step, helium is used in the critical portion of the cycle (the nose of the isothermal transformation curve). In the second phase, nitrogen replaces helium for the rest of the cycle. The following are some application cases.

Case One. The two-step fluidized-bed quenching process was applied in austempering 4340 medium-carbon steel tools to replace salt processing; that is, the parts were austenitized at 920 °C (1690 °F), quenched in salt at 315 °C (600 °F), and then held for 30 min at that temperature. In fluidized-bed quenching, helium was used for the first 30 to 60 s and then the carrying gas was switched from helium to nitrogen for the remainder of the cycle. For the two-step process, the quench temperature was reduced from 330 to 295 °C (625 to 565 °F). The hardness of these parts was lower than that of those treated with the salt process. The desired result was obtained by slight reductions in the fluidized-bed temperature.

Case Two. In marquenching hot die steel H13, a fluidized bed at approximately 320 °C (610 °F) was used for 5 to 7 min in the initial critical period. When the bed temperature increased to between 500 and 520 °C (930 and 970 °F) due to the heat extracted from the hot dies, the dies were removed and finally quenched in a cold-quench fluidized bed operating at 40 °C (105 °F). The results of a typical cooling process are given in Fig. 13. The marquenching of H13 tool steels was also implemented by initially quenching the parts in a cold- or ambient-quench fluidized bed for 7 min, then transferring them to a second bed at 350 °C (660 °F), and finally cooling in a fluidized bed at ambient temperature.

Continuous Quenching. Continuous fluidized-bed quenching exhibits high flexibility and improved process control, especially when operating together with fluidized-bed heating. The most typical example uses fluidized beds for the heating and cooling operations to perform wire patenting, as shown in Fig. 14. In between two tanks for austenitizing and austempering at a temperature of approximately 500 °C (930 °F), a short, water-cooled tank for fluidized-bed quenching at approximately 100 °C (210 °F) is installed. The wire to be patented is placed in this tank for a short time so that its temperature only decreases to approximately 500 °C (930 °F). Sealed quenching with an inert gas (nitrogen)-purged hood traveling between heating furnaces and quenching fluidized beds is also a practical case.

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