Electrically Heated Fluid Bed as a Low-Carbon Option for Pyrometallurgical Processes

Kamal Adham[1] (✉), S. Francey[1], and C. McIntyre[1]

[1] Hatch Ltd, Mississauga, ON, Canada
KAdham@Hatch.ca

Abstract. Using a "green electricity" heating source, produced from renewable resources such as wind/solar/hydro, pyrometallurgical processes can lower their carbon footprint significantly. Fluid beds are commonly used for drying ores, calcining concentrates, and decomposing metallic salts, normally with energy input from fossil fuel combustion. Electrically heated fluid beds can be used instead of the fuel-burning units, as a low-carbon option for pyrometallurgical processes. Heating can be provided in several ways, including fluidizing gas-heating, in-bed indirect heating, and in-bed direct heating. These methods and their applicability to different metallurgical processes are described in this paper.

Keywords: Fluid bed · Electrical heating · Low carbon

1 Introduction

Carbonaceous fuels are commonly used to heat solids in metallurgical processes such as drying, calcination, and various high-temperature reactions. Fluid beds are commonly used for many of those high-temperature processes, in part due to their excellent heat transfer capability. Fluid beds can also be heated electrically, and when green electricity is used, the carbon footprint of these processes can be lowered significantly. This paper describes three methods of electric heating, fluidizing gas heating, in-bed indirect heating and in-bed direct heating, and the applicability of these methods to different metallurgical processes.

2 Heating the Fluidizing Gas

In a conventional fluid bed dryer, the fluidizing gas is heated by the combustion of a carbonaceous fuel in an external burner, sometimes referred to as a hot gas generator. The flue gas from the hot gas generator is directed to the wind box of the fluid bed dryer. The hot gas passes through the tuyeres or distributor plate, fluidizing and drying the solids. As an alternative to combustion, electric resistance heating can be used to heat the fluidizing gas upstream of the fluid bed dryer, as depicted in Fig. 1. A variety of

Proceedings of the 61st Conference of Metallurgists, COM 2022,
https://doi.org/10.1007/978-3-031-17425-4_17

electric resistance gas heater configurations are available on the market, such as duct or in-line heaters and circulation heaters.

The maximum temperature of the gas output is limited by the maximum continuous operating temperatures that can be sustained by the heating elements in a given gas environment. For certain gas mixtures, there may be other limitations associated with the decomposition of gaseous components at high temperatures and potential fouling/ deposition on heating element surfaces.

Efficiencies of conversion of electric energy to useful heat in excess of 95% can be achieved in electric resistance heating systems. The cost and heater size will depend on the amount of energy input, the target temperature, operating pressure, and the gas flow rate and composition. As the large-scale heavy industry seeks out electrification solutions to support decarbonization efforts, the development of higher capacity, high-temperature electric resistance gas heating systems is being pursued.

In fluid bed dryer applications, there are limitations on the maximum temperature of the fluidizing gas that can be accepted, and these limits tend to be within the temperature range that the electric resistance gas heaters can provide. For example, mechanical constraints for a conventional fluid bed dryer wind box, tuyeres, and distributor plate typically limit the maximum fluidizing gas temperature to approximately 800 °C. Process-specific considerations may also limit the maximum gas temperature at the tuyere discharge. In the case of potash drying, for example, gas temperatures in excess of 600 °C are usually avoided to prevent the sintering of the potash fertilizer. Similar principles can be considered for fluid bed applications other than drying that also require a supply of hot fluidizing gas.

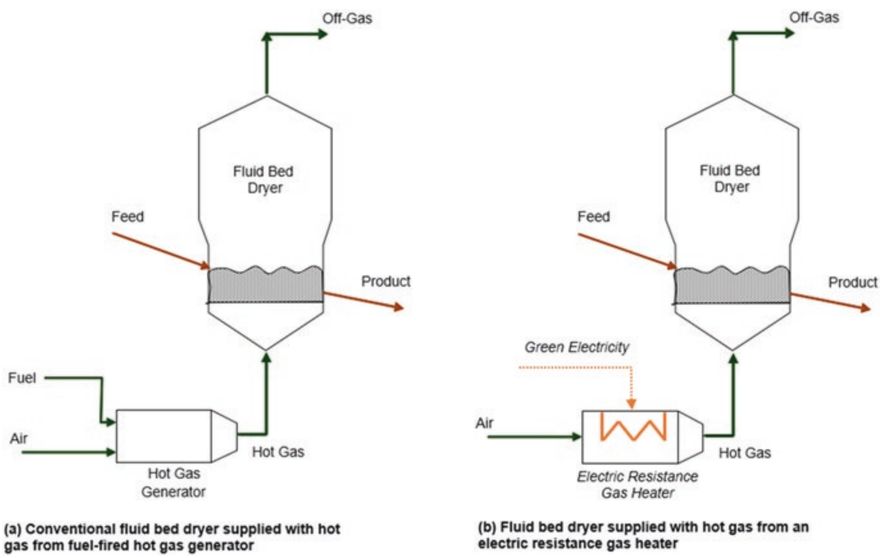

Fig. 1. Depiction of fluidizing gas heating upstream of a fluid bed dryer, using (**a**) fuel-fired hot gas generator or (**b**) electric resistance gas heater.

3 In-Bed Indirect Heating

3.1 Conventional In-Bed Combustion

In conventional fluid beds, carbonaceous fuels (gaseous, liquid, or solid) can be injected into the hot solids and made to burn with the upward flow of fluidizing air. Such in-bed combustion is very effective and efficient, as the energy release is almost completely and instantaneously absorbed by the solids. For example, gaseous combustion generally occurs within the first 25–30 mm of bed material [1]; however, this combustion only occurs when bed temperatures are sufficient to sustain fluidized bed combustion. Critical bed temperatures are generally above 650 °C [1, 2] before which combustion will not occur within the particle bed, but instead immediately above it, requiring the generated heat to pass downwards through the particles. Combustion within the bed will stabilize at higher temperatures, generally over 750 °C [2].

Fluid beds involving liquid or solid fuels require specialized injectors to supply the fuel to the bed. Moreover, solid fuel combustion results in ash residue following combustion which demands ash handling systems and potentially solids separation techniques downstream of the fluidized bed [3].

Careful design of fluid beds implementing in-bed combustion is required since the fluidizing velocity is inherently tied to the desired temperature. As the temperature set point increases, more fuel is required, thereby changing the hydrodynamic characteristics of the bed [1]. Furthermore, the combustion of large amounts of fuel will increase the size of the fluid bed reactor, and the downstream off-gas treating equipment.

3.2 In-Bed Indirect Electric Heating

Electrical heating using in-bed elements (Fig. 2) can be as efficient as combustion, but its effectiveness depends on the maximum element temperature and its lifespan. An in-bed electrical heater operates by converting electrical energy to heat energy through the Joule effect (also known as resistive heating). This heat is transferred to the particles

Fig. 2. Immersion heating element.

either directly through particles contacting the element's surface or indirectly through convection with the fluidizing gas.

Immersing electric elements into the bed will naturally overcome several of the difficulties associated to in-bed combustion. By decoupling the temperature control from the process material balance, off-gas volumes are reduced shrinking downstream equipment, and there is no effect on gas compositions, fluidization regime, or residuals like ash or coke. In addition, tubular electrical elements (Fig. 3) can offer wider ranges of temperature control since there is no required minimum combustion temperature. However, immersing surfaces inside a fluid bed exposes them to high rates of erosion. Erosion concerns can be mitigated through material selection, placement of the elements with adequate space above the distributor plate, and maintaining lower velocity fluidization regimes (ex. bubbling).

While certain electric elements can reach very high temperatures, upwards of 1400 °C, temperatures must be limited within a fluidized bed due to the increased mechanical loading from the particles. Surface temperatures for the electrical element should therefore be typically limited to 1000 °C to avoid mechanical damage to the element.

There must also be careful consideration for local hot spots near the element causing particle sintering due to constrained movement within the coils. Conventional immersed tube banks in fluid beds generally use center-to-center spacings of 2–4 times the outer diameter of the tubes to allow for free-flowing of particles over the surfaces. Additionally, electric heating elements are not recommended to be used with sticky particles due to the increase of fouling associated with these materials.

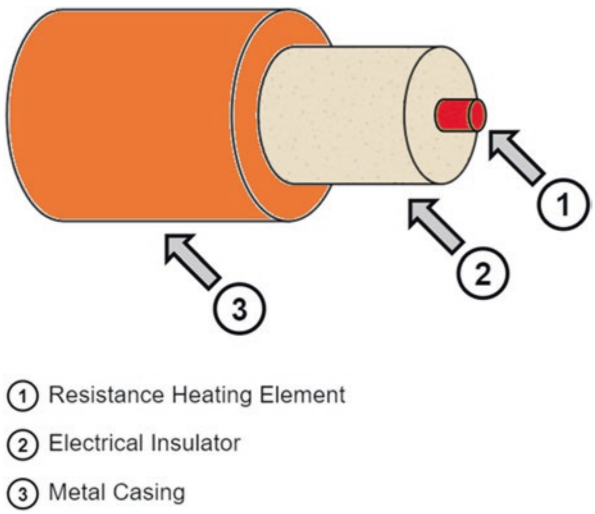

Fig. 3. Cross-section of tubular electric heating element.

4 In-Bed Direct Heating

A number of methods can be used for the electrical in-bed direct heating of a fluidized bed, including microwave, induction, and ohmic heating. Here, we concentrate on the more proven ohmic heating, also known as the electrothermal fluid bed, which can be used for conductive material (e.g., graphite or petroleum coke).

4.1 Electrothermal Fluid Bed

Passage of electricity through a bed of electrically conducting particles can generate a significant amount of heat. However, the particulate bed should have reasonable resistance to the flow of current and not be prone to arcing. The bed resistance depends on many parameters, including the chemical nature of the solids, the surface properties and shape of the particles, the fluid bed voidage, the fluidization velocity, and the properties of fluidizing gas.

For a given gas (e.g., nitrogen or CO) if the fluidizing velocity is increased, the resistance of the bed increases, but if the fluidizing velocity is too low and the bed is not uniformly fluidized, localized hot spots can emerge. Ideally, the resistance offered by the conducting particles generates enough heat within the bed to maintain it in an isothermal condition. A typical electro-thermal fluidized bed reactor [4] equipped with two electrodes (one in the center and another in a graphite crucible) is depicted in Fig. 4.

Electrothermal fluidized bed reactors are very energy efficient, as a minimum amount of external heating or transfer of heat would be required, while the electrical current heats up the bed in situ. However, a mandatory requirement for a reactor of this type is a bed of solids which is electrically conducting and does not volatilize during heating. This problem can sometimes be overcome by mixing a nonconducting solid feed (e.g., iron ore) with a conducting solid additive (e.g., coke as reductant).

This direct method of heating and reacting minerals in an electrothermal fluidized bed has been used in a number of pyrometallurgical operations, mostly for the treatment of carbonaceous material. However, significant limitations for applying the electrothermal fluid beds to new processes exist and include:

- Voltage differential leading to arcing and particle sintering
- Conductivity of material required for electrothermal heating
- Material of construction considerations for the electrodes versus the fluidized bed's environment, to avoid chemical or physical degradation of the electrodes.

4.2 Treatment of Carbonaceous Material

Many carbonaceous materials are good candidates for the electrothermal fluid beds, being conductive particulates with low volatilization at high temperatures. Here we consider two industrial examples of petroleum coke and particulate graphite.

Petroleum coke, as received from the refiners, may not be suitable for making satisfactory electrodes, unless volatiles are removed by high-temperature calcination. The

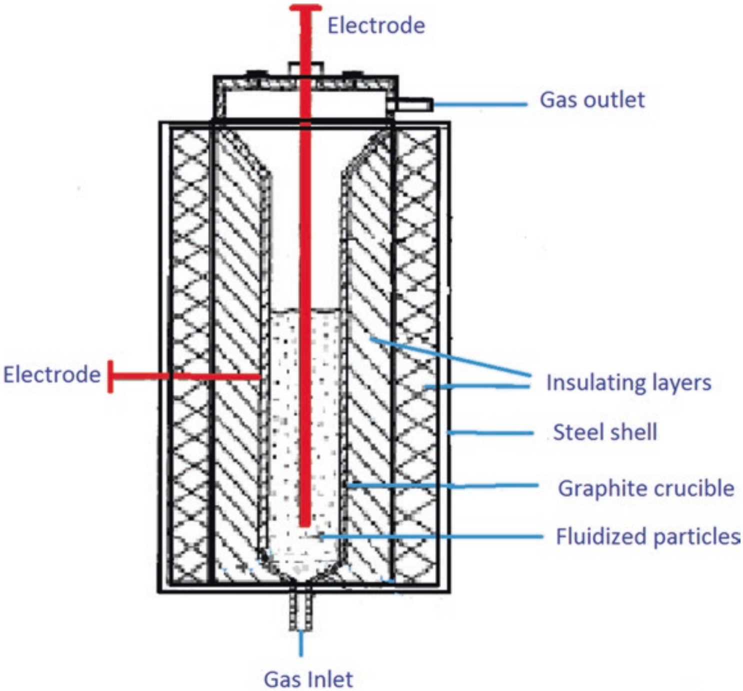

Fig. 4. General features of a graphite electrothermal fluid bed.

energy necessary for the calcination of petroleum coke can be supplied by burning part of the coke itself, but it can also be provided by a green electricity source. Based on the tests in a 1 t/h pilot plant [5], an example case is considered here to demonstrate some of the key parameters governing the operation of an electrothermal fluid bed for petroleum coke. Assuming a maximum electrode voltage differential of 400 V (to avoid arcing) and an AC power factor of 0.8, a current load of 3125 amp would be required for every 1 MW energy input. Using approximately 2.2 in^2/kW electrode surface area, the required electrode surface would be about 2200 in^2 (1.4 m^2).

Natural graphite requires purification, for use in many existing and emerging battery applications. Purification of particulate graphite, to achieve +99.9% carbon content with minimum metallic impurities, can be achieved in electrothermal fluid beds, with a chlorine reagent or with temperature alone.

While thermal purification of graphite at temperatures over 2800 °C is a known option, such ultra-high temperature furnaces are expensive to build and operate [6]. Ultra-high temperatures are required to volatilize most of the silica and other metallic oxides, as shown in Table 1.

For the ultra-high temperature fluidized beds used for graphite purification, it is essential to have excellent thermal insulation and a proper temperature-resistant reactor vessel design. For most ultra-high temperature reactors, graphite is chosen as the construction material and the column is generally insulated with suitable refractory bricks or granules.

Table 1. Typical natural graphite impurities' melting and boiling points.

Oxide impurity	Melting point (°C)	Boiling point (°C)
Silica (SiO_2)	1670	2230
Iron oxide (FeO)	1420	3400
Calcium oxide (CaO)	2570	2850

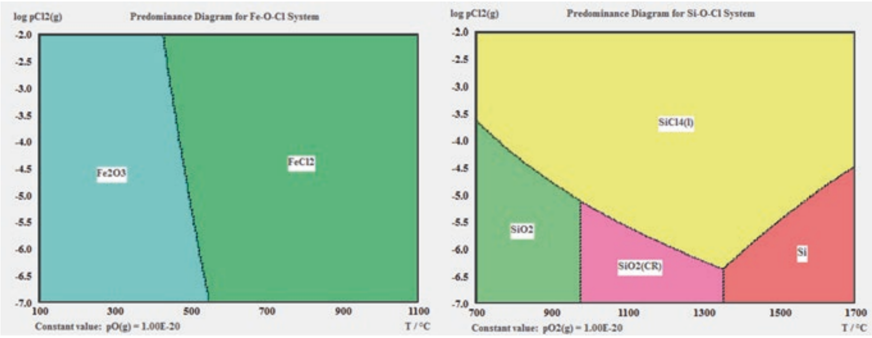

Fig. 5. Lower electrothermal reactor temperatures can be used with the chlorine reagent, as predicted by this HSC® chemical equilibrium simulation.

Using chlorine in a lower temperature electrothermal fluid bed is another option to purify graphite [7]. Chemical reactions that occur between the graphite impurities and the chlorine gas are generally categorized as carbochlorination, where some of the carbon value that is present in excess in the graphite structure, reduces the oxides (turning into CO) and the chlorine gas reacts with the metallic values to turn them into volatile chlorides (as shown in Fig. 5). Most of the metallic impurities can be chlorinated and volatilized at lower temperatures than 1000 °C, but some (e.g., Si) require higher temperatures (up to 1500 °C). However, previous processes have achieved limited commercial success because of the costs associated with chlorine usage (cost and equipment damage) and other chemicals required to treat the reactor's offgas. Chlorine treatment of natural graphite resources can only be commercially successful if these drawbacks are addressed through process and equipment improvements.

References

1. Gao W, Kong L, Hodgson P. Fluidized-bed heat treating equipment. 2014. https://doi.org/10.31399/asm.hb.v04b.a0005927.
2. Friedman J, Li H. Natural gas combustion in a fluidized bed heat-treating furnace. Combust Sci Technol. 2005;177(11):2211–41. https://doi.org/10.1080/00102200500240844.
3. Yang WC. Handbook of fluidization and fluid-particle systems. 1st ed. Boca Raton: CRC Press; 2003. https://doi.org/10.1201/9780203912744.
4. Gupta CK, Sathiyamoorthy D. Fluid bed technology in materials processing. Boca Raton: CRC Press; 1998. p. 310–1.

5. Paquet JL, Foulkes PB. Calcination of fluid coke in an electrically heated fluidized bed. Can J Chem Eng. 1965;43:94–6.
6. Fedorov SS, for Brookhaven National Laboratory, et al. Ultra-high temperature continuous reactors based on electro-thermal fluidized bed concept. J Fluids Eng-Trans ASME. 2016:3–47.
7. Adham K, Bowes G. Natural graphite purification through chlorination in fluidized bed reactor. In: Extraction 2018. The minerals, metals & materials series. 2018. p. 2505–12.