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CURRENT AND POTENTIAL APPLICATIONS OF FLUID-BED TECHNOLOGY IN THE FERROALLOY INDUSTRY

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ABSTRACT

The potential application of fluidized beds in several sectors of the ferroalloy industry is promising. They can be used in the direct reduction of iron ores to produce a feed for steelmaking, in the reduction of manganese dioxide to produce a lesser oxide for feeding to smelters, in the preheating of chromite for the production of ferrochrome, and in the calcining and pre-reduction of nickel laterites for the production of ferronickel. This paper discusses the potential of fluidized beds in theses processes and highlights the advantages of the technology over other technologies, such as rotary kilns. Two primary advantages—(1) that fluidized beds can treat fine materials and (2) that fluidized beds can be integrated with smelters in a way that allows for more efficient use of energy—may well see the technology gain prominence as more deposits of lower grade are mined and industries strive to use their resources more efficiently. In discussing the potential of the technology in the ferroalloy industry, this paper focuses on the application of fluidized beds in the smelting of chromite, nickel laterites, and manganese ores. Central to the successful operation of this technology is a knowledge of how particle properties influence the behaviour and design of fluidized beds.

1. INTRODUCTION

Some time ago Mintek identified a trend in the mineral industry, one of increasing use of finely sized (less than 3 mm) concentrates rather than large chunks (greater than 50 mm) as feed in pyrometallurgical operations. This trend reflects the need to process ore deposits of ever-lower grade. Fluidized beds are ideally suited to the processing of these finely sized raw materials. Given the size of the minerals industry and the depletion of many high-grade deposits, we expect this technology to be applied more extensively. Fluidized beds, moreover, offer better utilization of energy and lower pollutant emissions [1]. This benefit is becoming increasingly important as the price of energy goes up and stricter legislation is applied to protect the environment.

The ferroalloy industry is not exempt from these restrictions. It faces a number of serious challenges. It, too, must come to grips with decreasing quality of raw materials, increasing energy costs and strict environmental regulations [2]. In the production of ferrochromium, for example, costs of electricity and reductants account for approximately 50% of total operating costs. An advanced process design that allows for full utilization of energy carried by furnace off-gas can reduce the overall electricity consumption and CO_2 emissions.

The changes that need to be brought about to accommodate those restrictions can be realized by the application of fluidized-bed technologies. Fluidized-bed systems can be used for preheating and pre-reduction of the furnace charge. The advantages of the technology are its ability to process fine raw materials, its compact design (small foot print), its relatively low capital and operating costs, its simple process control and its high energy efficiency. This paper discusses the operation of fluidized beds in three sectors of the industry: (1) in the preheating of chromite for the production of ferrochrome, (2) in the calcining and pre-reduction of nickel laterites for the production of ferronickel, and (3) in the reduction of manganese dioxide to lower oxides for feeding to smelters.

2. PARTICLE CHARACTERIZATION AND FLOW REGIMES

The British scientist Derek Geldart developed a classification that relates the general behaviour of fluidized beds to particle size and the difference between particle and gas densities (see Figure 1) [3, 4]. It classifies particles into four groups, labelled C, A, B, and D (in order of increasing particle size). Group C particles are cohesive, because the interparticle forces are larger than the gravitational forces acting on the particles. Group C particles clump together and the bed does not fluidize well. The interparticle forces of Group A particles are not as large as the gravitational forces, and beds of these particles fluidize well. The same holds for Group B (sand-like) particles. What distinguishes the two groups, however, is the rate of defluidization: a bed of Group A particles does not defluidize immediately when the fluidizing gas is stopped suddenly. The fluidizing behaviour of Group A particles is, moreover, affected by the amount of fines (particles finer than 44 μm) in the bed. Beds of Group D particles behave similarly to those of Group B particles, but they can also take the form of spouted fluidized beds. For processes in the ferroalloy industry particles should, ideally, fall into the two middle categories, Group A and Group B. The hashed region in Figure 1 covers the range of particle size and density of fine raw materials in the ferrochromium, ferronickel and ferromanganese industries.

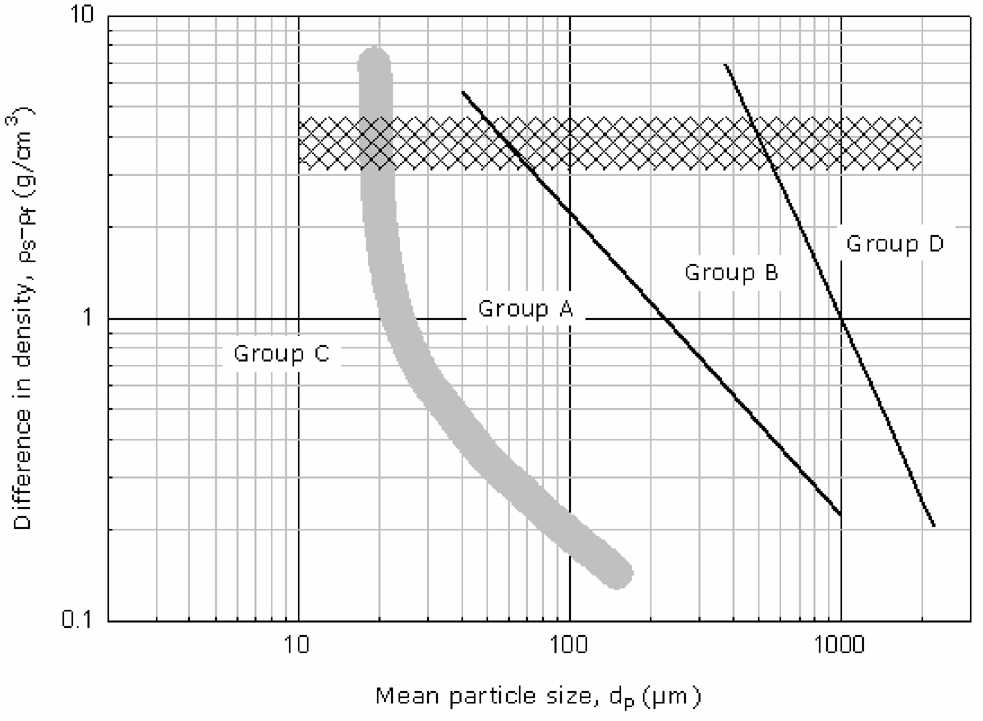

Figure 1: Geldart's classification diagram (at ambient conditions) [3]

How vigorously beds of particles from these two groups (A and B) fluidize depends on a third variable, that of the fluidizing velocity. As the fluidizing velocity is increased, so the fluidized bed passes through four regimes (see Figure 2 which shows the relationship between slip velocity [the difference between gas and particle velocities] and void fraction, ε). At and a little above the minimum fluidizing velocity, u_{mf}, the fluidized bed is described as a bubbling one. At higher gas velocities, the bed becomes turbulent. Finer particles are more readily elutriated; hence the need for cyclones in the freeboard to return these particles to the bed. Elutriation increases with increasing superficial gas velocity; along with this increase is an increase in the size of particles being elutriated. To capture the ever-increasing number and size of particles requires a change in design to an external cyclone and return leg (called a standpipe). The fluidized bed is a circulating one, and fluidization has moved into the fast-fluidized regime (see Figure 2). Solids circulate. Their concentration profile in the riser is a function of the combination of the rate of solids circulation and the superficial gas velocity.

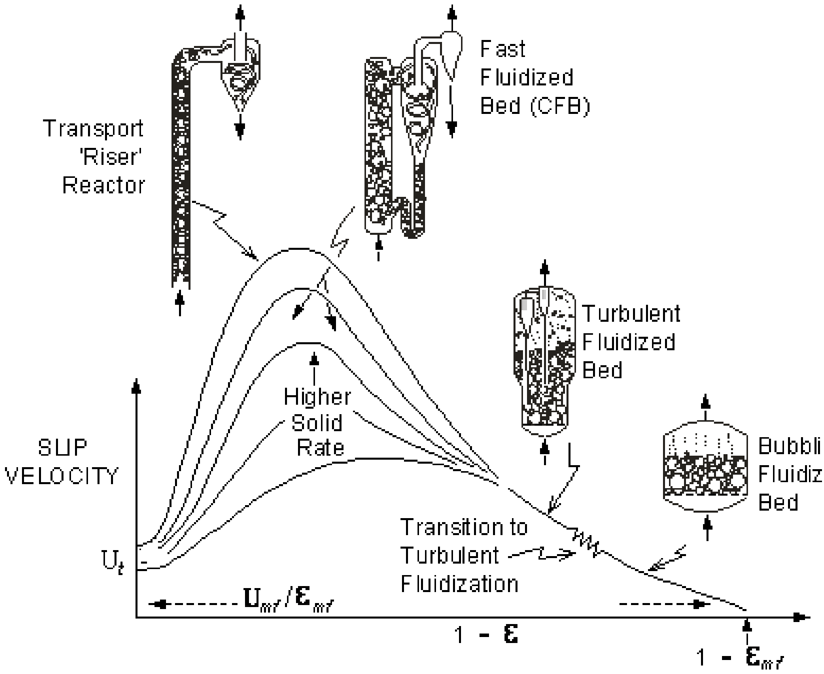

Figure 2: Qualitative fluidization map for fine solids (after Yerushalmi & Cankurt [5])

At higher superficial gas velocities, the slip velocity begins to drop (see Figure 2), and the system enters the pneumatic transport regime. Which regime one chooses to operate a fluidized bed will determine the design of the unit. Another variable, however, affects the ability of a bed to operate in one or other regime. That variable is the spread of particle sizes in the feed to the bed. For solids that are fine or that span a broad distribution of sizes, the fluidized bed may straddle two or more regimes of fluidization (see Figure 3). Should this happen, the bed may not be well mixed, or finer particles may be elutriated without recovery. Only the particle-size distribution denoted by “a” is comfortably accommodated in a single regime; beds of the other distributions either segregate into a fixed part or lose their fine particles to elutriation. Note that the constraints illustrated by Figure 3 are only constraints if the bed is to run in the bubbling mode. These constraints are bounded by minimum fluidizing velocity, u_{mf}, at the low end and terminal velocity, u_t, at the upper end. To operate a bed in the fast-fluidization or pneumatic-transport regimes requires only that terminal velocity of all the particles be exceeded.

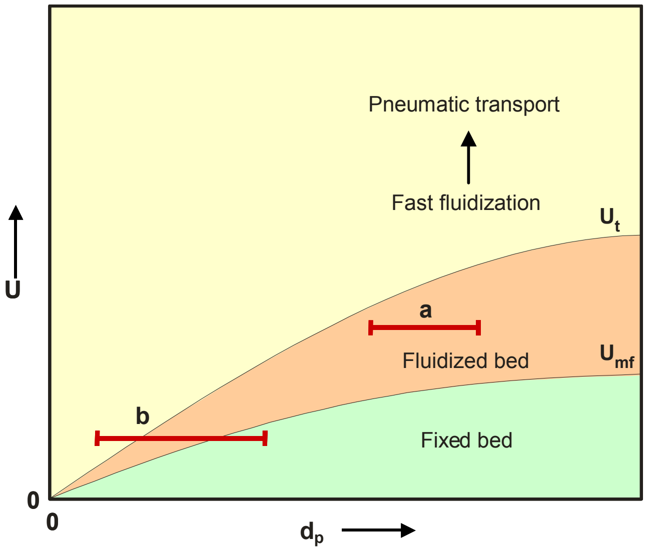

Figure 3: Regimes of fluidization

The analysis of fluidization illustrated in Geldart’s diagram (Figure 1) assumes a behaviour in particles that is unaffected by high-temperature processes. Particles that contain low-melting point phases may be subject to a constraint in maximum temperature. These particles cannot be processed at temperatures exceeding this limit. Higher temperatures form liquid phases that lead to agglomeration and subsequent defluidization.

3. FLUIDIZED BEDS IN THE FERROALLOY INDUSTRY

Electric-arc furnaces are central to the production of ferroalloys. Often, the raw materials or concentrates are pre-treated before they are fed to the smelter. Pre-treatment may include drying, pre-heating, pre-reduction or calcining. Submerged-arc furnaces, moreover, require the feed be lumpy; fine ores need to be pelletized, sintered or briquetted. The standard industrial unit for pre-treatment is the rotary kiln. It and its attendant difficulties have been around for many years.

These difficulties have been overcome by the application of fluidized beds in the direct reduction of iron ore. Nowadays approximately 70% of the iron ore produced is fine ore, which has to be agglomerated (pelletized or sintered with coke) prior to use in conventional iron-making processes. The direct treatment of fine ores is an attractive option in that it does away with sintering, which is a dirty process, and replaces expensive coke with cheaper reductants. Not having a sintering plant and coke ovens saves on costs and emissions. Fluidized-bed reactors, both bubbling and circulating, are being used in the direct reduction of iron ore [6–8]. The FINMET process, developed by Siemens VAI, and Circored process, developed by Lurgi, are the only industrially available and commercially operated direct reduction technologies for the production of hot briquetted iron from iron ore fines.

3.1 Ferrochromium Production

Ferrochrome production is dominated by the Outokumpu process, which involves the agglomeration of chromite fines, followed by sintering, cooling, and screening [9]. Chromite pellets, coke and fluxes are preheated to 600–700°C in a shaft kiln and charged to a closed submerged-arc furnace. Furnace off-gas is used as an energy source in the sintering plant and preheating kiln [10].

Ferrochrome can be produced by another process. This is the DC-arc furnace, which can smelt fine ores without prior agglomeration. The consumption of electrical energy, however, is higher than that of submerged-arc furnace, because of high energy losses to the furnace roof and sidewalls [2,11]. Approximately 11% more electrical energy is required to produce a unit of Cr (in alloy) in the DC-arc smelter than in a similarly rated AC smelter. This disadvantage can, however, be overcome by pre-heating the feed in a fluidized bed or flash reactor. Mintek conducted exploratory pre-heating tests in a 150-mm-ID bubbling fluidized bed in 1984 [12]. Tests were subsequently scaled-up. A 300-mm-ID preheater was constructed and installed above a 200-kVA DC-furnace. The successful, simultaneous operation of these two units demonstrated that the predicted savings in electrical energy could be achieved. More recently laboratory-scale pre-heating tests with chromite ores and coals were carried out in a fluidized-bed facility at Lurgi Metallurgie and followed by a pilot-scale test in a four-stage flash preheater at Polysius AG. These tests confirmed that chromite ores and fluxes can be thermally treated up to a gas temperature of 1150ºC without succumbing to the forces of attrition and producing fines, or forming low-melting point phases and agglomerating.

Denton et al. [13] have compared various pre-heating scenarios and found out that the best option from an economic point of view is to use furnace off-gas to pre-heat the chromite and fluxes to 1200ºC. An economic evaluation showed that the operating costs for the proposed improved DC process are similar to the operating costs of the AC furnace process. However, the capital costs of the AC operation are much higher than those of the improved DC operation, due mainly to the elimination of pelletizing and sintering steps.

According to mass and energy balance calculations, fluidized-bed preheating of the feed to the DC-arc furnace requires approximately 72% of the furnace off-gas, the calorific value of which is 12.3 MJ/m^3 (at STP). The remaining 28% can be sold or used to generate electricity in a gas-fired turbine-generator system.

In the process proposed by Denton et al. [13] the sensible heat of the furnace and preheater off-gases is lost in gas cleaning systems. The thermal efficiency of this process can be further improved if air and furnace off-gas entering the fluidized-bed preheater are heated. A flowsheet for such a process is presented in Figure 4.

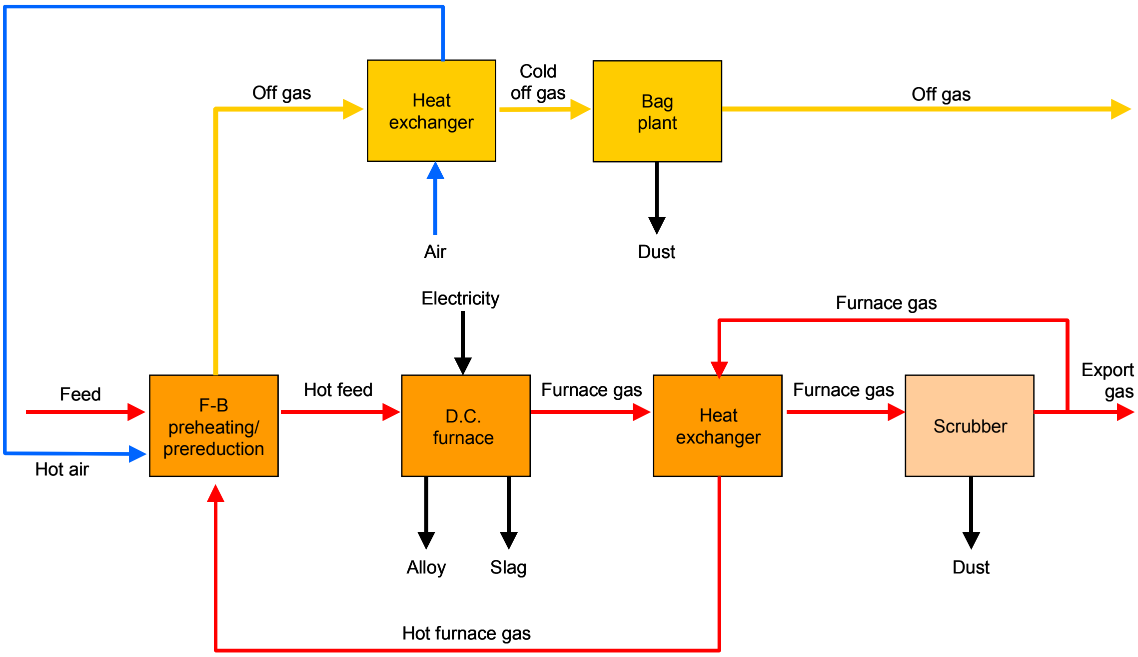

Figure 4: Flowsheet for an improved process for chromite smelting

Mass and energy balance calculations for this process were carried out with assumptions identical to those used in [13]. The chemical analyses and physical properties of raw materials are shown in Tables 1 and 2 respectively. The calculation results for three options – base case (all feed at 25ºC), preheating with air and furnace off-gas at 25ºC, and preheating with air and furnace off-gas at 500ºC – are summarized in Table 3.

Table 1: Chemical analyses of raw materials, %wt.

Material	*Chromite*	*Coal*	*Limestone*	*Silica*
Fixed carbon		53.02		
Volatiles		26.71		
Moisture	0.88	3.54		
Ash		16.73		
Al_2O_3	13.80	5.478	0.45	
CaO	0.46	0.110	51.56	
Cr_2O_3	44.10	0.238		
Fe_2O_3	7.08	1.384		
FeO	18.01	—		0.5
MgO	10.40	0.092	3.28	
MnO	0.24	—		
SiO_2	4.23	8.310	4.2	99.5
TiO_2	0.80	0.468		

Table 2: Physical properties of raw material particles

Property	*Chromite*	*Limestone*	*Silica*
Average particle size, µm	104	44	103
Particle density, kg/m^3	4200	2500	2600
Specific heat capacity, J/kg·K	690	830	740
Thermal conductivity, W/m·K	1.75	4.82	13.8
Minimum fluidization velocity, m/s	0.015	0.002	0.009
Terminal velocity, m/s	0.734	0.121	0.496

Table 3:Flowsheet summary

Parameter	*Base case*	*Option 1 [13]*	*Option 2*
Furnace power, MW	62.4	47.8	47.8
Process energy, MWh/t alloy	3.97	2.87	2.87
Limestone, kt/a	28.0	30.5	30.5
Silica, kt/a	25.0	22.5	22.5
Coal, kt/a	99.2	99.2	99.2
Furnace off-gas, kt/a	130.8	130.8	130.8
Gas to preheater, kt/a	—	92.0	65.9
Air to preheater, kt/a	—	223.8	160.3
Preheater off-gas, kt/a	—	330.3	240.7
Export gas, kt/a	—	35.6	61.7

In Option 2, the furnace off-gas consumption in the preheater drops to approximately 52%, and air usage drops by 28%, which results in the 27% reduction of the preheater off-gas volume. It means that a smaller and cheaper preheater can be installed, and less energy is required to pump air into it. The amount of export gas increases from 35.6 kt/a to 61.7 kt/a. If this gas were used to generate electricity in an open-cycle gas-fired turbine with a thermal efficiency of 45%, the power generated would be 9.6 MW, or 20% of power required in the DC furnace. The same amount of energy generated in a coal-fired power station with a thermal efficiency 35% would require 26 kt/a of high-quality bituminous coal with a net calorific value of 30 MJ/kg. If the fixed carbon content in this coal is 75%, the reduction in carbon emission would be 19.5 kt C/a or 71.5 kt CO_2/a.

3.2 Ferronickel Production

The majority of the world's nickel resources (~60%) are contained in laterite ores. Existing nickel plants treating lateritic ore have significant cost deficiencies due to low energy efficiency, material handling problems and emission control issues. In a typical ferronickel plant, rotary kilns are used for drying and pre-reduction, followed by AC furnaces for smelting [14, 15]. The main causes of high operating costs in ferronickel smelters are:

- High energy consumption due to limited use of hot gases generated in furnaces and kilns and significant losses of sensible energy in these processes
- Smelting furnace integrity (high thermal load on furnace side walls)
- Complexity of the processes associated with material-handling systems and batch operation

To overcome the problems associated with high production costs, Falconbridge developed in the late 1990s a new technology for ferronickel production called NST (Nickel Smelting Technology) [16]. The NST process consists of four stages:

- Drying and milling
- Calcining
- Fluidized-bed in-situ pre-reduction with coal
- DC-arc furnace smelting

A simplified diagram of the calcining and pre-reduction steps is shown in Figure 5 [17]. Wet ore is milled (to –1 mm) and dried in a system that combines a hammer mill with a flash dryer; it is then stored in a dry ore silo. Dry ore is calcined in a multi-stage, counter-current flash calciner at 1000ºC. Hot gases generated by the combustion of coal are used in both the dryer and calciner. Pre-reduction of calcined ore is carried out in a fluidized-bed reactor in which pulverized coal is gasified at 930ºC. Partially reduced ore is hot-fed to a twin-electrode DC-arc furnace where it is smelted at 1600ºC. The furnace off-gas is combusted, cooled with dilution air, and directed to the calciner combustion chamber to recover energy.

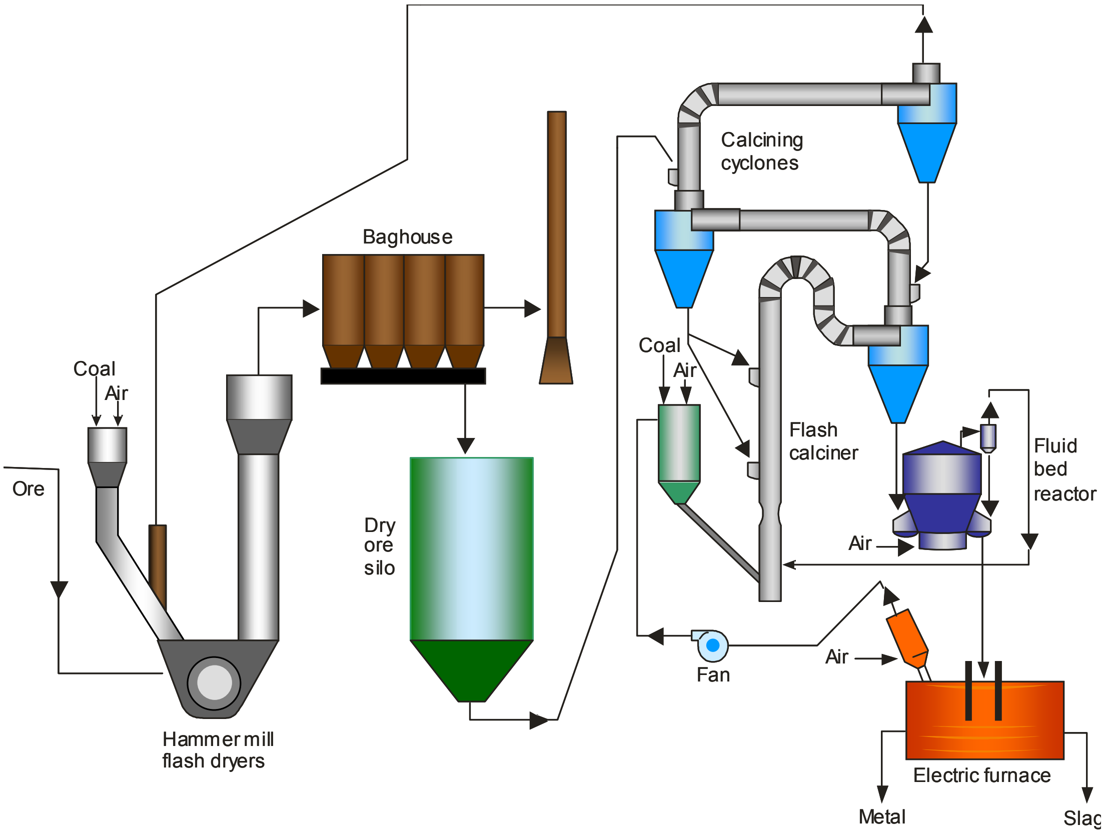

Figure 5: Flowsheet of the Falconbridge NST process [17]

The main advantages of the NST technology compared with the conventional process are:

- Higher thermal efficiency
- Higher availability
- No dust; no pelletization
- Compact design (smaller footprint)

- Lower capital costs
- Lower operating costs

The NST process will be used in the Koniambo ferronickel plant (New Caledonia), which is due to go into commercial operation in 2007.

Outokumpu Lurgi Metallurgie has developed a two-stage fluidized-bed process for the calcination and reduction of laterite fines with reformed natural gas [18, 19]. The schematic diagram of this process is shown in Figure 6. The laterite fines are dried and preheated in a suspension preheater. The dry material is fed into a CFB calciner where it is heated to 900–1000ºC to remove chemically bonded water. Calcining is carried out with the off-gas from the pre-reduction unit and some additional fuel. The calcined ore is transferred to a bubbling fluidized-bed reactor where it is reduced with gas produced in an auto-thermal catalytic reformer.

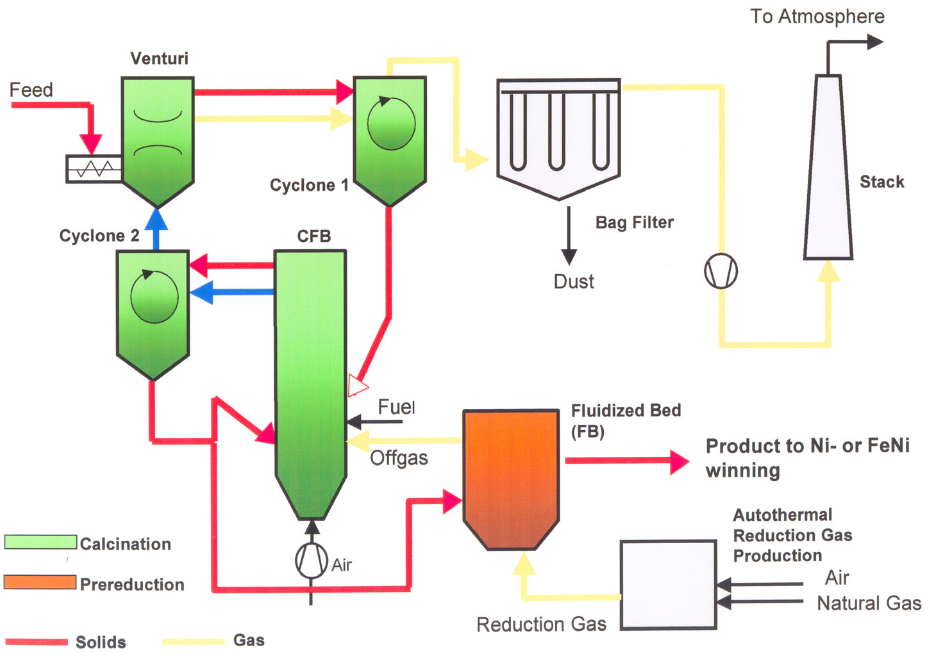

Figure 6: Flowsheet of the Lurgi calcination/prereduction process [17]

The theoretical energy requirement for drying, calcinations and reduction of a laterite ore with 35% free moisture is approximately 3200 MJ/t dry feed. If the thermal efficiency of the plant is 80%, the total energy consumption would be approximately 4000 MJ/t dry feed [19]. Smelting of pre-reduced laterite ore generates a CO-rich gas (~90 vol.% CO) at a rate of about 43 m^3(STP)/t dry feed. Utilizing this gas for drying and calcining can reduce the total energy consumption in these steps by more than 12%. Alternatively, the furnace off-gas can be cleaned and burned in a gas turbine to generate electrical energy. Off-gas leaving an 80-MW DC-arc furnace smelting 140 t dry feed/h can be used to generate approximately 8 MW of electric power in a turbine-generator system with a thermal efficiency of 45%.

3.3 Ferromanganese Production

Thermodynamic considerations indicate that the reduction of MnO_2 and Mn_2O_3 (bixbyite) to Mn_3O_4 (hausmannite) proceeds by thermal decomposition. The further reduction to MnO requires a reducing gas. The reduction reaction is exothermic and very fast, especially if hydrogen is present in the reducing gas.

A two-stage process for the direct production of ferromanganese from sand concentrates (48–53% Mn) has been developed by BHP [20, 21]. In the first stage, MnO_2 fines (average particle size 200 µm) are heated and pre-reduced in a bubbling fluidized bed. In the second stage, pre-reduced ore is smelted in a DC-arc furnace with char or coal as reductant. Furnace off-gas from the smelting stage is used in the fluidized-bed reactor to reduce MnO_2 to MnO. The degree of reduction exceeds 98%. Simultaneously, iron oxides in the concentrate are reduced to Fe_3O_4 (magnetite), FeO (wűstite), or metallic iron, depending on the $(CO+H_2)/(CO_2+H_2O)$ ratio in the bed. The presence of quartz in the ore restricts the maximum operating temperature in the fluidized-bed reactor to 900ºC. At higher temperatures, the formation of molten silicates can lead to the agglomeration of ore and flux particles and their subsequent defluidization. The rapid release of energy in places where the ore meets the bed can produce local hot spots. Sufficient bed inventory and vigorous mixing are necessary to ensure the quick dissipation of released energy and to avoid the formation of liquid phases. The process offers improved thermal efficiencies and, therefore, savings in electrical energy; but, to our knowledge, its development has never moved beyond testing at pilot scale.

4. CONCLUSIONS

The last several decades have seen a number of metallurgical processes adopting fluidized beds. Despite significant efforts put in their development, only a few applications have been implemented commercially. Fluidized beds combined with DC-arc furnaces make possible the treatment of fine ores without prior pelletization or briqueting. Both operations in the combination are high-intensity processes with relatively high specific capacities.

As the need in the ferroalloy industry to utilize fine ores and cheap reductants becomes more pressing, so fluidized beds offer a means for realizing the need. Not only do fluidized beds make possible the drying, calcining and pre-reduction of these feeds, they also do so more efficiently and with lower emissions. Pre-treatment step can use furnace off-gas as the energy source. Fine particles of chromite, nickel laterite and manganese ores are amenable to fluidization because they fall into groups B and A of Geldart's classification.

The cost of electrical energy is a considerable part of operating costs in the ferroalloy industry. Significant savings can be achieved if a portion of the electricity required in the furnace were to derive from the utilization of the furnace off-gas.

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