ADDING VALUE TO SOLID MINERAL PROCESSING: THE ROLE OF CHEMICAL ENGINEERING

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ABSTRACT
Nigeria is richly endowed with solid minerals. Each of the states in the country is blessed with at least one mineral resource. However, the solid minerals of the country such as barite, iron ore and tin are not being fully exploited in spite of the fact that they are available in commercial deposits. This is largely due to the under developed state of the solid minerals sector of the nation. In order to achieve development in solid minerals and for value chain addition, Nigeria needs the expertise and professional intervention of chemical engineers. Chemical engineering is that branch of engineering that deals with the design, construction, installation, operation and maintenance of processes for the conversion of raw materials to the desired finished products. In the light of this definition, Chemical Engineering as a profession indubitably has indispensable roles to play in the development of the solid minerals sector of Nigeria. This paper focuses on the role of Chemical engineering in solid mineral development using iron ore processing as an example. Iron ore is the largest solid mineral that is processed in Nigeria so far.

***Keywords**: Solid minerals, Chemical engineering, beneficiation, process, development, exploitation, iron ore.*

1.0 INTRODUCTION

Chemical engineering is a branch of engineering that applies physical sciences (physics and chemistry) and life sciences (microbiology and biochemistry) together with applied mathematics and economics to produce, transform, transport and properly use chemicals, materials and energy. Essentially, chemical engineers design large-scale processes that convert chemicals, raw materials, living cells, microorganisms and energy into useful forms and products (Wikipedia, 2016). Among the raw materials that are converted into useful products by chemical engineering processes are mineral ores.

Generally, operations in the solid minerals sector of any country can be broadly classified into exploration, exploitation, and processing.

1.1 Exploration

Exploration encompasses all activities that are carried out in order to establish or ascertain the availability of solid minerals deposit in a particular location/region. This includes the quantity of the deposit, the precise location of the deposit underground as well as the geological characteristics of the site. Exploration is usually carried out by geologists and surveyors
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1.2 Exploitation

This involves the use of the appropriate techniques to mine (bring out) the minerals from their deposits underground to the surface of the earth.

1.3 Processing

The processing stage involves the transportation of the minerals to temporary storage prior to processing via beneficiation or refining of the minerals and the conversion of the refined minerals to the desired finished products for the end-users.

Development in solid minerals is possible if and only if the value added chain is perfected such that the final products meet local and international specifications/standards; as the ultimate aim of any firm or nation is to market her products profitably both locally and internationally. The role of Chemical Engineering in solid minerals development includes the design of process machinery for the successful transportation of the raw minerals from the mines to the beneficiation facility, the beneficiation of the minerals and finally, the conversion of the minerals to the desired products. At this stage, the indispensable roles of

Chemical Engineering in solid mineral development can be appreciated.

2.0 SOLID MINERALS IN NIGERIA

Naturally, no solid mineral is found in its pure state. They are mined as ores because of the impurities they contain. These impurities must be separated from the minerals before they can be used. Hence, there is need for beneficiation/purification of the minerals after they are unearthed from their deposits. Figure 1 depicts the various solid minerals in Nigeria and their locations (Chinago *et al*., 2015) and Table 1 lists the minerals and the locations they are found in Nigeria (Malomo, 2007)

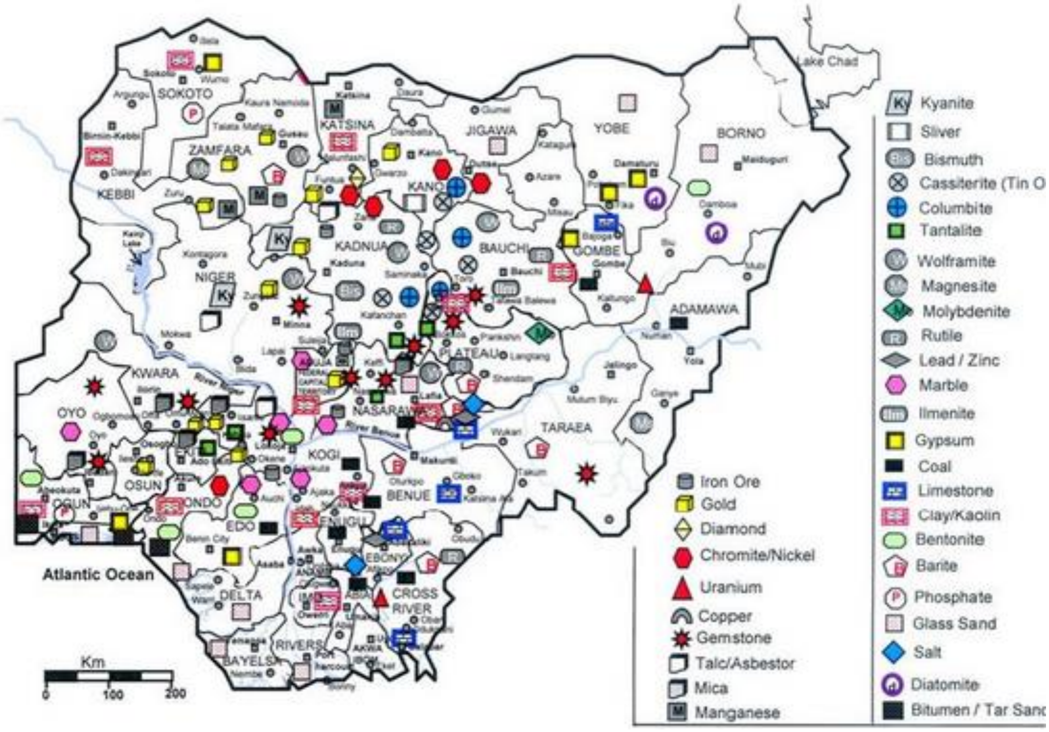


Figure 1: Solid Minerals in Nigeria (Chinago *et al*., 2015).

Table 1: Solid Minerals and their Locations (Malomo, 2007)

MINERAL	LOCATIONS
Kaolin	Katsina, Plateau, Ogun, Bauchi, Ekiti, Ondo, Edo Anambra, Cross River, Akwa Ibom, Abia, Kogi, Enugu, Imo, Benue, Nasarawa, Yobe, Delta, Niger, Kano, and Osun States
Diatomite	Yobe, Borno, and Gombe states
Glass Sand	Cross River, Akwa Ibom, Abia, Imo, Ondo, Lagos, Delta, Rivers, Bayelsa, Ogun, Niger, Nasarawa, Kaduna, Bauchi, Katsina, Kano, Zamfara, Taraba, Sokoto, Jigawa
Gypsum	Adamawa, Taraba, Benue, Edo, Yobe, Sokoto, Gombe, Ogun, Ebonyi, and Borno States
Coal	Benue, Enugu, Nasarawa, Gombe, Edo, Anambra, Abia, and Ondo States
Lignite	Anambra, Imo and Delta,
Kyanite	Kaduna, Niger, Ekiti, and Oyo States
Limestone	Enugu, Abia, Anambra, Cross River, Akwa Ibom, Ogun, Edo, Benue, Nasarawa, Borno, Gombe, Kebbi, Sokoto, Adamawa, Ebonyi, Imo and Yobe States
Salt	Nasarawa , Taraba, Kebbi, Cross Rivers, Bayelsa, Benue, Gombe, and Ebonyi States
Talc	Niger, Osun, Ekiti, Oyo, Ogun, Ondo, Plateau, Kogi, Kaduna, Cross River States and FCT
Marble	Oyo, Edo, Nasarawa, Kogi, Katsina, Niger and FCT
Phosphate	Ogun, Sokoto, Ondo, Kogi, Abia and Cross River states
Dolomite	Kogi, Oyo, Edo, Niger, Nasarawa, Kaduna States and FCT
Feldspar	Ekiti, Kogi, Kwara, Osun, Nasarawa, Ogun, Ondo, Plateau, Niger, Borno, Adamawa, Edo, Kebbi, Katsina, Taraba and Bauchi States

MINERAL	LOCATIONS
Clay (ball clay)	Widely located all over the country.
Bitumen	Ondo, Ogun, Delta and Edo States
Barite	Benue, Cross River, Ebonyi, Adamawa, Yobe, Nasarawa, Gombe, Plateau, Taraba States
Mica	Kogi, Kwara, Nasarawa, Niger, Plateau, Gombe, Bauchi, Borno, Katsina, Kebbi, Benue, Kaduna, Adamawa and Oyo States
Gemstones (topaz, emerald, garnet, sapphire, fluorspar, aquamarine, tourmaline, fluorspar, etc.)	Plateau, Bauchi, Yobe, Borno, Oyo, Ondo, Kwara, Kogi, Ekiti, Nasarawa, Kano, Kaduna, Zamfara and Niger states
Trona (Soda Ash)	Yobe, Adamawa, Bauchi, Borno and Taraba states
Bauxite	Taraba, Adamawa, Yobe, Kebbi, Sokoto, Borno Ekiti, Plateau, Benue, and Cross River States
Bentonite	Yobe, Abia, Anambra, Adamawa, Edo, Imo, Ebonyi, Akwa Ibom, Cross River, Gombe, Kebbi, Borno States
Copper Ores (Chalcopyrite, Malachite)	Bauchi, Kano and Nasarawa states
Graphite	Niger, Gombe, Katsina, Adamawa, Kaduna, Bauchi, and Taraba states
Ilmenite	Plateau, Nasarawa and Bauchi States
Manganese ore (Pyrolusite)	Plateau and Nasarawa Bayelsa and Cross River and Zamfara states
Monazite	Niger, Plateau and Nasarawa states
Quartz	Niger, Kogi, Katsina, Kebbi, Bauchi, Plateau, Ekiti and Ebonyi states
Rutile	Plateau, Nasarawa, and Kogi States
Tantalite	Niger, Osun, Kwara, Kogi, Kaduna, Bauchi states and FCT
Uranium	Cross River, Adamawa, Taraba, Plateau, Bauchi, and Kano States
Wolframite (Tungsten ore)	Kwara, Kogi and Plateau States
Zircon	Plateau, Bauchi, Taraba, Kaduna and Nasarawa states
Flourspar	Ebonyi, Benue and Taraba states
Columbite	Plateau, Kano, Kaduna, Bauchi, Kogi, Kwara, Nasarawa States
Gold	Cross Rivers, Edo, Kaduna, Katsina, Kebbi, Niger,, Osun, Zamfara States
Zircon	Nasarawa, Plateau, Kaduna, and Taraba states
Galena (Lead ore)	Nasarawa, Plateau, Taraba, Bauchi, Gombe, Ebonyi, Imo, Kano and Benue states; FCT
Sphalerite (Zinc ore)	Nasarawa, Plateau, Taraba, Bauchi, Gombe, Ebonyi, Imo, Kano and Benue states; FCT
Cassiterite (Tin ore)	Plateau, Bauchi, Kano, Cross Rivers, Ekiti, Kaduna, Nasarawa, Taraba States
Columbite	Bauchi, Plateau, Kaduna, Nasaraw, and Taraba states
Iron Ore	Kogi, Bauchi, Kaduna and Plateau states, Nasrawa

The solid mineral deposits are equivalent to wealth deposits which are potential sources of foreign exchange for the diversification of the economy of Nigeria. The proper exploitation of the minerals in the Table 1 above can fast-track the nation's recovery from economic recession.

2.1 A Case study of Iron ore

Iron ore is one of the most popular minerals found in Nigeria. Iron ores are rocks and minerals from which metallic iron can be economically extracted. The ores are usually rich in iron oxides and vary in colour from dark grey, bright yellow, deep purple, to rusty red. The iron itself is usually found in the form of magnetite (Fe_3O_4, 72.4% Fe), hematite (Fe_2O_3, 69.9% Fe), goethite (FeO(OH), 62.9% Fe), limonite (FeO(OH).n(H_2O)) or siderite (FeCO3, 48.2% Fe).

Ores containing very high quantities of hematite or magnetite (greater than 60% iron) are known as "natural ore" or "direct shipping ore", meaning they can be fed directly into iron-making blast furnaces. Iron ore is the raw material used to make pig iron, which is one of the main raw materials for steel. 98% of the mined iron ore is used to make steel. Indeed, it has been argued that iron ore is "more integral to the global economy than any other commodity, except perhaps oil" (Wikipedia1, 2016).

In Nigeria, Iron ore is found in commercial quantity in Kogi, Bauchi, Plateau, Kaduna and Nassarawa States. The industrial applications of steel are numerous and it is one of the products of the beneficiation of solid minerals which can be exported if the steel mills of Nigeria are fully revived. The following sections focus on some of the unit operations involved in the beneficiation of iron ore as a case study.

Beneficiation of minerals, also called mineral processing, implies processing of mineral resources to enhance its potential value for the benefits of humankind. Therefore, the objective of the mineral processing is to render mineral resources beneficial to the modern life of humankind. Indeed, they occur as a textual intergrowth of various mineral components, and need further treatment before they can be used. Essentially the technology of mineral beneficiation resides in the separation of the mineral components by the least energy-intensive means (Inoune, n.d).

2.2 Iron ore beneficiation plant

The process flow for iron ore beneficiation can take different forms as illustrated in Figures 2A and 2B. Iron ore is collected from different plants and blended, and stored in a stockpile. These are then conveyed to a surge bin from where they are classified into particles of the size range of – 1mm.

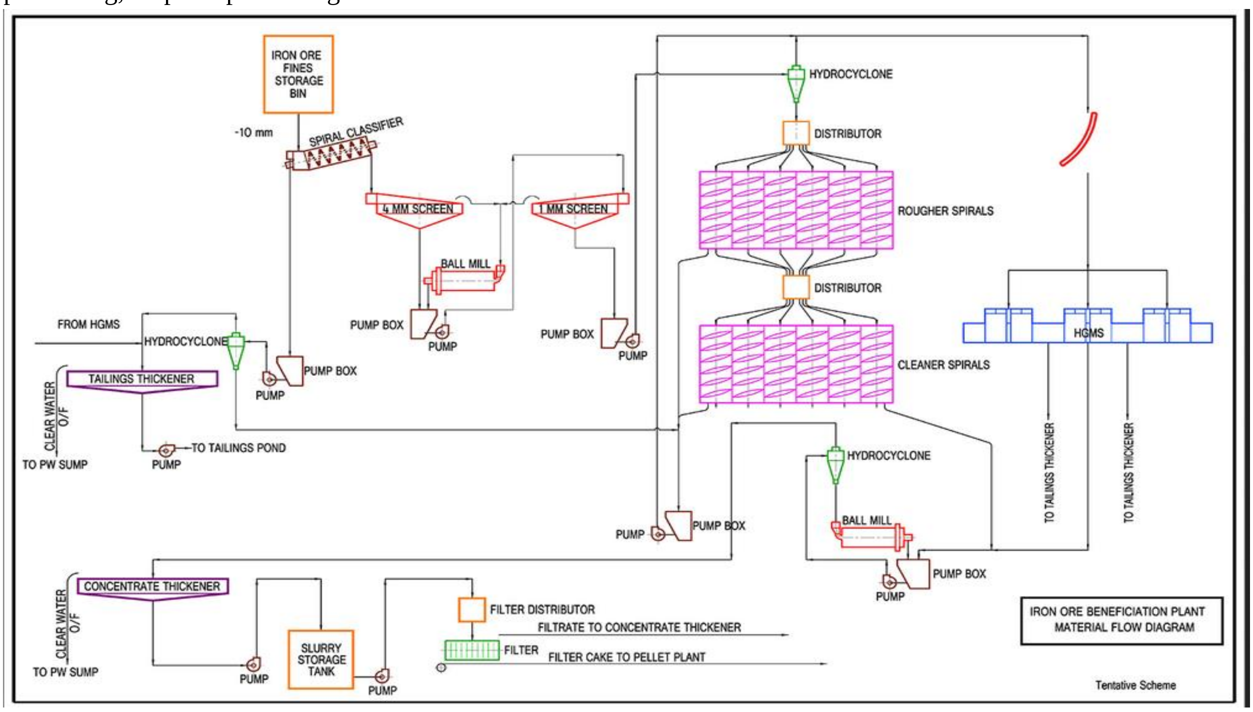


Figure 2A: Iron ore beneficiation process (*Iron Ore Beneficiation,* n.d)

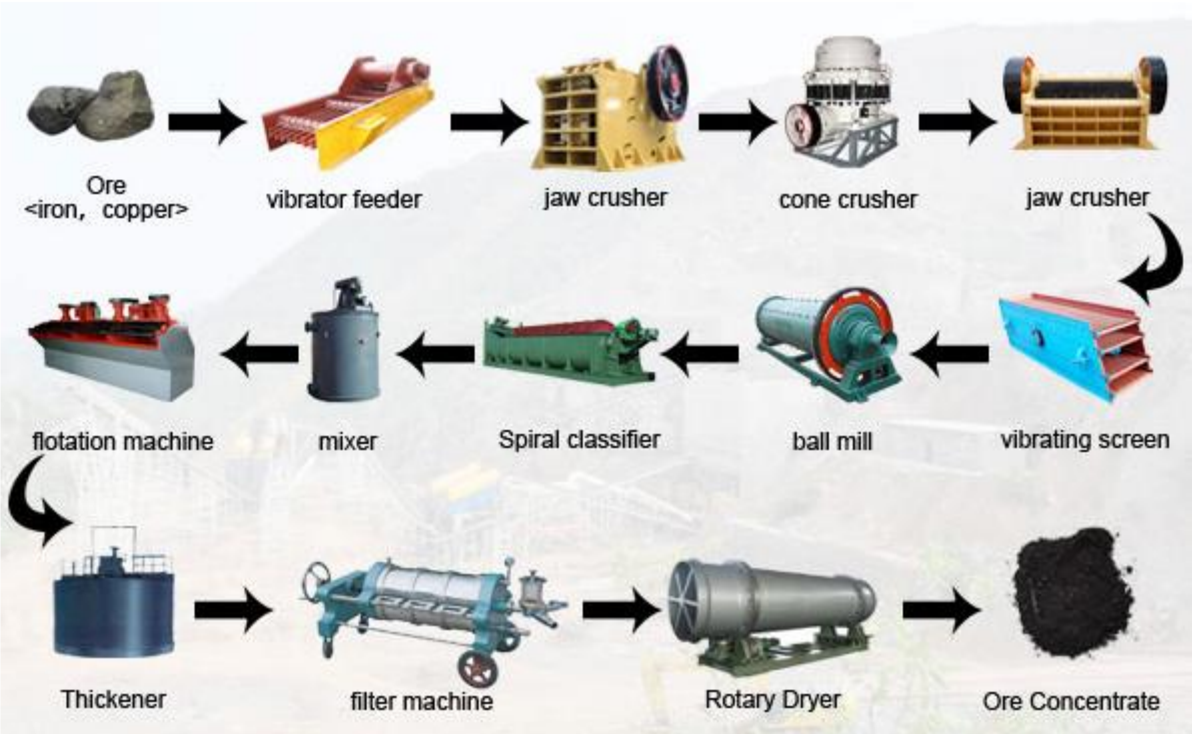


Figure 2B: Iron ore beneficiation process (Kefan Machinery, 2012)

2.3 Classification

Classification involves sorting the initial feed into different size ranges. The aim of classification is to obtain 100% -1mm particles, which is the suitable particle size for gravity separation. This is achieved by screening and milling. First the ore is screened for + 4mm and – 4mm particles. The undersize -4mm fraction is pumped to another screen, where the – 1mm fraction is screened off. The oversize + 4mm fraction and the + 1mm fraction from the second screen are ground together in a ball mill, in closed circuit with a screen, to obtain 100% – 1mm particles. The product is washed and then pumped to spirals for gravity separation. The concentrate from the spirals is then pumped to a concentrate thickener. The concentrate thickener product is then filtered to get a product of maximum 8% moisture. The filter cake is conveyed to a stockpile *(VT Corp*, 2016).

The major unit operations that are involved in the process depicted in Figures 2A and 2B are further discussed below.

2.3.1 Grinding mill

Size reduction (comminution) of the ore either from the mine, or at some intermediate stage takes place in the grinding mill, thereby, reducing the feed to powder. The product passes through a screen of say 40 mesh (where a mesh is the number of holes per inch of the screen). This occurs by the actions of compression, impact or attrition. Example is a hammer mill (Figure 3), which operates by impact (Gulin, 2013).

Figure 3: PF Impact crusher (Gulin, 2013)

In the hammer mill there is a horizontal, high speed rotor, turning in a horizontal cylindrical casing. The ore or material is fed in through the top of the casing, and the particles are broken by a set of swinging hammers pinned to a rotor disk. All the feed particles are impacted by the hammers. They break into pieces, and fly upon a stationary anvil plate inside the casing, which breaks them into smaller particles. Thereafter, they are rubbed into powder by the hammers and pushed through a screen.

2.3.2 Screens

Screens are devices that separate particulate matter according to their sizes. In operation the solid particles are dropped on or thrown against the screen. The screen surfaces have to be agitated in some manner, such as gyrating or vibrating either mechanically or electrically. Particles that are smaller than the screen openings pass through it, while those particles that are larger than the screen openings are retained. To know the maximum and minimum sizes of the particles that pass through screen, the solid particles are often passed through a series of screens. Screening is sometimes done wet, but is often done dry. Screens are made from woven metal wires, silk or plastic cloth, example shown in Figure 4. They may consist of metal bars, or perforated metal plates. These metals are usually steel or stainless steel. Screens finer than 150 mesh are not normally used, because other methods of separating such fines are more economical. Specific types of screening equipment include: stationary screen, grizzly, gyrating screen, vibrating screen, centrifugal sifter (*Screening Machine, 2015).*

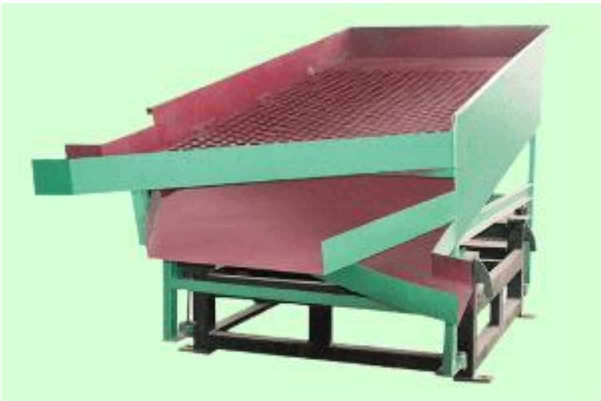


Figure 4: Screening Machine (*Screening Machine, 2015*).

2.3.3 The Spiral Separator.

The spiral separator shown in Figure 5 is a device for separating slurry components by density. The device consists of a tower around which a sluice is wound in a spiral configuration. At the base of the sluice, slots are installed to collect the separated particles. As larger and heavier particles travel faster and faster down the sluice, they experience more drag, and thus move towards the centre of the sluice and travel slower. Lighter particles move towards the edge of the sluice and travel faster. At the bottom of the sluice higher and lower density parts are separated by slots. Wash water inlets may be added along the length of the spiral to aid the separation of lighter materials (*Spiral Separator, 2016*).

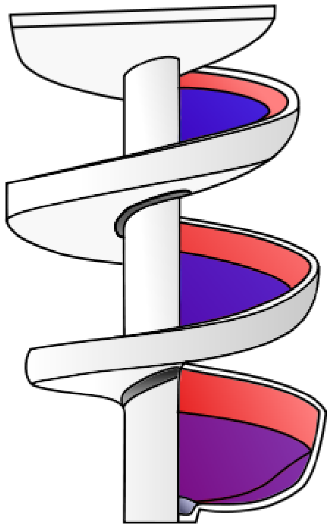
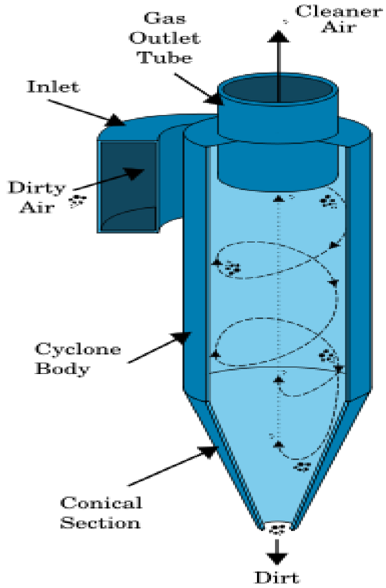


Figure 5: Spiral Separator. (*Spiral separator, 2016*)

2.3.4 The Cyclone Separator

The cyclone separator, as shown in Figure 6 is a device for separating particulates from gases or liquids by vortex separation, where rotational and gravitational forces are used to separate mixtures of particles and fluids. A cyclone that separates particulates from liquid is called a hydrocyclone. In the operation of the cyclone, a high speed rotating gas flow is established in a partly cylindrical and partly conical container. The air flow in the cyclone is helical, beginning at the top and ending at the bottom, where it exits the cyclone. Larger or denser particles have too much inertia and can’t follow the tight curve of the flow. They move outward, and strike the walls of the container. Thereafter, they fall to the bottom of the cyclone where they are removed. At the conical part at the bottom of the cyclone, the radius of rotation of the flow gets smaller, thus separating smaller particles. The cut point of the cyclone is defined as the particle size that will be removed with 50% efficiency. Particles larger than the cut point will be removed with a greater efficiency and particles smaller than the cut point will be removed with smaller efficiency (*Cyclone Separator, 2016*)



Figure

Figure 6: A Cyclone Separator (Cyclone Separator, 2016

2.3.5 Thickener

In a thickener, particles of solid heavier than the suspended liquid are removed in a large settling box or settling tank (Figure 7). Here the fluid velocity is low and the particles have ample time to settle out. In industrial separators provision is made for continuous removal of settled solids (Thickener, 2013)

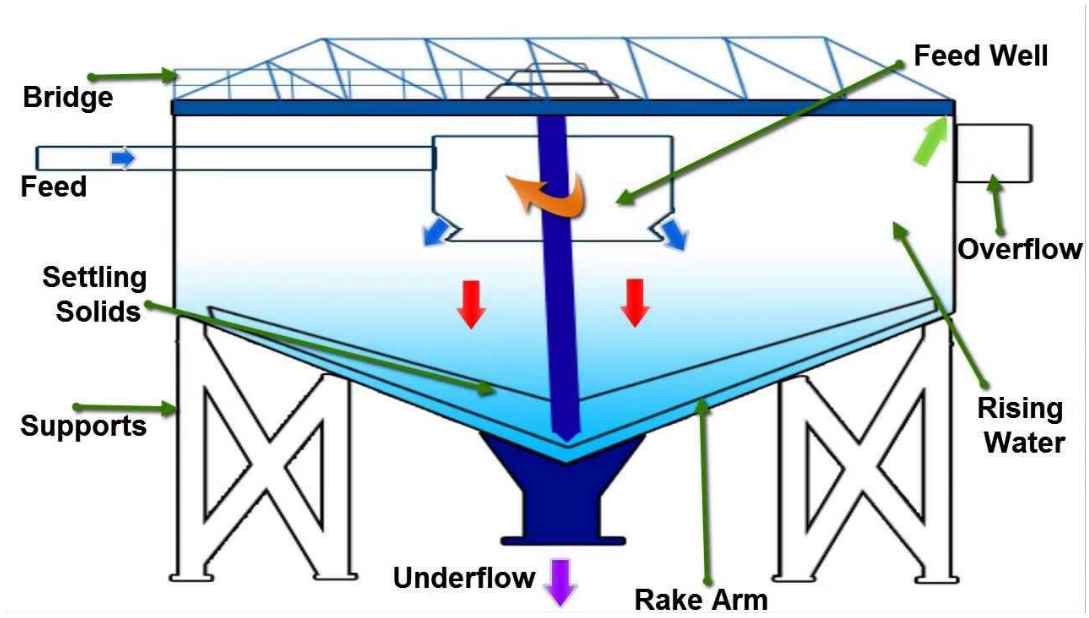


Figure 7: A Thickener (Thickener, 2013)

2.3.6 Froth floatation cells

Froth floatation is the process of separating hydrophobic and hydrophilic materials. In froth floatation minerals are separated from gangue. The hydrophobicity of valuable minerals and waste gangue are increased by application of surfactants or wetting agents. Before froth floatation can work the ore has to be reduced to fine grains of physically separate minerals, by crushing and grinding, i.e comminution. The ground ore is mixed with water to make a slurry, thereby making the desired mineral hydrophobic (if naturally not already hydrophobic). The slurry is mixed with an appropriate surfactant. The slurry of hydrophobic and hydrophilic material, called a pulp, is pumped into tanks, known as floatation cells, Figure 8. The tanks are aerated to produce bubbles. The hydrophobic materials get attached to the bubbles, and float to the top as a froth. The froth of concentrated mineral is collected as a concentrate.

The pulp that does not float is known as floatation tailings, and may be floated again to recover minerals that did not float the first time. This is called scavenging.

Froth floatation efficiency depends on the probabilities of particle – bubble contact, particle-bubble attachment, transport between pulp and froth, and froth collection in the product. Floatation often takes place in stages in series, to increase particle residence time, and increase the probability of particle bubble contact (Wikipedia2, 2016).

Figure 8: Froth floatation cell (Wikipedia2, 2016)

2.3.7 Filters

Filtration involves the removal of solid particles from a fluid by passing it through a medium, where the solids are deposited. Due to pressure difference across the medium, the fluid flows across the medium. Cake filters separate quite large amounts of solid as a cake of crystals or sludge. They operate with pressure above atmospheric on the upstream side of the medium, or with a vacuum at the downstream side of the medium. An example of a cake filter (Figure 9) is the horizontal tank pressure shell and leaf filter (Andritz, 2014)

Figure 9: Filter Press (Andritz, 2014)

3.0 ROLE OF CHEMICAL ENGINEERING IN THE ABOVE PROCESSES

Figures 2A and B depict a typical process (beneficiation of iron ore). The process consists of various unit operations that are linked. The system also portrays the value-added chain for iron ore. A critical look at the process in Figures 2A and B show that the unit operations involved are basically separation processes. With respect to the definition of chemical engineering profession and the beneficiation process described above (as a case study), the indispensable roles of chemical engineering in solid mineral development can be outlined as follows:

1. Preliminary design of economically feasible processes for the beneficiation and processing of the solid minerals in Nigeria.
2. Optimization and automation of the processes to meet international standards as well as to enhance profitability.
3. Construction and installation of process plant machinery at the production site.
4. Plant commissioning, operation and maintenance with a view to achieving design and production objectives/targets.
5. Quality control of the various end-products to ensure that international standards are met, as well as the end users.
6. Networking, design and implementation of marketing strategies to ensure sustainability of demand and supply (exportation) of end products thereby generating foreign exchange for the country.
7. In the area of research for innovations to meet with the global trend in processing of Nigeria solid minerals

4.0 CONCLUSION

No solid mineral exists in its pure state when it is mined. Solid minerals must undergo beneficiation to add value to them and convert them to a state that man can conveniently use to meet his needs. The role of chemical engineering in adding value to solid minerals has been highlighted in this paper using the beneficiation of iron ore as a case study. Beneficiation involves the application of appropriate technologies to optimally purify solid minerals. Development of these technologies (processes) calls for professional intervention of chemical engineers. This is because chemical engineering is the only branch of engineering that deals extensively and intensively with process design for raw material conversion. The principles of process plant design in chemical engineering can be applied by chemical engineers to develop efficient processes for the beneficiation and processing of Nigerian solid minerals towards diversifying the nation's economy and job creation.

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