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Chapter

Role of Surfactants in Mineral Processing: An Overview

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Abstract

Depletion of high-grade resources has necessitated the use of low-grade fines, which contain good amount of mineral values and also liberate in finer sizes. Froth flotation, a physico-chemical surface-based process, is the most established solution, both technologically and economically, compared to other alternatives for fines beneficiation. For a successful and effective flotation performance, an understanding of the mineral surface and proper selection of the surfactant/reagent regimes along with their molecular chemistry and their specific adsorption mechanism are mandated. This chapter focuses on the complexity of the flotation process along with adsorption and interaction mechanism of different surfactants in accordance to mineral surface characteristics and their dependency on many microevents. To further strengthen mineral flotation chemistry and advancement of mineral engineering, research gears at investigating new surfactants, specific for particular mineral surface. The selection of reagents/surfactants with appropriate chemical composition and their administration are of critical importance in view of varied mineralogy, chemical complexity and size consist of feed material. Cost-effective and lower cost flotation reagents can be synthesized through insertion of new functional groups, molecular modelling of reagents for more environment-friendly nature, modifying the structure of other chelating agents and novel green chemicals from renewable resources, adding aliphatic alcohol and carboxylic acid to bio-based collectors and adding chaotropic anions to alkyl and aryl surfactants and organic and inorganic salts having strong orientation with more proton donor and acceptor; addition of another cationic group to known cationic surfactants can be tried for enhanced flotation performance. The study also provides an idea on the effect of other parameters like pH, composition of pulp, zeta potential, electrostatic potential, etc. For envisagement of a successful flotation performance, proper selection of the reagent system according to the specific surface and understanding of the mineral surface-specific adsorption mechanism are mandated.

Keywords: flotation, ore fines, reagents, reagent system for specific objective

1. Introduction

The most innovative and ingenious process development of the century is the emergence of the froth flotation process for the treatment of low-grade ores. Froth flotation process, which uses the difference in hydrophobicity of minerals, is employed in several industries (mineral processing and others) for fines processing. It is a process of upgradation of minerals by taking advantage of differences in

physico-chemical surface properties between valuable and gangue minerals of two different minerals.

Froth flotation process can be effectively applied to the system where more amount of fine liberated valuable and gangue mineral grains are present rather than of interlocked forms [1]. Froth flotation, being an established method, has been known in a century's practice across the globe for its efficiency to eliminate impurities from different ores to produce good grade concentrate.

1.1 Froth flotation

The grade of mined ore is depleting day by day where as demand for metal and steel is increasing steeply. Improving the resource base and exploitation of iron ore resources through the processing and upgradation is the most important challenging task. A nation's socio-economic development completely depends on effective and judicious utilization of its mineral resources.

Proper utilization of wastes is achieved through balance between natural resource management and sustainable growth process to minimize the burden on ecological pyramid due to enormous growth of industrialization. With regard to the tailings management, reduction of tailing volume is feasible, if the maximum metallic content is extracted or recovered by a suitable technology [2]. The conventional ore processing and mining operations generate fines and slimes of huge quantities to the tune of 10–15% of run of mine which are generally of poorer grade and being discarded. These discarded tailing stockpiles occupy a huge space, which contain good metallic values, cause pollution to ground and surface water, and are having a negative impact to the environment. They need to be processed to recover metallic values for resource augmentation and to meet environmental stipulation.

These fines and slimes cannot be utilized directly as feed to metallurgical plants due to size specification; besides these occupy a huge space and cause environmental and ecological problems, which need to be clearly assessed. The scarcity of high-grade ore is compelling the mineral processing industries to look for low-grade ore fines. Hence it is essential to beneficiate and to recover the additional mineral values from these fines, not only to earn additional revenue to the mineral industries but also from the point of view of conservation of mineral wealth. These low-grade slimes can be considered as national resource rather than a waste of nuisance.

In the present days, the minerals liberated at extremely fine sizes, and in addition the ore typically consists of valuable mineral intergrowth with unwanted/gangue minerals making the mineral surface quite complex. This nature of particle characteristic compels to be separated by the technique that relies on surface properties. So the flotation technique is being developed to treat these low-grade ore and waste slimes.

Low-grade ores imply finer liberation size and cannot be upgraded by conventional gravity concentration techniques. Wet and dry low-intensity magnetic separation (LIMS) techniques are used to process ores that contain minerals with strong magnetic properties, such as magnetite and titanomagnetite. Wet high-gradient magnetic separators (WHGMS) and wet high-intensity magnetic separators (WHIMS) are used to separate the minerals having weak magnetic properties such as hematite, goethite and limonite from gangue minerals [3, 4]. Synchronically Xiong et al. [5] explained major problems about the WHIMS and WHGMS that when metallic ores are treated in these separators, matrix dogging and mechanical entrainment of nonmagnetic particles occur, because hematite ore contains a large amount of weakly magnetic particles along with it. The change from gravity-based separation to magnetic-based separation improved the iron grade by approximately 13%.

Concurrently, Pradip [6] examined that multigravity separation is the most effective technique for processing low-grade Indian iron ore slimes to decrease alumina content. However according to Roy and Das [7], this beneficiation method is not commercially successful due to its low capacity. Later on people combined two methods, i.e. magnetic separation and selective flocculation, and found good results. The gravity and magnetic methods, i.e. physical separation techniques, are restricted to coarse-grained sizes.

So, when the size is extremely fine, in case of slimes, the physico-chemical properties start dominating over physical properties; hence these methods are unable to give satisfactory results.

Hence, froth flotation is the single most important unit operation, which is the root solution to all these problems and used for the recovery and upgradation of valuable mineral, especially below 150. Froth flotation which uses the difference in physico-chemical surface properties of minerals is employed in several industries for fines processing. This chapter addresses how flotation has been and can be helpful in recovering the metallic values from the tailings, through a review of basics and fundamentals, efforts made earlier and future directions for research.

2. Fundamentals of froth flotation

The most important factor in froth flotation process is the selectivity, which means the choice of a suitable reagent to selectively modify the surface of desired mineral to enhance its hydrophobicity. This implies a thorough knowledge of the particle surface property, the mechanism of particle surface-reagent interaction and the correct type and quantity of the reagent to create the best selectivity conditions. Surfactants play the most important role for a successful operation of flotation process. To make the mineral float, the surface of such minerals has to be modified by adsorption of suitable surfactants in order to reduce the Gibbs' energy. Ensuring maximum floatability of desired minerals through maximum selectivity with the aid of reagents is the key element of flotation research and the driving force of flotation research efforts [8, 9]. From an early modest beginning to treat base metal sulphides, it has been established itself as the most versatile process for the treatment of oxide ores, carbonate ores, industrial minerals and fine coal. It is not an exaggeration to state that there is not a single mineral or ore system which cannot be treated by froth flotation (**Figure 1**).

In flotation of minerals, contact angle plays a major role in hydrophobicity as it is directly proportional to hydrophobicity. The more the contact angle, the greater is the hydrophobicity and the more is the floatability.

Despite numerous years of research and development work since 1900, flotation is still not fully interpretable and remains a challenge, as there is involvement of the major phases (macroprocesses) and the number of inter-related events (microprocesses) (**Figure 2**).

Ensuring maximum floatability of desired minerals (with good grade and high recovery) through maximum selectivity with the aid of reagents/surfactants is the key element and driving force of a successful flotation research.

Flotation of different minerals is broadly divided into three main types:

a. Salt-type flotation

b. Sulphide flotation

c. Oxide flotation

- Salt-type minerals include carbonate, phosphate, sulphate, tungstate and some halide compounds. They are known for their ionic bonding and moderate solubility in water. Salt-type minerals are difficult to float because they contain common cations; hence modifying agents, e.g. ammonium phosphate, calcium sulphate, sodium sulphate, nickel chloride, zinc chloride, sodium chromate, barite, celestite, gypsum, etc., are used to obtain the selectivity.

- Sulphide minerals are less electronegative than oxide minerals; hence it forms fewer ionic bonds than oxygen. Sulphur has greater tendency to form covalent bonds, especially S-S linkages, e.g. chalcopyrite, cuprite, pyrite, sphalerite, galena, etc.

- Oxide minerals include metal oxides, carbonates, silicates and fatty acids having saturated and unsaturated hydrocarbon chains that are used to float it, e.g. hematite, magnetite, goethite, quartz, malachite, etc.

Generally flotation is practised in two different ways around the globe:

1. **Direct flotation**—The flotation in which surfactants are added to selectively float the value minerals while the gangue minerals are collected in the tailing launder

2. **Reverse flotation**—The flotation in which surfactants are selectively added to float the gangue minerals while the value minerals remained depressed with specific reagents as pulp product

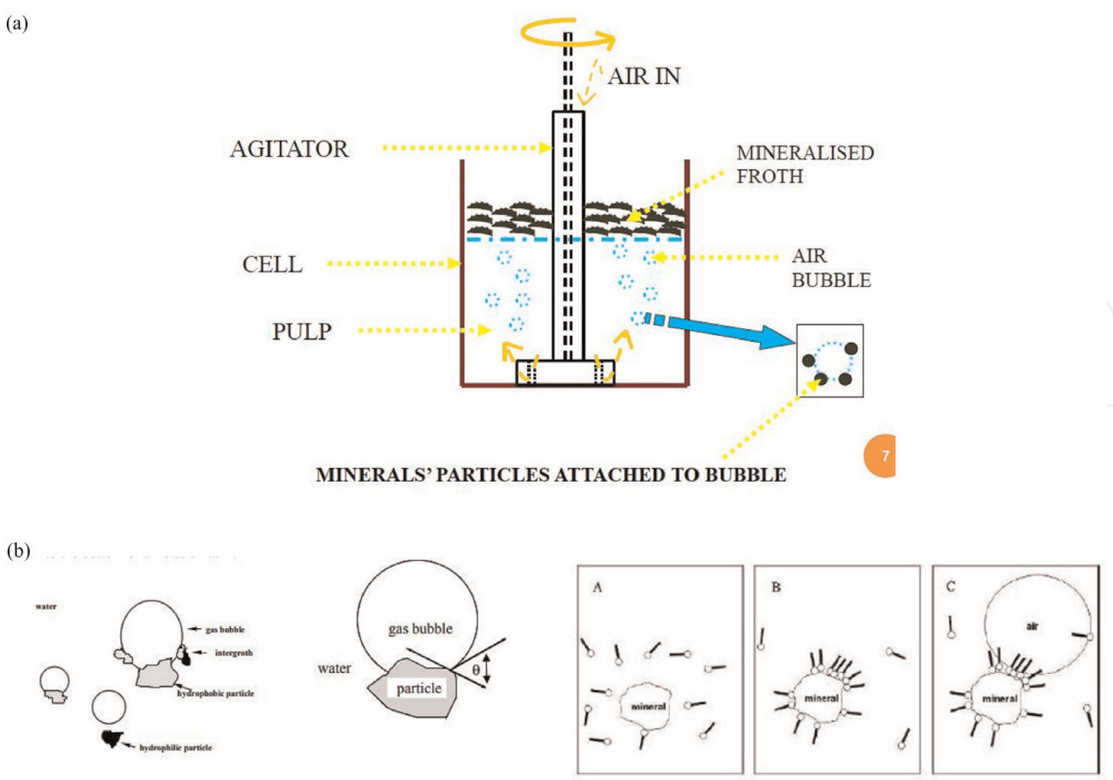


Figure 1.
(a) Schematic representation of flotation process and (b) flotation mechanism and role of contact angle [10].

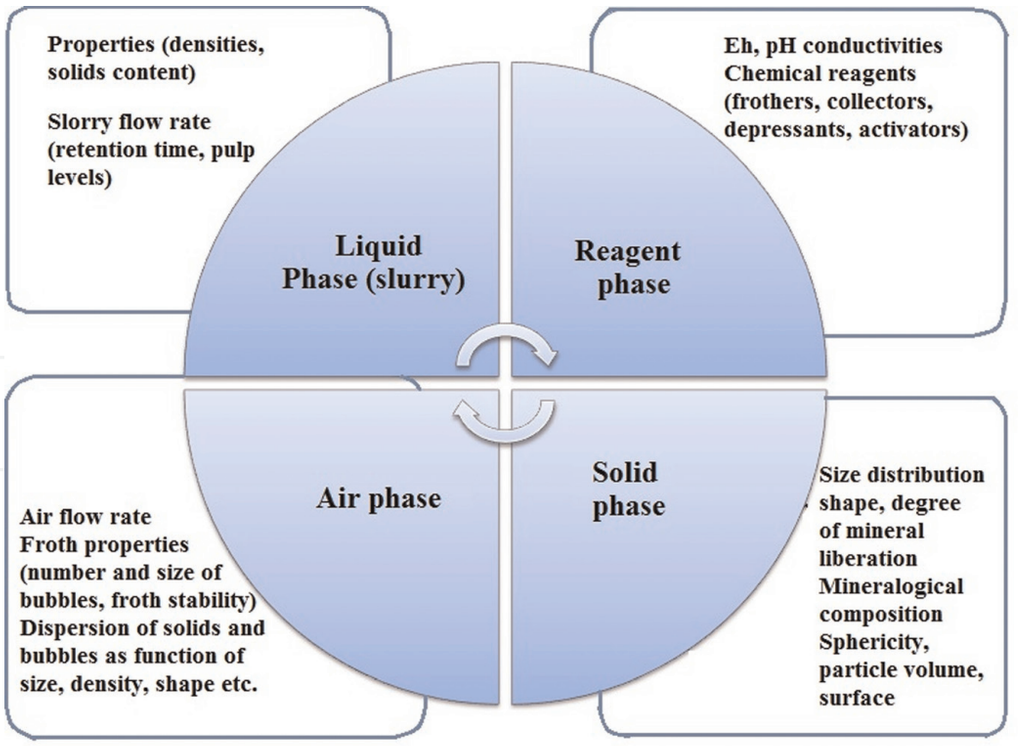


Figure 2.
Process and phases in flotation [11].

2.1 Origin of surface charge and zeta potential

When mineral is suspended in water, charged species/ions (potential determining ions) are transferred upon the surface which develops an electric charge or electric double layer. In the case of oxide minerals, H^+ and OH^- ions are the principal potential determining ions, and they interact with water and produce surface hydroxyls [12]:

$$MOH_2^+ \xleftarrow{+H^+} MOH \xrightarrow{-H^+} MO \tag{1}$$

Due to the charge inequality, a double layer around the particle's surface is created. The potential difference between the stern layer and diffused layer is known as **zeta potential**.

At certain pH, an equal number of positive and negative surface sites are created, where the surface is having no specific charge, termed as **point of zero charge (PZC)**.

These two terms have great influence on the flotation performance of mineral at specific pH.

Zeta potential denotes charge properties of particles and in turn implies adsorption, penetration and adherence of certain substances. Processes such as adsorption, particularly surfactants or macromolecules, can alter the interfacial behaviour of the solids markedly. Adsorption and desorption of potential determining ions (H^+ and OH^- ions) play an important role in accounting the surface charge:

$$\underset{(Positively\ charged\ surface)}{M-OH_2^+ + H_2O} \overset{H_3O^+_{(aq)}}{\longleftrightarrow} \underset{(Uncharged\ surface\ PZC)}{M-OH} \overset{OH^-_{(aq)}}{\longleftrightarrow} \underset{(Negetively\ Charged\ surface)}{M-O^- + H_2O} \tag{2}$$

Minerals	pH_{PZC}	pH_{IEP}
Quartz, SiO_2	<5	2.5
Cassiterite, SnO_2	<5.5	2.0–55
Sulphides, MeS	—	2.1–7.0
Diamond, C	—	3.5
Rutile, TiO_2	4.8–5.3	5.5
Ilmenite, $FeTiO_3$	5, 6	—
Hematite, Fe_2O_3	6.5–8.5	5.98–7.01
Barite, $BaSO_4$	—	6.0–8.1
Tenorite, CuO	6.5–8.5	6.0–7.6
Dolomite, $(Ca, Mg)CO_3$	—	7.5
Alumina, Al_2O_3	8–9.1	5–9.6
Magnesite, $MgCO_3$	—	7.5
Periclase, MgO	—	12.0

Table 1.
Represents the pH_{PZC} and pH_{IEP} of some minerals, which has been modified from the data of Parks [13] and Kosmulski [14].

In Eqs. (1) and (2), *M* denotes the metal.

In the case of iron ores, the isoelectric point of natural hematite varies in between 5.98 and 7.01, depending upon the association of gangues. If the hematite particles are not liberated completely, then isoelectric point will be closer to quartz. The zeta potential of quartz depends on the hydroxylation of quartz surface at different pH values and the interaction of amine species. The pH_{PZC} and pH_{iep} values for various oxides and hydroxides of alumina vary widely (pH 5–9.6) depending upon the association of other minerals [11]. The pH_{iep} of quartz is at pH = 2.5, below which it acquires a positive charge, and above this pH, the quartz surface acquires negative charge (**Table 1**).

3. Flotation reagents

The reagents are added to the system in order to create proper environment for the particles to adhere to the air bubbles and recovered. The minerals are characterized by the functional groups as non-polar minerals, polar minerals and heteropolar minerals. The non-polar minerals are those whose surface is predominantly of weak molecular bonds with very little polarity. The group of minerals, which consist of both polar and non-polar groups, are termed as heteropolar and constitute a large group of minerals, e.g. gibbsite (consisting of aluminium hydroxide $Al(OH)_3$), bauxite (consisting of aluminium hydroxide), hematite (Fe_2O_3), etc. The polarities of heteropolar minerals vary according to the proportion of polar minerals. Those groups of minerals, whose surface is predominantly of strong covalent bond or ionic bond, are termed as polar minerals and are hydrophilic.

3.1 Collectors

Collectors can be classified into ionizing and nonionizing based on their reaction with water. The nonionizing compounds do not dissociate into ions when contacted

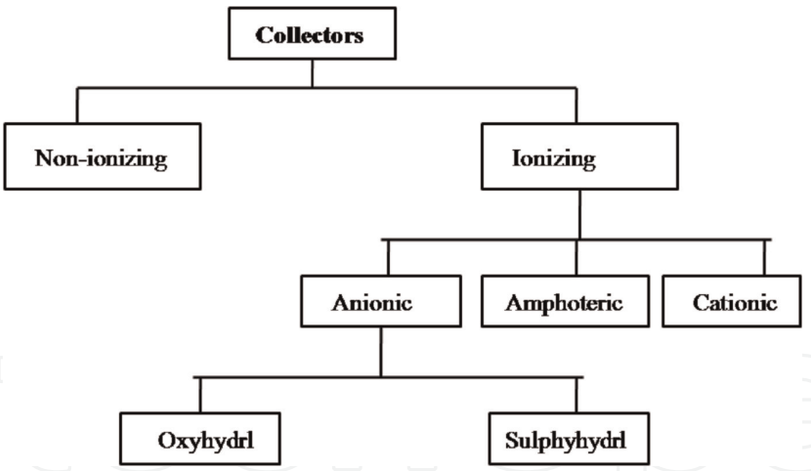


Figure 3.
Classification of collectors.

with water, while the ionizing compounds dissociate into ions in water. To float minerals, hydrophobicity/enhanced hydrophobicity has to be imparted to them, which is obtained by adding a special type of surfactants known as collectors to the pulp, which is further agitated or conditioned for adsorption to take place. Collectors are the chemical compounds which render hydrophobicity through adsorption and are further divided into ionizing compounds (dissociate into ions in water) and nonionizing compounds (which are practically insoluble and render the mineral water-repellent by covering its surface with a thin film) [15].

Ionizing collectors have been used widely in flotation era, e.g. sodium ethyl xanthate, potassium isopropyl xanthate, etc. They are composed of complex molecules asymmetric in structure and are heteropolar, i.e. the molecule contains a non-polar hydrocarbon group and a polar ionic group. The non-polar part of the molecule is a hydrocarbon radical which has pronounced water-repellent properties, and the polar part has the property of reacting with water.

Examples of nonionizing compounds are kerosene, creosote, grease, etc., which possess inherent hydrophobic property and do not dissociate in any polar liquids.

Based on classification of ionized groups, the collectors have been classified as shown in **Figure 3**.

Till now six main types of collectors are used in the mineral industry:

a. Anionic collector

b. Cationic collector

c. Mixed collector

d. Amphoteric collector

e. Bio-collector

f. Ionic liquids

(a) Anionic collector

- Anionic collectors are opted for minerals when the surface bears a net positive charge and these collectors ionize in the solution to give negative charge. Floatability assessments of oxide and carbonate ores are generally carried out by using highly soluble collectors consisting of organic

molecules varying 10–18 carbon chain length [16]. Fatty acids (a distilled tall oil containing ~91% oleic and linoleic acid, 6% resin acid and 3% unsaponifiables) are used as collectors for mineral oxides with dosages in the range of 0.45–0.67 kg/ton [17]. Fatty acids, resin acids, soaps, alkyl sulphates and sulphonates are generally used to float iron oxide bearing minerals.

(b) Cationic collector

- Cationic collectors are opted for minerals when the surface bears a net negative charge and these collectors ionize in the solution to give positive charge. Organic bases containing a hydrocarbon group and salts of these bases are generally chlorides and acetates. This group includes the primary aliphatic amines, diamines, quaternary ammonium salts and ether amine products. Longer amphipathic linear chain molecules are more confirmatively adsorbed at the liquid/gas interface, as they are more hydrophobic through van der Waals interactive forces.

(c) Mixed collector

- The use of surfactant mixture was studied by several researchers and found that the surfactant mixtures can have an advantage over the use of single surfactant [18–20].

- Mixed collectors provide increased flotation selectivity and increased recovery with reduction in reagent consumption. The adsorption of single surfactants at the solid-liquid interface has been comprehensively studied, but the study of adsorption of mixed surfactant solutions has been limited.

(d) Amphoteric collector

- Amphoteric collectors are the surfactants having good acidic and basic group in their molecular structure and can function as a cation, anion and neutral molecules depending on the pH of the aqueous medium. The effect of cationic group is accentuated most in acidic media, while the anionic group is accentuated in alkaline media.

(e) Bio-collector

- Microbial flotation reagents are currently gaining attention as natural bacteria can be used in place of toxic chemicals from the environmental point of view, e.g. *Bacillus polymyxa*, *Paenibacillus polymyxa* and *Rhodococcus opacus*, for flotation of iron oxide minerals.

(f) Ionic liquids

- Ionic liquids are the salts having poorly coordinated ions and exist in liquid state below 100°C, but these liquids are gaining the attention of researchers due to their easier handling properties, interesting electrochemical properties, low vapour pressure, low volatility and flammability, high viscosity, dual natural polarity, good thermal stability, low surface tension and wide range of miscibility with water and other organic solvents and most importantly their environment-friendly nature.

- Ionic liquids are more suitable surfactants than conventional classical salts because of their versatility to switch their role as anionic and cationic part as per the requirement, which is due to the presence of large organic cations with a variety of associated anions.

Sahoo et al. [21, 22] experimented the flotation of pure quartz as well as low banded hematite quartzite (BHQ) having quartz as major impurity using tricaprylmethyl ammonium salicylate (TOMAS), an ammonium-based ionic liquid, Aliquat 336, tetrahexylammonium chloride (THEX) and dodecylammonium chloride as collectors and found that ionic liquids performed better than conventional surfactants. Due to the chaotropic character of anions of ionic liquids, they easily pair with ions of mineral surfaces, thus inducing increased hydrophobicity compared to conventional surfactants. It was observed that with lower concentration of ionic liquids, higher recovery and grade were achieved, and the reverse condition was observed in the case of conventional surfactants.

Adsorption between mineral surface and reagents occur by various means, which is represented in **Figure 4**.

3.2 Frothers

Frothers are organic compounds, which dissociate into ions and decrease the surface tension at the air-water interface, thus stabilizing the froth consisting of a multitude of mineral-laden air bubbles and inducing buoyancy effect on the mineralized surface.

When brought into contact with water, the water dipoles readily associate with the polar group while virtually having no affinity to the non-polar group. The non-polar group is projected into the air phase which leaves the polar group on the air surface orienting towards the water. A frother is required to provide conditions amicable to

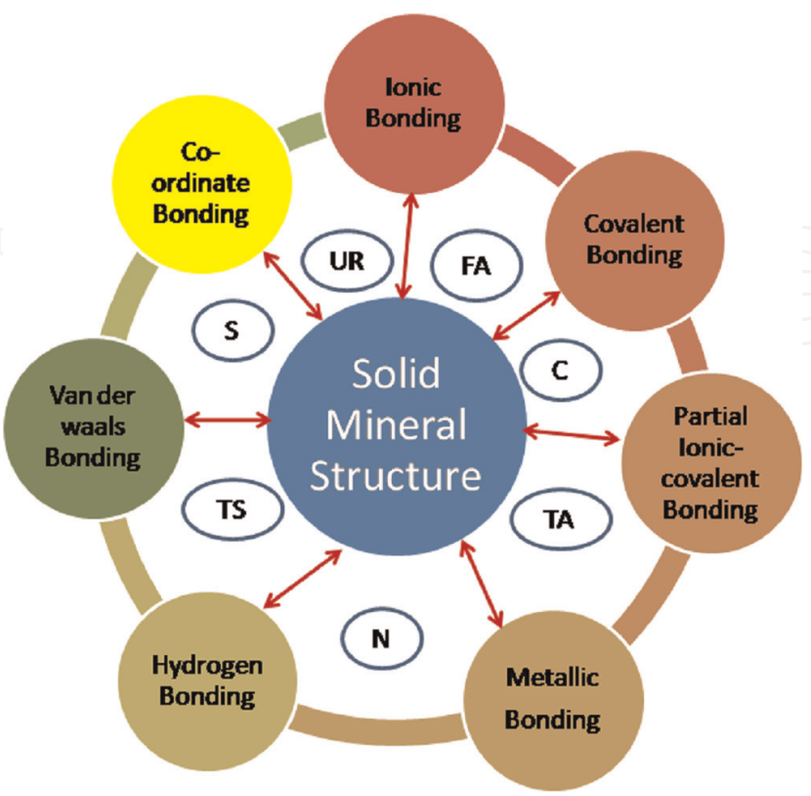


Figure 4.
Types of bonding adsorption between mineral surface and reagents.

the formation of froth that is stable enough to prevent undesirable froth breakage. The stability of bubble attachment to hydrophobic particles is further stabilized by the action of frother. A good frother should have negligible collecting power, should not affect the state of the particle surface and should act entirely in the liquid phase to produce froths which are just stable enough to retain the floated particles [15].

Frothers are consisted of aliphatic, aromatic, cyclic and polyglycol alcohol groups, e.g. methyl isobutyl carbinol (MIBC), cresylic acid or cresol, pine oil, etc. When surface-active groups of frother react with water, the water dipoles combine with the polar groups and hydrate them, but there is practically no reaction with the non-polar hydrocarbon group. Thus, the heteropolar structure of the frother molecule enhances its concentration at the air-water interface, with the non-polar groups oriented towards the air and the polar groups towards the water.

Hence, the frothing action is due to the ability of the frother to reduce the water surface tension, thus stabilizing the air bubbles. Frothers are generally soluble in water; otherwise they would be distributed very unevenly in the water, and their surface-active properties would not be fully effective.

Organic acids, amines and alcohols are the most common types of frothers. The alcohols are the most widely used because they have practically no collecting properties and in this respect are preferable to other frothers. The presence of collecting and frothing properties in the same reagent may make selective flotation difficult [16].

3.3 Modifiers

These are chemical compounds added to the flotation pulps to enhance collector-mineral adsorption, that is, to improve the selectivity. This may be achieved by either (a) creating an environment or revitalizing the floatability of the desired mineral, (b) by suppressing the flotation activity of the undesired mineral (at a particular stage of flotation operation), (c) by removing the deleterious elements which hinder effective flotation of desired minerals or (d) by providing the proper pulp nature for the selective adsorption between the mineral and collector.

3.3.1 Activators

These chemicals are added, prior to collector addition, to react with the mineral surface and produce compounds on the surface which are highly responsive to collector adsorption, e.g. the use of ‘sulphidisers’ in activation of oxidized minerals of base metal sulphides. The deleterious effect of oxidation is overcome by the creation of a pseudo-sulphide surface to oxidized mineral, which would then respond favourably with the sulphydryl collector added, e.g. copper sulphate, cyanide, lime, etc.

3.3.2 Depressants

These are used to suppress the floatability of a mineral when it is not desired in case of multimineral system. Several natural polymers and their derivatives have been suggested as depressants for iron oxide in reverse flotation due to the presence of large number of hydroxyl groups and large molecular sizes. The depression mechanism is may be due to the blocking of surface sites for collector adsorption, resulting in hydrophilic surface and forming bridges of hydroxyl groups.

For example, in reverse flotation of iron ore, starch is used as depressant for iron ore and zinc sulphate as depressant for ZnS in Pb-Zn flotation.

Reagents	Application	Classification	Composition	Functioning process
Collectors Collectors	1. Hematitic ore 2. Hematitic ore 3. Ultrafine hematite particles Goethite	Anionic collectors 1. Fatty acids 2. Alkyl sulphates and sulphonates (C12-C16) 3. Oleic acid and lauric acid 4. Hydroxamates Amphoteric collectors 5. Hexanoic acid, octanoic acid, decanoic acid, dodecanoic acid, tetradecanoic acid, stearic acid Sarcosinates and sulphosuccinates 1. Dodecyltrimethylammonium bromide 2. *Mycobacterium phlei*, *Bacillus polymyxa*, *Paenibacillus polymyxa*, *Rhodococcus opacus*, *Bacillus subtilis*, *R. erythropolis* Sodium oleate fatty acid	Tall oil containing 91% oleic acid, 6% resin acid and 3% unsaponifiables 10^{-3} molar, 10^{-4} molar concentration 70–100 mg/L Liquid emulsion 5–20% solution	Chemisorption on hematite surface, surface precipitation Chemisorption Classical chemisorption Microbial strain Form hydrophobic floccules of hematite particles Chemisorption
Collectors	1. Silica (quartz) 2. Both alumina and silica 3. Alumina	Cationic collector 1. Etheramine and etherdiamines 2. Fatty amine (dodecylamine, decyletheramine) 3. Quaternary ammonium compounds 4. Gemini surfactant Cetyltrimethylammonium bromide, hexadecyltrimethylammonium bromide SOKEM (503C, 504C, 520C, 521C, 522C, 523C, 524C, 525C, 701C, 720C) Cationic, anionic and nonionic polyacrylamide	In kerosene 5–10% solution Undiluted 20–30% neutralization degree with acetic acid or NaOH	Electrostatic adsorption Hydrogen bonding with the surface exhibiting low interaction with collectors
Collectors	Silica	Anionic collectors Fatty acids	Activation by Ca^{2+} ions	Strong chemical bonding between mineral surface and collector
Collectors	Magnetite	1. Maleic acid 2. Ethyl oleate 3. Polyethylene glycol monooleate 4. Maleic acid ester 5. Quaternary ammonium surfactant	10–50 mg/L	Electrostatic adsorption High solubilization capacity, stronger biological activity
Collectors	Phosphorous	Anionic collectors 1. Carboxylate surfactants 2. Fatty acid 3. Flotigam EDA manufactured by Clariant		Surface chemisorption
Mixed collectors	Silica Iron oxides	1. Blending diamines and monoamines 2. Amalgamation of ammines with kerosene 3. Conjunction of diesel oil and	20–30% blending Mass ratio of 1:4 Mass ratio of	Co-adsorption of collector on silicate surface by hydrocarbon tail-tail interaction increasing

Reagents	Application	Classification	Composition	Functioning process
		ether amine 4. Non-phenol ethoxylated with ethylene oxide and etheramine 5. Mixture of amine and hydrochloric acid 6. *N*-dodecyl ethylene diamine (mixture of 1-bromododecane, ethanol and ethylenediamine 7. Mixture of primary ether monoamine, oxyethylated nonylphenol and oxyethylated fatty alcohol 1. Non-polar oils emulsified with fatty acids 2. Fatty acids (anionic collectors) and amphoteric collectors	1:2 Mass ratio of 4:1 ether monoamine to nonylphenol	hydrophobicity Decreased surface tension at liquid-gas interface and reduce froth depth
Frothers	All iron oxides, silica, alumina, phosphorus	1. Pine oil (alpha-terpineol) 2. Cresylic 'acid' (cresols) 3. Polypropylene glycols 4. DF (Dow Froth) 200, DF 250, DF 450 5. Fuel oil 6. Aliphatic alcohols, 7. MIBC	The reagents are used as undiluted and also prepared as solution in H_2O	Provides most viscous, stable froth, have collecting action Less viscous but stable froth, have collecting action Fine, fragile froth; inert to rubber Slightly stable froth Slightly stable froths Fine-textured froth; frequently used with ores containing slimes
Modifying agents	Direct and reverse iron ore flotation	1. Lime (CaO) or slaked lime $Ca(OH)_2$ 2. Soda ash, NaOH Caustic soda, NaOH Sulphuric acid, H_2SO_4 3. Ca^{2+} ($CaCl_2$), Mg^{2+} ($MgCl_2$) 4. Na_2SiO_3 5. Starch, dextrin Quebracho, tannic acid, gaur gum, PAM	Slurry Dry 5–10% solution 10% solution Solution Solution of 0.30–0.80 kg/ton Solution of 0.5–1.2 kg/ton	pH regulator; disperses gangue slimes Activates silica with fatty acid collectors Disperses siliceous gangue slimes; Fragile froth Depress iron-bearing minerals

Table 2.
Reagent types used in mineral oxide industries (specifically for iron ores).

3.3.3 Dispersants

These are used to minimize the deleterious effect of undesired slime coating (**Tables 2** and **3**), e.g. sodium silicate and sodium metasilicate.

3.3.4 pH regulators

The pH regulators help in maintaining adequate pH of the pulp, which determines the selective separation of minerals. These are achieved by variety of bases and acids.

Classification of collectors	Type	Composition and dosages	Method of adsorption
1. Anionic collectors	• Xanthates • Thiocarbonates • Dithiophosphates • Thiocarbamides • Thiocarbanilides • Mercaptans • Thioles • Mixture of xanthate and dixanthogen	Consists of sulphydryl groups	Forms dixanthogen on pyrite surface and then hydrophobicity is generated Hydrophobic chain interactions
2. Mixed collectors		Optimum ratio 2:3	Co-adsorption of xanthate and dixanthogen Hydrophobic chain interaction of dixanthogen and reduction of electrostatic repulsion between ionic head groups of xanthate that are shield from each other by dixanthogen molecules

Table 3.
Reagent types used in mineral sulphide industries.

4. Flotation practice

In industries froth flotation is a continuous process involving a regular flow of feed pulp and separation of minerals into the regular respective product streams. The major elements of flotation operations are:

i. Feed preparation

ii. Mode, quantity and point of reagent addition

iii. Flotation circuit configuration and flexibility

iv. Product removal and dewatering

4.1 Importance of reagent conditioning

As the choice of specific reagent for a given ore is difficult and challenging, so is the selection of quantity, mode and time of addition of the reagents. The selection of reagent quantity does not pose much problem as a more or less precise reagent type and quantity for a specific ore system are available through reagent manufacturers and practising personnel. Whether the total quantity is to be added at different stages is a matter of difficult choice and is to be based upon carefully laboratory investigation regarding the case of floatability of minerals.

Adsorption of surfactant is in direct correlation with the solid-water-air interfaces as the main role of surfactants is to modify the properties of interfaces for increased adsorption of reagents and enhanced flotation process. Modified starches and blended polymers can be better alternatives to normal starches due to their higher solubility and better flocculation action.

4.2 Applications of flotation other than mineral industries

Application of flotation has been envisaged in other areas besides mineral engineering. Some of the examples are:

1. Deinking of paper in paper recycling
2. Flotation of wastewater treatment
3. Processing of oil sands

5. Conclusions

- There is a trade-off between the pH of the slurry, surfactants and the mineral surface for maximum flotation performance. It can thus be concluded that the length of alkyl chain, arrangement of atoms, nature and type of bonds present within the surfactants and regulation of pH in the flotation pulp are solely for an effective and successful flotation.

- Mineral surface and collector chemistry interaction is the first and critical step in flotation. The larger the electronegativity of the group, the stronger is the acting solid intensity, and the larger the radical section of collector, the stronger the selectivity of collector.

- Surfactants containing alcohol group and amine group have inherent frothing property along with their collecting capability.

- Though the cost of hydroxamate is higher than fatty acids, its superiority over fatty acids in flotation of the fine-grained oxide ore deserves further attention for industrial application. Research is geared at (a) developing alternate cheaper reagents with similar performances as hydroxamates, (b) modifying the structure of fatty acids for similar or better results than hydroxamates, (c) application of other chelating agents for enhanced flotation response, (d) successfully using flotation of silicated ores and other minerals, and (e) using green surfactants and solvents given their advantage of biodegradability and sustainability. However their high cost at present continues to be a barrier preventing their use although their benefits have been well realized.

- For cationic surfactants, another cationic group can be inserted, which can be further upgraded to dicationic and tricationic surfactants, which will work out well for reverse flotation process.

- For the use of depressants, more kosmotropic ions can be added to existing polymers to enhance their depressing action.

As discussed earlier, froth flotation has the ability to treat any mineral and thus reigns supreme as it is the most versatile concentration process for ore fines. A universal solution for all minerals is not possible but it depends on a case-by-case basis as each mineral ore has different compositions. The challenging aspect of the interaction of value and gangue minerals of any ore could be overcome by specifically improved reagents. A universal specific reagent recipe cannot be proposed for any ore flotation due to variation of mineralogical composition of different ores, tailings and slimes. The knowledge and research about surfactant chemistry have to be given due recognition and used judiciously through encouraging innovative, simple and customized reagent regimes for given ore deposits.

Conflict of interest

No potential conflict of interest was reported by the authors.

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