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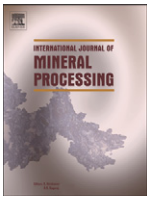

An overview of reverse flotation process for coal

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A B S T R A C T

Flotation is one of the most effective technologies for the up-gradation of coal fines of particle size below 0.5 mm because of the inherent hydrophobic nature of coal. Contrary to this, reverse flotation of coal in which coal particles are depressed and gangue particles floated, was developed as an alternative process to minimise the sulphur content in the coal. This method can also be applied to reduce the ash content of coal by floating the mineral matter present in coal. Therefore the mechanism and performance of this process treating different types of coal have become an active research topic and several literatures have also been published. Despite the research efforts, this process has yet to find application in the coal preparation industry which it deserves. In the present review article, an effort was made to understand the basic mechanism of this process along with the effect of variables and chemicals used on its performance. Finally, some challenging issues that need special attention are highlighted to further improve the process.

Contents

Abbreviations: pzc, point of zero charge; iep, iso-electric point; μm, micrometre; mol/L, moles per litre; CMC, critical micelle concentration; DTAB, dodecyl tri-methyl ammonium bromide; DTAC, dodecyl tri-methyl ammonium chloride; CTAB, cetyl tri-methyl ammonium bromide; HTAB, hexadecyl tri-methyl ammonium bromide; HPYB, hexadecyl pyridinium bromide; HPYC, hexadecyl pyridinium chloride; MIBC, methyl isobutyl carbinol; TTAB, myristyl-trimethyl ammonium bromide; SDS, sodium dodecyl sulphate; PAM, polyacrylamide; DDA, dodecyl amine; DAH, dodecyl amine chloride.

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1. Introduction

Flotation is one of the prime mineral processing methods that has found wide application from separation of complex ores such as sulphides of lead–zinc and copper–zinc to platinum, nickel and gold hosting sulphides, to oxides like hematite, cassiterite, oxidised minerals such as malachite, cerussite and finally to non-metallic ores like fluorites, phosphates as well as coal (Wills and Napier-Munn, 2006). Since its commercial introduction in 1905 and patent in 1906 (Wills and Napier-Munn, 2006; Gupta and Yan, 2006), flotation has advanced tremendously in terms of process, reagents and equipment's used, achieving the basic aim of separation of valuable minerals from gangue particles by exploiting the differences in their physico-chemical properties. One such development is the reverse flotation in which the gangue is floated by use of suitable reagents while the valuables remain in the suspension and collected as product/concentrate. This method is completely opposite to the direct or conventional flotation and hence is termed as reverse flotation. It is widely used in the processing of iron-ores, diasporic–bauxite ores, phosphate rocks, kaolin minerals etc. In iron ore processing, the reverse flotation of silica and silicates has been tested successfully by both cationic and anionic reagents to obtain purified ferriferous concentrates (Houot, 1983; Ma et al., 2011; Pradip et al., 1993; Pradip, 2006). Much work regarding the reverse flotation of diasporic ores has been reported which involve the effective flotation and collection of alumina–silicate gangue minerals such as pyrophyllite, illite, kaolinite and chlorite using cationic reagents like alkyl amine and carboxy hydro-oxidoxime (Xu et al., 2004; Wang et al., 2004). For phosphate rocks, direct flotation is sometimes ineffective due to similar physico-chemical properties of phosphates and carbonates (Gharabaghi et al., 2009; Kawatra and Carlson, 2013; Sekhar and Jain, 2009). So reverse flotation is considered to be an alternate route in which carbonate minerals are floated by anionic collectors at acidic pH while siliceous gangues at neutral pH using cationic amine collectors (Mohammadkhani et al., 2011; Sis and Chander, 2003; Tanaka et al., 1988).

In the case of coal, flotation is by far the most commonly used beneficiation method in the finer sized range. Coal because of its natural hydrophobicity is collected in the froth while mineral gangues remain in the pulp as tailings. There are several research articles published on flotation of coal and its allied research topics covering both basic science as well as on applied research. The idea of reverse flotation for coal started with the first patent done by Eveson in 1961 on bituminous coal in which shale i.e. the mineral matter was floated and reported in the froth phase while the clean coal was depressed and remained in the suspension. The concept was further developed for the selective removal of pyritic sulphur from US coals by several investigators (Baker et al., 1973; Miller, 1973, 1975, 1978; Miller and Deurbrouck, 1982; Lin, 1982; Miller et al., 1984). Consequently the study of reverse flotation of coal with a motive to lower the ash content of coal was carried out by many scientists and researchers (Stonestreet and Franzidis, 1988, 1989, 1992; Vamvuka and Agridiotis, 2001; Pawlik and Laskowski, 2003a,b; Melo, 2005; Ding and Laskowski, 2006a,b; Patil and Laskowski, 2008, Zhang et al., 2013; Ozturk and Temel, 2013; Xia and Yang, 2013a).

The driving force behind the works done so far to develop reverse flotation as a viable processing tool to produce clean coal is the advantages associated with it. Coal makes up around 60 to 80% of the flotation feed and as the coal rises, with it gangue particles also raise which cannot be avoided. This problem is known as ash entrainment which is inevitable during direct flotation and adversely affects the quality of product (Angadi and Suresh, 2005; Angadi et al., 2012). Here coal reverse flotation can provide a good substitute as the gangue particles are floated with some coal entrainment. But in comparison to ash entrainment, coal entrainment will be lesser significant due to coarser size of coal particles and smaller physical mass transfer of coal into the froth. Another benefit is the reduction of mass transfer as the gangue material makes up 15 to 35% of the feed. So the concentrate mass is lowered and the overall carrying capacity of the froth is reduced which implies that reverse flotation can be carried out at higher pulp densities and using small sized equipments. In addition to the above two benefits, the others are enhanced application of column cell technology and consistency of gangue floatability. Column cells with their lower carrying capacity fit well with the reduced yield factor in reverse flotation at higher pulp density and feed rates. The gangue minerals in comparison to coal have consistent chemical nature and well defined structures which impart them uniform floatability. Above all these coal reverse flotation may prove to be a better option for coals with poor floatability characteristics which do not give sufficient recovery with forward flotation.

Even though the coal reverse flotation process has some obvious advantages over forward flotation and a development period of around 50 years starting from 1960s, it is still an established route neither for ash reduction nor for pyrite removal. This indicates that there is scope of improvement and more work need to be done in order to bring the process to the commercialization stage.

Hence the objective of this review is to bring forth the developments done so far in the field of coal reverse flotation with focus mainly on ash reduction and discuss the effects of reagents and process conditions required for exploring new horizons.

2. Area of application

As explained above, reverse flotation appears to be an emerged process in the recent past for different minerals as well as for coal. In the case of coal, there are two areas in which it is being applied with an objective either to reduce the sulphur content or ash content. The details about each one are explained further.

2.1. Sulphur removal

Sulphur is a detrimental element in coal which limits the scope for use of coal. It is a typical problem in most of the U.S. coal deposits along with other deposits in other part of the world. Also it is present in coal in three forms i.e. pyritic, organic and sulphatic among which only pyritic sulphur can be removed by physical means (Parekh and Miller, 1999). So any process targeted towards the minimization of sulphur will be seen as a value addition. In 1975 Miller developed a two stage froth flotation process in which first conventional flotation of coal was carried out and the concentrate thus obtained was subjected to re-flotation of pyrite. During the second stage of flotation the froth of the first stage was conditioned with dextrin (Aero Depressant 633) to depress the coal and subsequently potassium amyl xanthate was used as collector to float pyrite. This method demonstrated its potential in pyrite rejection by as much as 80% along with ash rejection from 31.8% to 7.8%. The work was demonstrated not only at the laboratory level but also at the pilot plant scale (Miller, 1973). In another study by Miller et al. (1984) using a well-defined dextrin sample with potassium amyl xanthate and methyl isobutyl carbinol (MIBC), it was found that dextrin adsorbed on both coal and pyrite but the flotation response of pyrite to xanthate was not affected at all. Another study on different U.S. coals showed that pyritic sulphur can be brought down to 1.22%