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Analysis of Removal of Pyrite from Scheelite Ore by Flotation Combination in Shaking Table

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Abstract

Shaking table and flotation are often used in scheelite (CaWO4) beneficiation, and usually they are applied in sequence. In this paper, analysis of mineral movement have been investigated in shaking table in which pulp was conditioned with xanthate as a collector and fed, heavy scheelite was concentrated, while heavy pyrite removed directly on the deck by the action of collector. Artificially mixed mineral with 1% scheelite and 2% pyrite was used in CFD simulations and experiments. Through CFD simulations, it was found that pyrite particles, which were hydrophobic by collector, were attached to the water-air interface and subjected to upward buoyancy, which increased the density difference between scheelite and pyrite particles and enabled the separation of both minerals in the shaking table. The experiment results showed that the concentrate grade in conventional table concentration was 23.5% WO3, the separation efficiency was 77.89%, while the concentrate grade of scheelite in the table concentration of xanthate presence was 65.0% WO3 and the separation efficiency was 80.88%. The combination of flotation in table with collector addition not only eliminated the flotation to remove pyrite after table but also resulted in a lower rate of scheelite loss.

1. Introduction

Gravity concentration and flotation are the most widely used conventional methods for scheelite processing [1, 2].

Scheelite is present in major tungsten deposits, including the skarn deposit [3,4], and other valuable metals besides scheelite are present in the ores of the skarn deposit, the most abundant of which is present in the sulphide mineral form [3,4].

In recent years, the most innovative approach of scheelite beneficiation has been to optimize the separation process by using selective reagents [5,6,7] to selectively separate scheelite from calcite with similar flotation properties of scheelite, the combination of gravity, magnetic and flotation, and recovery of valuable minerals from the ore of scheelite-sulphide [1,2,3].

The beneficiation process of scheelite to produce concentrates that meet international trade standards generally uses two separation schemes: pre-separation-flotation and gravity-flotation.

The optimization of designing gravity concentration circuits for some heavy minerals such as scheelite had been described in detail [1,2,3]. Jigs, spirals, shaking tables and centrifugal concentrators are often used in practice and especially, shaking tables are needed for final separation. Flotation is needed not only to separate the fine scheelite particles that cannot be recovered by gravity concentration [5,6], but also to remove impurities (e.g. pyrite) in scheelite ores. Generally, the scheelite ores containing sulphides are concentrated by gravity separation before they are floated using collectors such as butyl xanthate to separate scheelite from other valuable sulphides [5,6,7,8]. During flotation of scheelite from other minerals, the floatability of pyrite is similar to the floatability of other minerals, which makes flotation difficult [9,10,11,12]. Generally, if there are great amount of pyrites in scheelite ore, pyrite and scheelite concentrates are respectively

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separated by scheelite-pyrite flotation and are sent to the consumers' if there are small amount of pyrites in scheelite ore, pyrite is separated by scheelite-pyrite flotation processing and throwed away [13,14].

The similarity between scheelite and other sulphides in their densities makes the gravity separation more difficult and decreases the grade of scheelite concentrate.

A shaking table is a gravity concentrator to separate minerals in the thin water film that flows over an inclined plane using difference of minerals in their densities and it is used to separate tungsten, tin, iron, tantalum, barium, titanium, zirconium and, to a lesser extent, gold, silver, thorium, uranium and now also used in recycling of packaging plastics [15,16,17,18].

The significance of the many design and operating variables and their interactions have been reviewed by Sivamohan and Forssberg [19], and the development of a mathematical model of a shaking table is described by Manser et al. [20]. The separation on the shaking table is controlled by a number of operating variables, such as wash water, feed pulp density, deck slope, amplitude, and feed rate, and the importance of these variables in the model development is discussed [21,22]

Fine scheelite particles are heavy, so they flow into concentrate launder, and light minerals such as quartz and calcite are washed into tailing launder by water flow. As the iron sulphides such as pyrite are heavy, they may flow into the concentrate launder degrading the quality of scheelite concentrate.

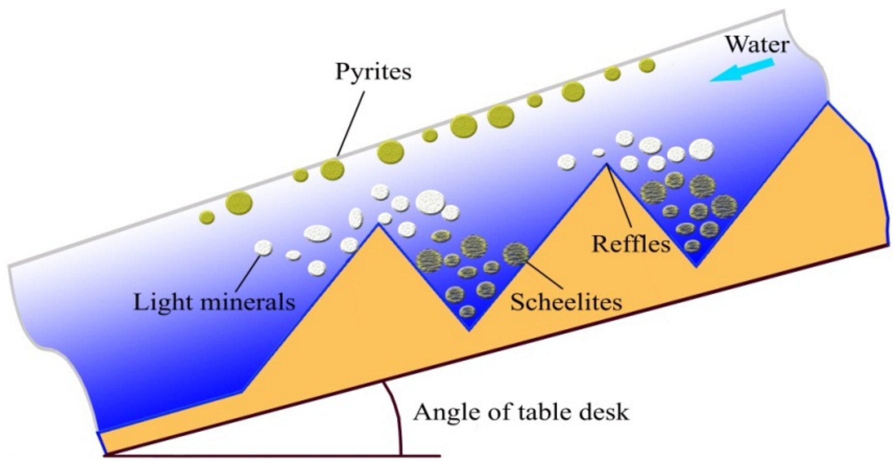


Figure1. Concentration of scheelite and floating of pyrite on the table.

For the table concentration of scheelite ore containing pyrite, pulp is conditioned with collector and then fed onto the table. Heavy scheelite particles are concentrated by gravity while the surfaces of pyrite particles are rendered hydrophobic by the action of collector. Hydrophobic pyrite particles may be in contact with the air at water surface or go over riffles by shaking motion of the table, attatched to air and after will be floated on the water surface (Figure1).

Density of pyrites floated on the water surface is less and therefore, the density difference with scheelite exists and pyrite particles are washed away into tailing as light minerals such as quartz. Consequently, the combination of gravity and flotation on table may allow scheelite to be concentrated while pyrite to be washed into tailing, and thus the grade of scheelite concentrate may be raised.

Xanthate added into the pulp is the collector often used in flotation of pyrite. No frother is used because it is not necessary to produce bubbles.

Dosage of collector such as xanthate was added according to the pyrite content in scheelite ore. As scheelite is a non-sulphide mineral, it does not interact with collectors and does not float on the water surface.

This method can be viewed as a combination of gravity and flotation on shaking table.

The combination of gravity and flotation on the table allows simultaneous gravity separation of scheelite and removal of pyrite to obtain a high grade scheelite concentrate, and no subsequent separation flotation is required. As a result, the process of scheelite beneficiation is simplified.

Gravity separation combined with flotation has been proposed and used previously in mineral processing practice.

The separation process in the combined flotation on table was simulated by CFD and experimentally tested to confirm the validity of the approach.

Simulation of the separation process in this method was attempted by the computational fluid dynamics-CFD.

In recent years, Computational Fluid Dynamics-CFD has widely used in simulating phenomena which take place in fluid media, such as gravity separation and flotation. In the field of gravity concentrator, CFD had been used for simulating particle flows in hydro cyclone [23,24], jigs [25,26] and thickener [27]. Researchers have simulated the process of separation of magnetite particles from quartz ones in Knelson concentrator using CFD before comparing the result with the experiment data and analysing error, and thus confirmed scientific accuracy of magnetite separation in Knelson concentrator [28]. These have been carried out by using hybrid Euler–Lagrangian model, dense discrete phase model (DDPM), and the Realizable Mixture k-ε turbulence model has been selected to model the turbulence of fluid phase due to its swirling nature. Using CFD-DEM, segregation [29] of a multi-dispersed population of grains in air-table was simulated and combined qualitative and quantitative assessments of process conditions such as deck shape, and new formal vibrating table gravity concentration [30,31] was researched.

CFD simulation models for bubble-particle attachment [32,33] and bubble-particle detachment in flotation machine [10] have been used to calculate collision probability, attachment and bubble stability in each location of flotation cell, corresponding to the results observed in flotation practice. Recent studies [35,36] classified the models for flotation as Euler-Euler continuity, bubble number density, transport equation for concentration of particle, particle or bubble motion and Euler-Lagrangian, and gave the results obtained through modelling and simulation of flotation equipment. They also proposed more efficient CFD models for the flotation with the parameters considering the bubble-particle interaction and the influence of turbulent flow.

However, there is not enough information on the CFD simulation of combination gravity and floatation on the table. It was also difficult to find the results of experiments and separation of this method combined with flotation on a table.

The combination of gravity concentration and flotation on the shaking table has the advantage of preventing the co-entry of similar gangue minerals into the table concentrate and increasing the concentrate grade and recovery index.

The aim of the study was to simulate this screening process with CFD and to validate the approach through experiments.

2. Study methodology

The study was carried out in three stages.

The first step was to simulate the process of gravity separation of scheelite in the table and washing of pyrite was floated by collector and washed with tailings by CFD.

The second stage was confirmed by experiments on the samples made of scheelite, pyrite and quartz, and whether scheelite was separated in the experimental table and pyrite was washed with tailings.

The third step was to verify the validity of this study with simulated results and experimental data.

2.1. Principle basis of this study

The floating of pyrite by collectors is a process in which the sum of the forces acting on pyrite particles is smaller than the adhesive force of pyrite particles to the air surface, so that pyrite particles float on the water surface.

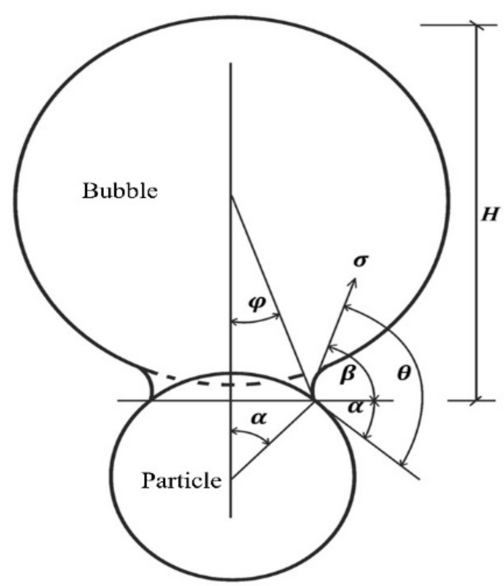


Figure2. Model of mineral particle attached air bubble

The attachment of pyrite particles to the air surface on the table plate is similar to the attachment of mineral particles to the air bubbles in the water inside the cell and to the floatation of the particles.

To determine the adhesive force of mineral particle to air, this model is used for the attachment of mineral particles that contact and adhere to float during flotation (Figure2) [33,34,35].

In Figure2, the forces acting on pyrite particle attached air bubble include capillary force, buoyancy, pressure force, gravity force etc. The capillary force acts along the tangent to the gas–liquid-solid interface at the three-phase contact line and can be described as:

$$F_c = 2\,\pi R_p \sigma sin\alpha sin\,(\theta - \alpha) \quad (1)$$

Where are:

F_c – the capillary force (N),

R_p- the particle radius (m),

σ - liquid surface tension (N/m),

θ -contact angle (degree),

α - polar angle (α is half of the contact angle).

H is length of bubble.

The force, which supports the particle attachment to the interface, is the buoyancy, F_b of the particle volume immersed in the liquid phase. This force can be described by

$$F_b = \frac{\pi R_p^3 \rho_l g}{3}(2 + 3cos\alpha - cos^3\alpha) \quad (2)$$

Where are:

ρ_l - density of liquid (kg/m^3),

g - the acceleration due to gravity (m/s^2).

The other relevant force on the particle is the particle weight. This force F_g can be described by

$$F_g = \frac{4\pi R_p^3 \rho_p g}{3} \quad (3)$$

Where are:

ρ_p - density of mineral particle (kg/m^3).

The pressure force F_p, coming from the hydrostatic pressure over area enclosed by the three-phase contact line is described by

$$F_p = \pi R_p^2 H sin^2\alpha \rho_l g - \pi R_p^2 sin\alpha \frac{2\sigma}{R_b} \quad (4)$$

Where are:

R_b - radius of bubble (m).

The pressure force F_p acting on particles influenced by air bubbles in deep water of flotation machine. However, if pyrites are attached to a larger air bubble (air bubble is vast, R_b is infinite), the pressure force will be disregard.

Consequently, the force F_{ad} for pyrite particles to attach to the water-air interface must be greater than the sum of the capillary, buoyancy, pressure, and gravity forces acting on the particles.

$$F_{ad} = 2\,\pi R_p \sigma sin\alpha\, sin(\theta - \alpha) + \frac{\pi R_p^3 \rho_1 g}{3}(2 - 3cos\alpha + cos^3\alpha) - \frac{4\pi R_p^3 \rho_p g}{3} \quad (5)$$

If adhesion is smaller than separation force, the mineral particles settle down.

The floating of heavy minerals on the table is different from the process of collision, attachment and detachment of mineral particles from air bubbles in the flotation cell.

During flotation, the pulp is agitated in a reagent agitator and enters the flotation cell.

The air flows into the flotation cell through the air inlet pipe and the mineral particles are attached to the air bubbles in the deep water layer by collectors and frothers and floated onto the water surface.

In the table, air is not injected, but hydrophobic mineral particles float on the water surface.

The reason is that the collector and pyrite particles are subjected to sufficient reagent stirring due to the shaking action on the feed box and plates in the table, when the collector is added to the pulp feed tank before feeding the table.

Gravity concentration is similar to thin-film flow concentration on inclined deck, but the movement of heavy pyrite particles differs from scheelite by collector action.

Pyrite particles rendered hydrophobic by the action of xanthate might come into contact with the air at water surface or be carried over the riffles by the shaking motion of the table. If they attach to the air at the surface, they could then float (Figure1). Density of pyrite was less and therefore, the pyrite particles floating on the water surface were washed away into tailing as light minerals.

If only the sum of various forces including gravity and hydrodynamic force on the mineral particles is less than attachment force to the bubble, particles will float onto water surface, but if the sum is larger than the force, particles will settle down.

The aim is to ensure the pyrites float onto the water surface and wash away into tailings with the lateral water flow, and not coming into the table concentrate.

2.2. Simulation of separation processing by CFD

2.2.1. Model of CFD simulation

CFD simulations are the process of solving the continuity equation of fluid and the momentum balance equation by numerical analysis.

In order to study the flow behavior of the different phases, continuity equation and momentum balance equations for each phase was formulated. Both the solid phases have been treated as continua. The unsteady state continuity equation for the fluid/solid phase i can thus be written as literature [36]:

$$\frac{\partial \alpha_i}{\partial t} + \nabla \cdot (\alpha_i V_i) = 0 \quad (6)$$

Where are:

α_i - the volume fraction of the i_{th} phase,

V_i - the velocity vector of the i_{th} phase (m/s).

The momentum equation for the liquid phase l is given as:

$$\frac{\partial(\rho_i \alpha_{ki} V_i)}{\partial t} + \nabla \cdot (\alpha_l \rho_l V_l V_s) = -\alpha_k \nabla p + \nabla \cdot \bar{\bar{\tau}}_l + \alpha_l \rho_l g + \sum_{s=1}^{2} k_{sl} (V_s - V_l) \quad (7)$$

Where are:

g – the acceleration due to gravity (m/s^2),

$\bar{\bar{\tau}}_l$ - the stress tensor for the l_{th} phase (N/m^2) ,

∇p - the pressure gradient (N/m^2),

K_{sl} - the interaction coefficient between the liquid and the solid phase.

The solid momentum balance equation for the buoyant particles can be written as follow [36]:

$$\frac{\partial(\rho_s \alpha_s V_s)}{\partial t} + \nabla \cdot (\alpha_l \rho_l V_l V_s) = -\alpha_s \nabla p - \nabla p_s + \nabla \cdot \bar{\bar{\tau}}_s + \alpha_k \rho_k g + F_{ad} \quad (8)$$

Where are:

$\bar{\bar{\tau}}_s$ - the stress tensor for the solid phase (N/m^2),

∇p_s - the pressure gradient due to the solids (N/m^2),

F_{ad} - the adhesive force (N).

2.2.2. Boundary condition of CFD simulation

The geometry of the shaking table was created and the meshing of the domain was done using the commercial software, Gambit 2.4.6. The domain was meshed with a structured mesh consisting of 211870 nodes. The length and width of the table was 900×380mm. In Figure3, the feed area and wash water area were set as inlets, while the concentrate area and tailing area were set as outlets.

Other pertinent details are given in Table 1, which was also used to analyze the data.

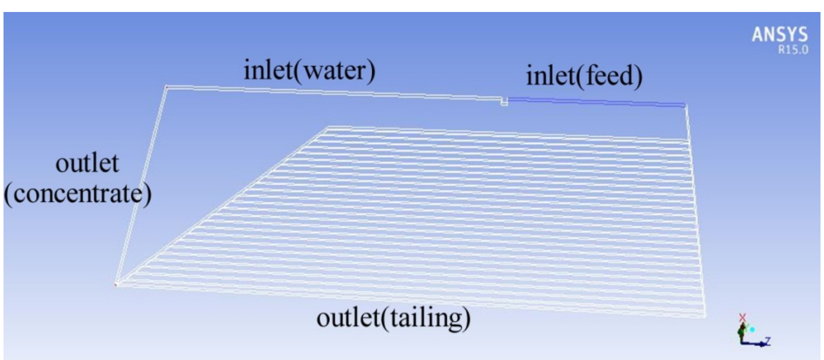


Figure3. Meshed geometrical model of table

Table 1. Parameters used in simulation studies.

Remarks	Parameter Value
Distance between riffles	12mm
Height of the riffles	3mm
Slop angle of the riffles	45°
Feed density	25%
Length of stroke	8~12mm
Stroke per minute	270~300r/min
Feed size	0.04~0.2mm
Lateral slop angle	1~3°
Longitudinal slop angle	0°
Inlet velocity of washing water normal to the cross section of the inlet	0.15m/s
Inlet velocity of the water and solids normal to the cross section of the inlet	0.1m/s
Volume fraction of scheelite particles at the inlet	0.0025
Volume fraction of pyrite particles at the inlet	0.005
Volume fraction of quartz particles at the inlet	0.9925
Density of scheelite	6000kg/m^3
Density of pyrite	5100kg/m^3
Density of quartz	2650kg/m^3
Density of water	998.2kg/m^3

2.3. Results of CFD Simulation

The model equations were solved for the entire domain with the boundary conditions given using the commercial CFD software, ANSYS 15.0.

2.3.1. Simulation of scheelite and pyrite gravity concentration in the table.

First, a simulation for the motion of the particles on the table without the addition of reagent was carried out. At outlet the velocity and the concentration gradient for all the phases are taken to be zero and the pressure is considered to be atmospheric. At the inlet, the velocity and volume fraction of all the phases are specified. At the wall, Moving Condition is specified for the motion of the table plate. A user defined function (UDF) was written for the boundary conditions to give motion of the table plate. The Phase-Coupled Simple algorithm was used for Pressure-Velocity Coupling. Second Order Upwind Scheme was used for the discretization of the moment balance equation and the continuity equation.

In order to get a converged solution, the Under-Relaxation Factors were kept at 0.3 for Pressure, 0.7 for Momentum, 0.8 for Turbulent Kinetic Energy, 0.8 for Turbulent Dissipation Rate and the others are 1. The time step was taken as 0.005s and the numbers of time step are 1000. The convergence criterion was set to 0.0001 for the residuals. The simulation was carried out for 6s.

Figure4-6 shows the contours of volume fraction of scheelite, pyrite and quartz particles over time.

Figure5 shows the contours of volume fraction of pyrites.

Figure6 shows the contours of volume fraction of quartz.

In simulation, the arrival time of scheelite and pyrite in concentrate area are of 6s. As shown in Figure4 and Figure5, heavy scheelite and pyrite are together in concentrate area. It was found that with 8mm, 280rpmin, table concentration was sufficient to capture all of the scheelite particles. All of quartz particles flowed over the tailing end (Figure6), but about all of pyrite particles were mixed with concentrate due to their heavy density.

2.3.2. Simulation of floated pyrite on the table.

Second, simulation for motion of the pyrite particles when reagents are added in the table was carried out. After obtaining a transient state solution using the Eulerian models as stated above, the DPM model was used with dosage of floatation reagent. A reversed flow at the outlet was observed in the presence of buoyant force.

In simulation of floated pyrite on the table, simulation condition is equal to prefer, but floating conditions of pyrite were added more.

When floating ores with a low pyrite content, a common collector such as butyl xanthate is often used at a dosage of 80-100 g/t-ore (approximately 20 mg/L in pulp, depending on pulp density) When dosage of butyl xanthate is usually 80~100 g/t (20mg/L-pulp), contact angle of pyrite particle is 70 degrees and its polar angle is 35 degrees [37].

A user defined function (UDF) was added in the source term for the momentum balance equation of pyrite particles to account for the buoyant force.

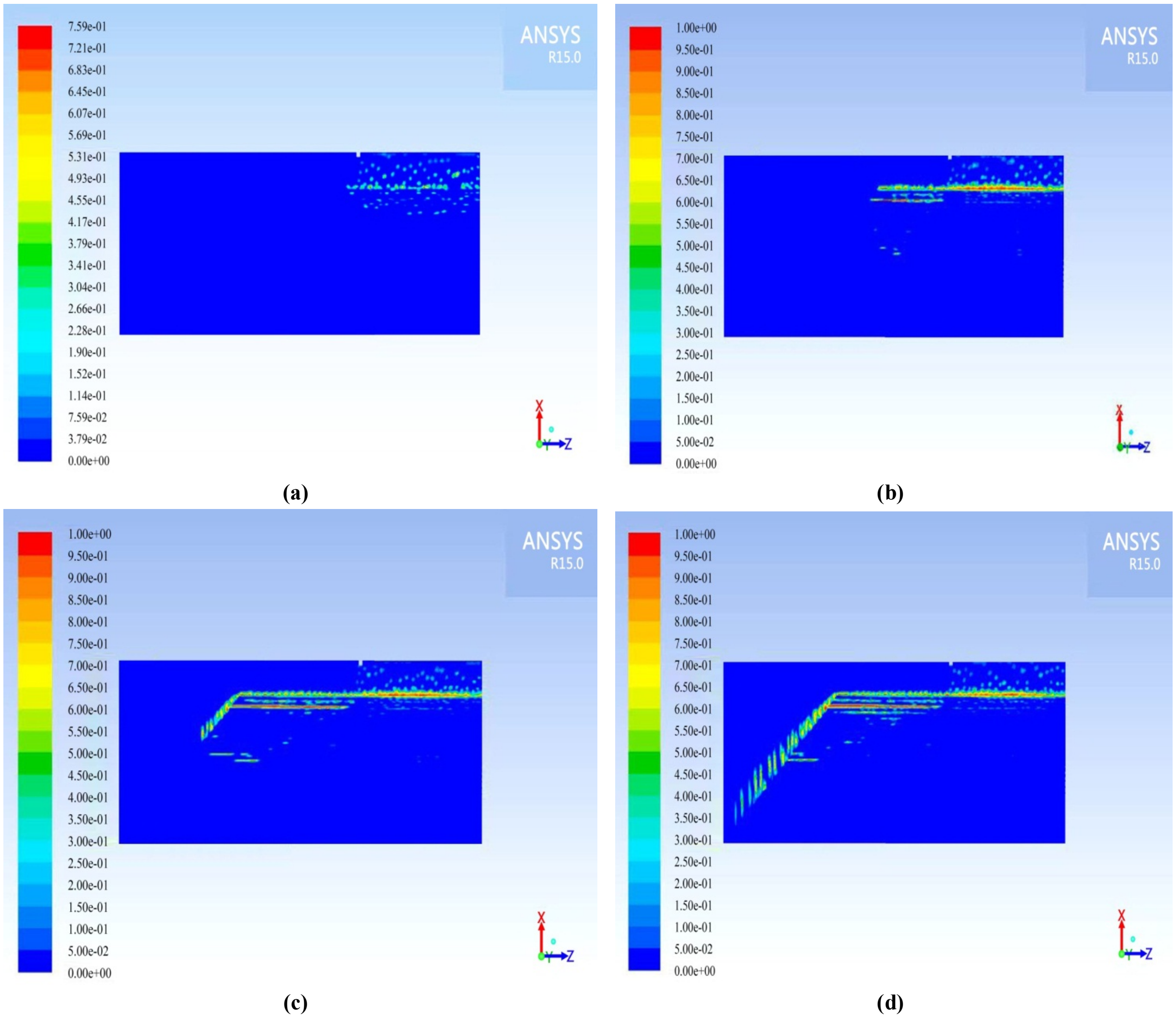


Figure4. Result of simulation of Scheelite. a) Time 1s; b) time 3s; c) time 4.5s; d) time 5s.

The simulation was again carried out in above first conditions. The result of simulation is shown in Figure7. As seen in the Figure 7, the motions of scheelite and quartz particle were same as prior. Only 95% of pyrite particles flew over the tailing end due to the buoyant force acting on these particles.

2.3.3. Influence of factors on simulation

In simulation major factors that make the pyrite particles flow are size of particles, the dosage of collectors, and polar angle of pyrite contacted bubble. (Figure2)

Table separation is based on size of scheelite particles and motion of pyrite particles depends on their size. Coarse particles will be settled due to their weight, fine pyrite particles will be floated onto water surface and washed down, although turbulent flow is strong. When butyl xanthate is added in solution, contact angle of pyrite is 71.9 degrees maximum diameter of pyrite attracted air bubble, D_{max} is 2.2 mm in Halimond tube [37]. Scheelite particles on size range of - 1.0 + 0.04 mm are separated by tables referred to as fine table. In the end, this number is taken as standard size of pyrite in calculation.

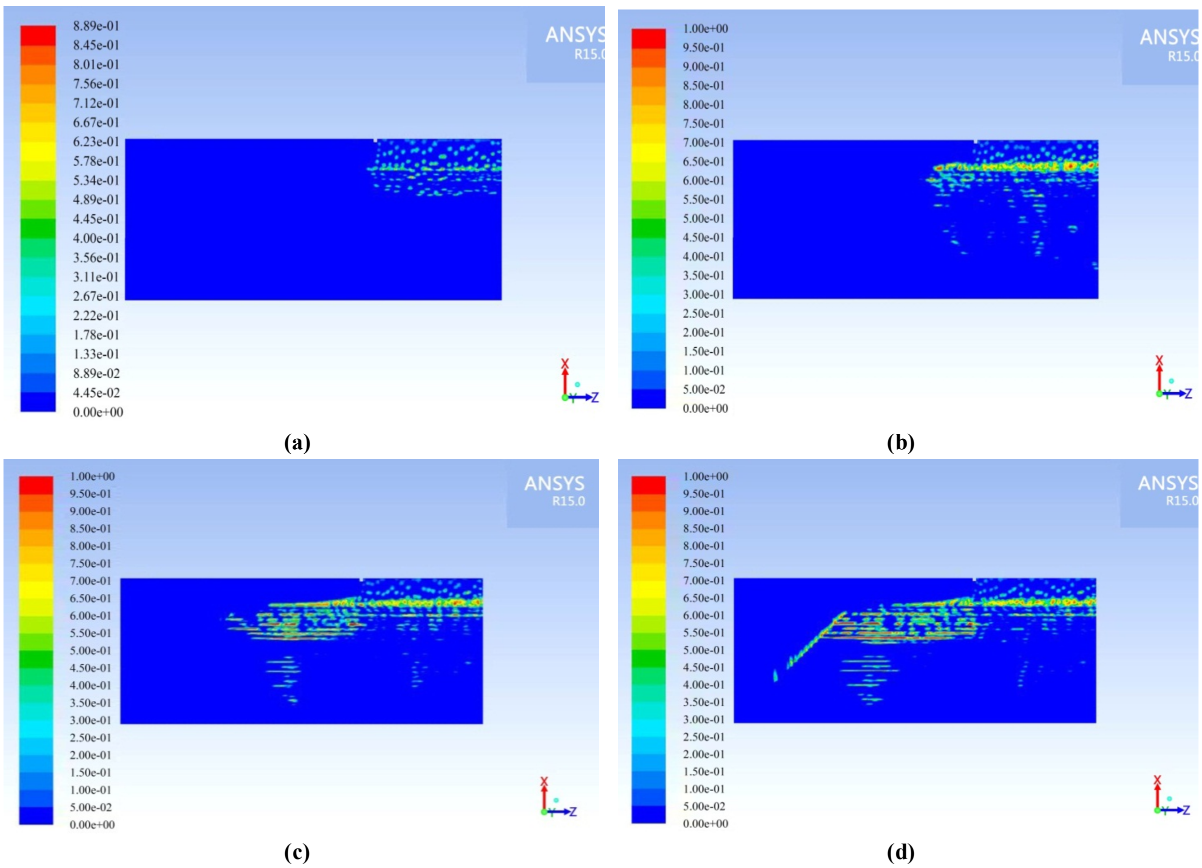
Another important factor is the dosage of collectors, and this directly influences the contact angle of pyrite surface. Pyrite surface is changed hydrophobic by collector, consequently its wettability will be decreased and attached to air surface. Change in the dosage of collector is equal to change of contact angle and hydrophobicity. As the dosage of collector changes, there will be some changes in the contact angle. while there is some relationship between dosage of collector and contact angle, limit dosage of collector does not lead to limit change of contact angle. Dosage of collector in flotation depends on the amount of sulphide such as pyrite and its quantity is fixed.

Therefore, in simulation it was considered that collector dosage affected motion of pyrite particles but not contact angle affected. In flotation contact angle of pyrite particles is 60~70° in amyl xanthate solution (1×10^{-3} M, pH 4.68, Eh -100~100 mV VS.SCE) [35,36], 80~95° in butyl xanthate solution (1×10-3 M,pH 10.0, Eh 150~300 mV VS.SCE), 60~70° in ethyl xanthate solution (1×10^{-3} M, pH 10.0, E_h 170~300 mV VS.SCE) [38,39]. Therefore, the size of pyrite particles varied from 60 to 90 degrees in simulation.

Factor affecting simulation is Polar angle contacted with air. If Polar angle is small, the particle is not attached to the air and settled in water. Polar angle depends on contact angle. When polar angle is half of contact angle, it becomes maximum, it is not modified.

In CFD simulation of pyrite floating, we made calculation with the fixed location of splitter, changing size of contact angle.

The changes in the contact angle don't influence the time which the pyrites are floated and washed away. Figure4 shows the contours of volume fraction of scheelites.



(a) (b) (c) (d)

Figure5. Result of simulation of pyrite. a) Time 1s; b) time 3s; c) time 4.5s; d) time 5s.

2.4. Results of table experiments

The second stage of the study was carried out by experiments with samples of scheelite, pyrite and quartz in the same simulation conditions.

Firstly, traditional table experiments were conducted. For the experiment, single minerals of scheelite, pyrite and quartz, of which grades are higher than 98%, were ground in laboratory ball mill to -1.0 +0.04 mm of particles. Mixed ore composed of 1% of scheelite and 1% of pyrite were used as representative of scheelite from Hochon area of DPR Korea with 5×10^{-2} kg of scheelite, 10×10^{-2} kg of pyrite and 4.85 kg of quartz. A pilot scale table with a size of 2100×1050 mm was used in experimental Wilfley table. Here splitter was put on the end of riffle and other conditions were optimally set for scheelite concentration.

The cumulated concentrate from experiments weighed 0.1447kg ~ 0.145kg and the grade was 23.5% WO_3 in 6 of experiment numbers.

Also, table experiments with addition of collector for scheelite ore were conducted. Sample and experiment conditions were the same as the first but butyl xanthate, collector, was added 80g/t –ore (20 mg/L –pulp) in agitator and agitated and fed. The position of splitter was the same as above experiment and the test was repeated 6 times. The cumulated concentrate from experiments weighed 0.052kg ~ 0.0537kg and the grade was 65.5% WO_3 in 6 of experiment numbers.

Experiment results showed that the grade was 65.5% WO_3.

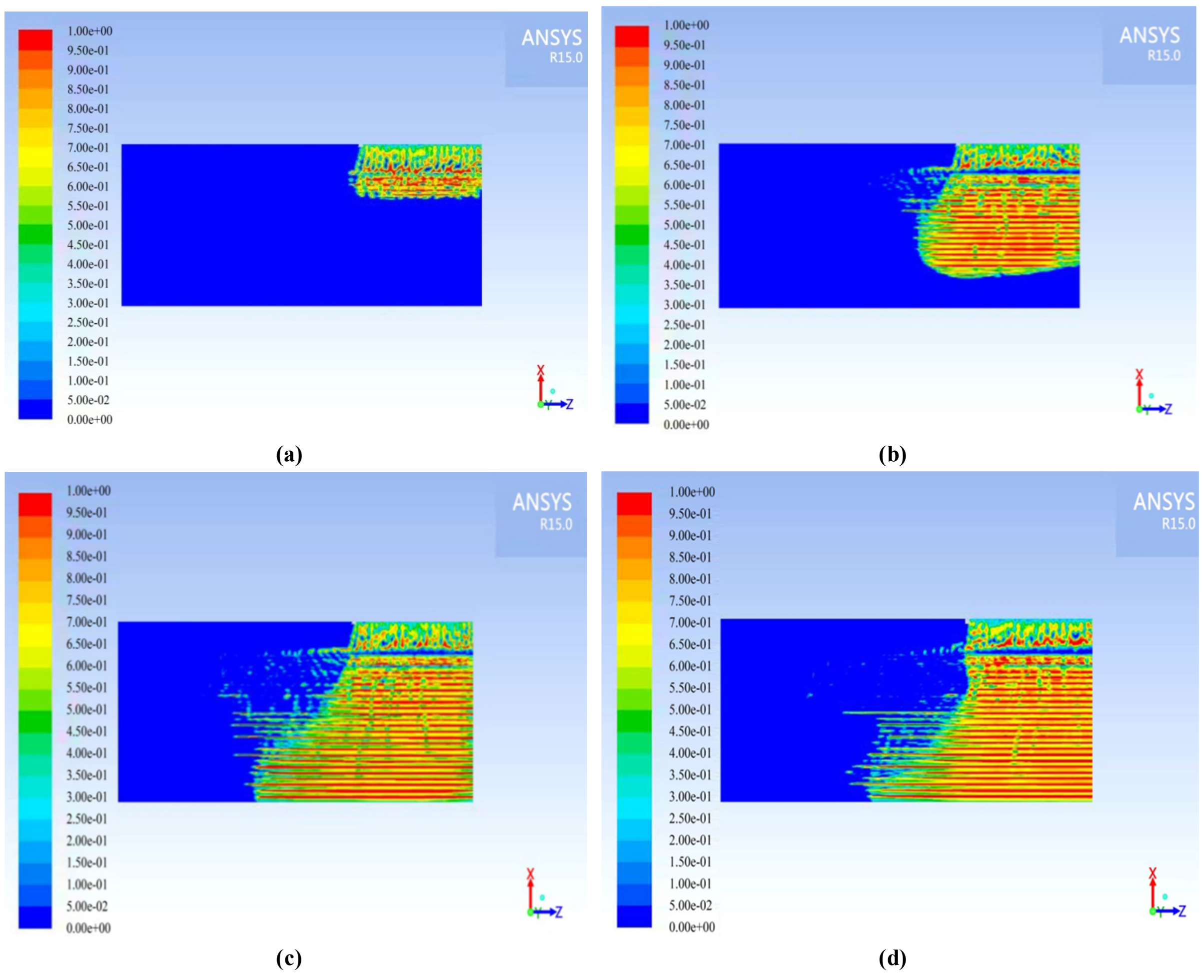


Figure6. Result of simulation of quartz. a) Time 1s; b) time 3s; c) time 4.5s; d) time 5s.

2.5. Validity assessment of this study by simulation and experimental data

The third step of this approach was to verify the validity of this study with simulated results and experimental data.

The separation result is characterized by the grade and recovery, but quality and quantity of table separation products are varied according to the position of splitter which divides feed into the concentrate and the tailing. To improve the grade, the splitter should be closer to the concentration launder, but to increase the recovery, it should be closer to the tailing launder

Therefore, the efficiency of separation (Es) is more appropriate for characterizing the table separation result [40]

$$E_S = R_V - R_g \tag{9}$$

Where are:

Es- the efficiency of separation (%),

RV - the recovery of the valuable mineral (%),

Rg - the recovery of the gangue into the concentrate (%).

It was found that with 8mm, 280r/min, table concentration was sufficient to capture the scheelite particles.

As shown in Figure3, splitter was set on the end of riffles.

From the data obtained in the simulation calculations of the conventional table, the concentrate grade, recovery and separation efficiency were calculated.

Scheelite feed quantity $Q_{fee,sch}$ was calculated from Mass Flow Rate of feed inlet in Fluxes of report item in simulation. $Q_{fee,sch}$ was scheelite amount of feed, $Q_{fee,pyr}$ was pyrite amount of feed and $\mathrm{Q_{fee,quar}}$ was quartz amount of feed. $\mathrm{Q_{fee}}$ was amount of feed expressed as sum of $\mathrm{Q_{fee,sch}}$, $Q_{fee,sch}$ and $Q_{fee,quar}$.

Scheelite concentrate quantity $Q_{con,sch}$ was calculated from Mass Flow Rate of concentrate outlet in Fluxes of report item, pyrite quantity $Q_{con,pyr}$ and quartz quantity $Q_{con,quar}$ was also calculatd from the same method. $Q_{con,sch}$ was scheelite amount of concentrate, $Q_{con,pyr}$ was pyrite amount of concentrate and $Q_{con,quar}$ was quartz amount of feed. Concentrate amount Q_{con} was sum of $Q_{con,sch}$, $Q_{con,pyr}$ and $Q_{con,quar}$.

In the simulation calculations, the content of scheelite in the ore was 1%, the content of pyrite 2%, and the content of quartz 97%, while in theory, WO_3 in the feed was 0.805%.

In the first simulation, Mass Flow Rate of inlet was 0.0144kg/s, $Q_{fee,sch}$, which is feed rate of scheelite. And Mass Flow Rate of Outlet, $Q_{con,sch}$ was 0.0144kg/s, which is discharge rate of scheelite. The concentrate rate was sum of $Q_{con,sch}$, and $Q_{con,pyr}$, 0.0432kg/s. The grade WO_3 of scheelite concentrate which is Scheelite mass ratio in concentrate was 26.84% WO_3 using formula $g_{sch} = 80.53 \times \frac{Q_{con,sch}}{Q_{con}}$. Therefore, grade of scheelite was only increased from 0.8053% WO_3 to 26.84% WO_3.

In the second simulation in which length of stroke was set 8mm and strokes per minute was 280, all of scheelite flew to concentrate and quartz particles came to tailing launder.

In the second simulation of flotation combined with the table, all scheelite flew into the concentrate launder, while pyrite and quartz were discharged into the tailing launder at length of stroke of 8 mm and strokes per minute of 280 rpm.

Pyrite particles flew over the tailing end because the buoyant force was acted on these particles. In the second simulation, similarly calculating, feeding rate, $Q_{fee,sch}$ was 0.0144Kg/s. $Q_{con,sch}$ was 0.0144Kg/s. Some pyrite was mixed into concentrate, this amount, $Q_{con,pyr}$ was 0.008 Kg/s. So Q_{con} was sum of $Q_{con,sch}$ and $Q_{con,pyr}$ 0.0152Kg/s. The grade of concentrate was 76.29% WO_3.

In the second simulation, almost of concentrate was scheelite, so the grade increased from 0.8053% WO_3 to 76.29% WO_3.

The results of CFD simulation indicate that the combination of gravity and flotation in the table improves the separation.

Next, we report the results of scheelite separation experiments in the table.

The conventional method without collector addition resulted in scheelite concentrate grade of 23.5%, concentrate recovery of 80-80.1%, and separation efficiency of 77.89%.

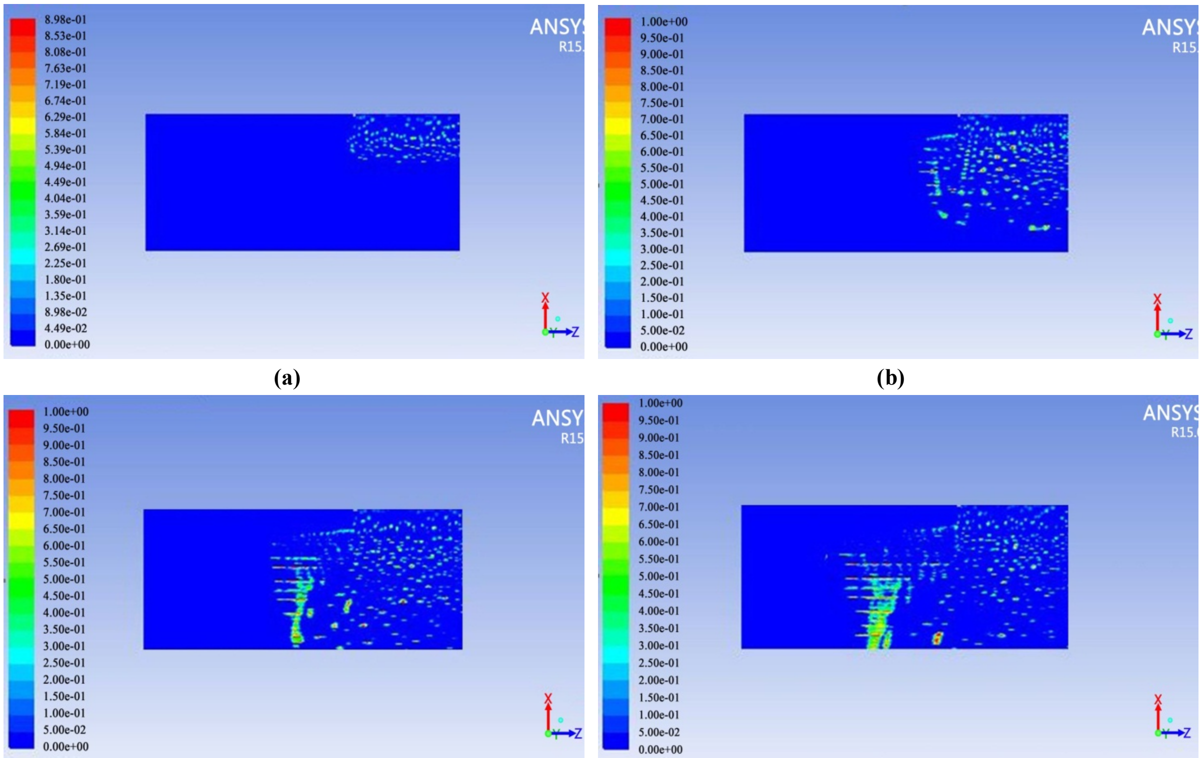
The experiments with the addition of collector showed that the concentrate grade was 65.5%, scheelite recovery 80.1-81.2%, and separation efficiency 79.76-80.88%.

Figure 8 shows the results of the table experiments in two ways.

The concentrate grade obtained in the first experiment was 23.5%, and the concentrate grade obtained in the second experiment was 65.5%, which was higher in the second experiment (Figure 8 a)).

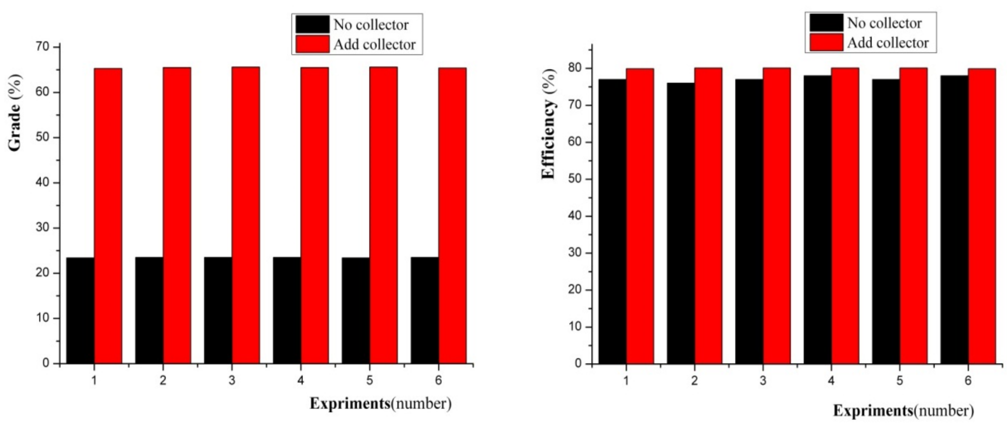
The separation efficiency was 77.89% in the first experiment, while the separation efficiency was 80.88% in the second experiment, which was higher in the second one (Figure 8 b)).

The results also show that the combination of flotation on the table not only significantly improved the concentrate grade of scheelite but also improved the separation efficiency of scheelite than the conventional method.



(a) (b) (c) (d)

Figure7. Result of simulation of floated pyrite. a) Time 1s; b) time 3s; c) time 4.5s; d) time 5s



(a) (b)

Figure8. Results of table experiments. a) Grade of scheelite; b) Separation efficiency (Black bar- traditional table with no collector, red bar- table with addition collector)

3. Discussion

The CFD simulation and experimental results showed that the addition of collector during the table separation resulted in an increase in the separation index.

In the CFD simulation, the theoretical WO_3 of the feed was 0.805% when the content of scheelite in the ore was 1%.

The first simulation results showed that the concentrate grade of scheelite increased from 0.805% to 26.84% with the mix of pyrite to the scheelite concentrate, while the recovery of scheelite concentrate was 99.98% and the separation efficiency was 0.98.

In the second simulation with collector addition, pyrite particles flowed into the tailings like quartz. Finally, in the second simulation, the concentrate grade was 76.29%, the recovery was 99.99%, and the separation efficiency was 0.9996, because the concentrate contained only scheelite.

The simulation results showed that the mix of pyrite to the concentrate resulted in a low concentrate grade and separation efficiency, whereas the absence of pyrite resulted in an increase in the scheelite concentrate grade and separation efficiency.

In the experiment, the ore grade was 0.77% for WO_3, as it was tested by artificially mixing scheelite, pyrite and quartz minerals with a purity of more than 95%.

The concentrate grade obtained in the conventional bed experiment was 23.5% and the separation efficiency was 77.89%. The concentrate grade obtained in the second experiment with collector was 65.5% and the separation efficiency was 80.88%.

Comparing the experimental results, it was also observed that the addition of pyrite to table concentrate showed higher scheelite concentrate grade and separation efficiency compared to pyrite.

There is also a difference in the concentrate grade and separation efficiency values between the results obtained in the simulation and experiment.

This discrepancy is due to the different size of the table slab in the simulation and experiment, the theoretical single mineral of scheelite in the simulation calculations, and the actual scheelite sample in the experiment.

Too high recovery in simulation and uncorrected recovery obtained in experiments might be also the reasons for disagreement. Although the positions of splitter were the same, gangue mineral might be mixed into concentration, this wasn't reflected in simulation.

Furthermore, in the simulation calculations, the pyrite particle size was calculated as the maximum particle size in the table, and in the experiments, the particle size was set to be in the range of 1 + 0.04 mm.

In the experiments, gangue was introduced into the concentrate zone to mix the concentrate with gangue, and in the simulations, the values of concentrate grade and separation efficiency were different because the concentrate and tailings were separated separately within the simulation time.

Also, the experimental values were considered more accurate because the simulation results did not reflect the amount of collector added, which is an important factor, and only the change of the contact angle was considered.

It is believed that the simulation calculation on an industrial table is difficult to obtain accurate values in the calculation because of the huge computational time required, and the precision experiments should be continued in the future and the influence of the factors should be considered more accurately.

From the simulation and experimental results, it was concluded that the combination of flotation in the table caused pyrite to float to the tailings and to raise the concentrate grade of scheelite, which was followed by gravity separation, and that the separation of scheelite and pyrite was not necessary.

In certain cases, the rare metal ore contained a small amount of pyrite, which would necessarily be the flotation process to separate pyrite after gravity separation.

This method can exclude the flotation of pyrite separation and it was considered that gravity separation and flotation for the removal of pyrite could be replaced by simple shaking table alone.

The method has great potential for application in gravity-flotation of rare metal minerals such as tin, tungsten and tantalum, which contain little pyrite in the ore.

4. Conclusions

The method was proposed, in which ore containing heavy gangue minerals conditioned with collector were fed to shaking table so that heavy valuable minerals were concentrated while heavy gangue minerals were floated on water surface by the action of flotation reagent and removed directly on the deck.

In the shaking table, a method was proposed in which heavy valuable minerals, which were concentrated by conventional methods, were removed directly on the plate by floating the heavy minerals to be removed from the concentrate as light minerals on the water surface by collectors.

The separation process in table with scheelite ore containing 1% and 2% scheelite and pyrite, respectively, was simulated by CFD and verified by experiments.

Separation of scheelite and floated pyrite on table were simulated with CFD and compared with experiments.

The results of the simulation and experimental comparison of separation of scheelite and pyrite floated by collector on the table are as follows:

a. In simulation the time when scheelite particles reached concentrate launder was 6 seconds while the time when pyrite floated by flotation collector reached tailing launder was 5 seconds and it was confirmed that pyrite particles were washed to tailings on shaking table.

b. In experiments, the grade of concentrate produced with table combined with flotation and the efficiency of separation are respectively 65.0% WO_3, 80.88% whilst the grade of concentrate produced with ordinary table and the efficiency of separation are respectively 23.5% WO_3, 77.89%.

The combination of gravity and flotation on the shaking table can in some cases simplify the table-flotation process by only the table separation, while increasing the table separation index.

The method can be applied to table separation of rare metal minerals such as tin, tungsten and tantalum, which contain little pyrite in the ore.

Data Availability

The data used to support the findings of this study is available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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تحلیل حذف پیریت از سنگ معدن شیلیت با استفاده از ترکیب فلوتاسیون در میز لرزان

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کلمات کلیدی

میز لرزان
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چکیده

میز لرزان و فلوتاسیون اغلب در فرآوری شیلیت ($CaWO_4$) استفاده می‌شوند و معمولاً به ترتیب اعمال می‌شوند. در این مقاله، تجزیه و تحلیل حرکت کانی در میز لرزان بررسی شده است که در آن خمیر با زانتات به عنوان جمع‌کننده شرطی‌سازی شده و تغذیه می‌شود، شیلیت سنگین تغلیظ می‌شود، در حالی که پیریت سنگین مستقیماً روی عرشه توسط عمل جمع‌کننده حذف می‌شود. کانی مخلوط مصنوعی با ۱٪ شیلیت و ۲٪ پیریت در شبیه‌سازی‌ها و آزمایش‌های CFD استفاده شد. از طریق شبیه‌سازی‌های CFD، مشخص شد که ذرات پیریت، که توسط جمع‌کننده آبگریز بودند، به سطح مشترک آب-هوا متصل شده و در معرض شناوری رو به بالا قرار می‌گیرند که باعث افزایش اختلاف چگالی بین ذرات شیلیت و پیریت شده و جداسازی هر دو کانی را در میز لرزان امکان‌پذیر می‌کند. نتایج آزمایش نشان داد که عیار کنسانتره در غلظت مرسوم میز، ۲۳.۵٪ WO_3، و راندمان جداسازی ۷۷.۸۹٪ بود، در حالی که عیار کنسانتره شیلیت در غلظت میز با حضور زانتات، ۶۵.۰٪ WO_3 و راندمان جداسازی ۸۰.۸۸٪ بود. ترکیب فلوتاسیون در میز با افزودن کلکتور نه تنها نیاز به فلوتاسیون برای حذف پیریت پس از میز را از بین برد، بلکه منجر به کاهش میزان هدررفت شیلیت نیز شد.

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