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Mineralogy and surface chemistry coupled with hydrodynamics in copper sulphide flotation

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Abstract: Changes in mineral surfaces and gas dispersion can improve a flotation stage without increasing overall copper recovery. This critical review examines these interactions in copper-bearing carbonaceous shales, saline process waters and concentrator tailings. We compare published studies by feed material, operating conditions, measurements and position in the circuit. Copper-shale studies distinguish electrokinetic and wetting responses from the effects of frothers on bubble coalescence. International copper-ore studies examine carbonaceous coatings, clay mineralogy and the influence of water composition on slurry structure and separation. Together, these findings show which links between surface chemistry and hydrodynamics have been measured and which still need to be tested in ore slurries. A worked balance illustrates how upstream copper rejection can offset improved downstream flotation: the break-even loss of approximately 1.12% assumes fixed downstream recovery. We also distinguish the time quantities used in kinetic comparisons and propose a conditional procedure for selecting and validating CFD models. Current and deposited tailings are considered separately because their surface and processing histories differ. The review reports no new experimental recoveries or validated plant simulations.

Keywords: copper sulphide flotation, carbonaceous shale, surface chemistry, process water, slurry rheology, hydrodynamics, computational fluid dynamics

1. Introduction

A change upstream in a copper concentrator affects the material entering the rest of the circuit. Recirculated water and middlings carry part of that processing history back to earlier stages. Recovery in a single cell must therefore be assessed against the copper reaching an acceptable final product from the original feed, together with the associated energy, water and reagent demand. This becomes especially important when preconcentration, selective grinding, carbon removal and intensified flotation are combined.

The copper sulphide ores considered here present several related separation problems. In sediment-hosted ores, rejecting naturally floatable carbonaceous shale may also reject sulphides or composite particles containing copper. Polish studies of preflotation and concentrate segregation address this problem at different circuit positions (Foszcz and Drzymala, 2011; Konieczny et al., 2013). At Mount Isa, graphitic coatings and geological variability have been related to pyrite floatability and chalcopyrite losses (Grano et al., 1990; Yenial-Arslan et al., 2023). The mechanisms also occur in other flotation systems; the purpose here is to examine their combined effect in these copper duties. Transferring a treatment from final concentrate to untreated ore requires comparable mineral exposure, liberation, reagent history and water conditions, followed by testing at the intended circuit position.

Gerson and Napier-Munn (2013) described the need to study mineralogy, solution chemistry and surface properties alongside reliable flotation measurements. Equipment comparisons also need to separate collection in the pulp from transport through the froth (Mesa and Brito-Parada, 2019). Fluidised beds and reactor-separator cells make this distinction particularly relevant because their

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contacting and separation zones differ from those of conventional cells. Nominal residence times, vessel volumes and fitted rate constants must be interpreted with those differences in mind.

This review brings together measurements of copper-carrier associations, mineral surfaces, slurry rheology and gas dispersion to examine how they affect separation at different circuit positions. Table 1 compares the selected findings and the conditions under which they apply. Standard mass-balance relations provide a worked example of the effect of changing the recovery boundary. The scope includes copper sulphide ores and their current and deposited tailings. Studies of model minerals and other ores are identified where they help explain a mechanism; oxide-copper reagent regimes are outside the scope. The experiments and model-selection procedures proposed here remain to be tested. Fig, 1 shows the process boundary and feedback paths used in the discussion.

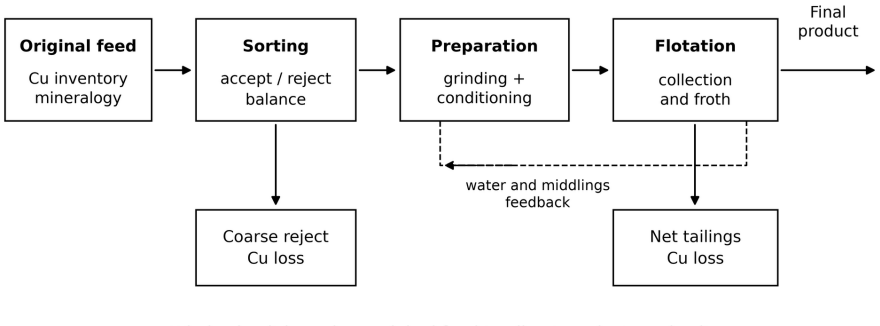


Fig. 1. Conceptual process boundary used in the review. Solid arrows denote material routes and the dashed path indicates recirculation or water feedback. All net copper exits remain in the overall balance. Original synthesis; not a plant layout or a simulated flowsheet

2. Scope and evidence assessment

2.1. Literature identification and selection

The study is a targeted critical review, not a systematic review or meta-analysis. A Scopus search was conducted on 16 September 2026 using the query TITLE-ABS-KEY(copper AND flotation AND (rheology OR "water quality" OR "coarse particle" OR "computational fluid dynamics" OR "organic carbon" OR sorting)) AND PUBYEAR > 2010 AND PUBYEAR < 2027. It returned 282 records. This number describes the discovery search only; it is not the number of studies fully screened or quantitatively compared. Selected DOI searches, reference tracing and publisher or institutional repository access were then used to retrieve relevant full texts, with retrieval completed on 17 September 2026.

The initial selection included twenty principal research or review papers and three contextual publications cited in the MEC2026 abstract. During revision, searches of publisher sites, DOI records and institutional repositories, together with reference tracing, yielded eleven further publications on copper-shale surfaces, carbonaceous copper ores, slurry rheology and surface modification. This additional retrieval was completed on 2 November 2026 without rerunning the Scopus search. Grano et al. (1990) was included as a foundational surface-analysis study outside the original search period. The bibliography contains thirty-four research or review publications and three published patent applications. The bauxite study is used as a methodological comparison. The supplementary register records the role of each source and the material available for assessment. Patent documents are considered as technical disclosures, not experimental validation.

Numerical comparisons were retained where the full-text tables or methods were available. Where access was limited to a publisher abstract or article preview, we used only the stated material, measurements and qualitative findings. We did not infer missing operating details or numerical optima. The selection is therefore suitable for comparing the cases discussed, but does not cover all copper flotation research.

For each study, we describe the feed, treatment, measured response and circuit position before comparing its findings with other work. Mechanistic studies are assessed against the questions they were designed to answer. Circuit performance is considered where the reported streams allow it. Reported observations, our interpretations and proposed tests are kept separate; no numerical quality score or pooled effect estimate is assigned.

2.2. Interpretation and reproducibility

Reported observations, calculations from published values, mechanistic interpretations and proposed validation requirements are distinguished throughout. Figs. 1, 4 and 5 are our conceptual schematics. Fig, 2 redraws published size-balance data, and Fig. 3 shows an analytical sensitivity calculation. Neither the schematics nor the calculated curve contains new experimental measurements. The supplementary material provides the data used in Figs. 2 and 3 and the calculation script.

Table 1 compares the measurements used to explain copper flotation. Surface charge, contact angle, coalescence, rheology and recovery each describe a different part of the process. The comparison shows which were measured together and where a proposed connection still needs a test on the same material under matched conditions.

Table 1. Comparative evidence linking copper-bearing materials to surface and process responses

Study	Material and measurements	Reported observation	Interpretation for the copper duty
Konieczny et al. (2013)	Polish ore preflotation; organic carbon and Cu partitioning	Carbon-rich froth also carried Cu; the two industrial cases had different operating conditions	Assess carbon rejection together with the destination of Cu in the prefloated product
Grano et al. (1990); Yenial-Arslan et al. (2023)	Mount Isa ore; surface analysis or geological-domain flotation	Graphitic coatings and rock properties were linked to pyrite floatability and chalcopyrite losses	Use the exposed surface and geological domain to explain selective losses
Peng et al. (2014)	Polish copper-bearing shale; zeta potential versus pH	Selected frothers changed the electrokinetic response	Pair the charge response with wettability and separation under the same water conditions
Szyszka and Szczepanski (2015)	Polished Rudna shale; sessile-drop and captive-bubble contact angles	Acetal and pyridine produced limited changes in the tested surface wettability	Distinguish frother action from an increase in particle hydrophobicity
Szyszka (2019)	Copper-bearing shale flotation; nominal and CCC-normalised frother concentration	The dose comparison depended on how concentration and coalescence suppression were expressed	Measure bubble dispersion when comparing frother systems
Zhang and Peng (2015); Zhang et al. (2015)	Copper-gold ore with added clays; rheology, flotation and water comparison	Bentonite strongly affected viscosity; seawater reduced its adverse effect in the tested system	Treat gangue identity and water composition as interacting variables
Paluchniak and Bakalarz (2025)	Polkowice ore in modified plant water; rougher and cleaning stages	The direction of the salinity response differed between stages	Select water conditions against final product quality and recovery
Cheng et al. (2025)	Fine chalcopyrite; grinding or nanoparticle collectors and surface characterisation	Surface roughness and wettability changed with treatment	Test surface modification together with collection and entrainment in an ore slurry
Quiero-Gelmi et al. (2024)	Copper concentrate thickening; yield stress, settling and compression	Rheological resistance increased at high solids concentration	Use as evidence for concentrate handling; measure flotation pulp separately
Suazo et al. (2026)	Copper rougher tailings in a fluidised bed; gas dispersion and tracer measurements	Hydrodynamic measurements accompanied metallurgical responses	Compare suspension and residence over the tested operating envelope

Study	Material and measurements	Reported observation	Interpretation for the copper duty
Witecki et al. (2026)	KGHM preconcentration route; reported stage and process balances	Higher flotation-stage recovery accompanied approximately unchanged process recovery	Retain the original-feed denominator when assessing upstream rejection

The studies are compared within their reported duties. The final column gives our interpretation for copper flotation; it does not imply that every source measured the full coupling between surface chemistry and hydrodynamics. The supplementary register lists all thirty-four academic sources.

3. Mineralogy and the boundary of recovery

3.1. Particle size and copper distribution

Particle size, mineral liberation and copper distribution answer different questions. A size distribution describes how much material is present in each class. A grade describes copper concentration within that class. Copper distribution describes the proportion of all copper carried by the class. Using dry mass fractions and consistent grade units, the copper distribution in size class i is

$$D_i = \frac{w_i c_i}{\Sigma_j w_j c_j} \quad (1)$$

where w_i is the dry mass fraction and c_i is the copper grade of class i. The denominator is the size reconstructed feed grade. Multiplying D_i by 100 expresses the distribution as a percentage. Recovery from a size class requires the additional measurement of where its copper reports after treatment; it cannot be inferred from D_i alone. The reconstructed feed assay should also be checked against an independently measured head sample, with differences assessed against sampling and analytical uncertainty.

Fig. 2 illustrates the distinction using the initial tailings data of Mambetaliyeva et al. (2026). The fraction below 45 µm contains 51.66% of the solids and 50.68% of the copper, at a grade of 0.169%. Reconstructing the head grade from the five rounded class assays gives 0.1722649% Cu, compatible with the source's reported feed grade of 0.17% after rounding. Its large share of the copper is therefore mainly a consequence of its large mass share. It does not show that this fraction is strongly enriched relative to the reported feed grade of approximately 0.17%. Nor does it establish that the copper is liberated or readily floatable. The five published size-class values and the calculation are supplied in the supplementary archive. These are legacy tailings studied in Kazakhstan; the distribution is an explanatory example and is not a measurement of a KGHM tailings stream.

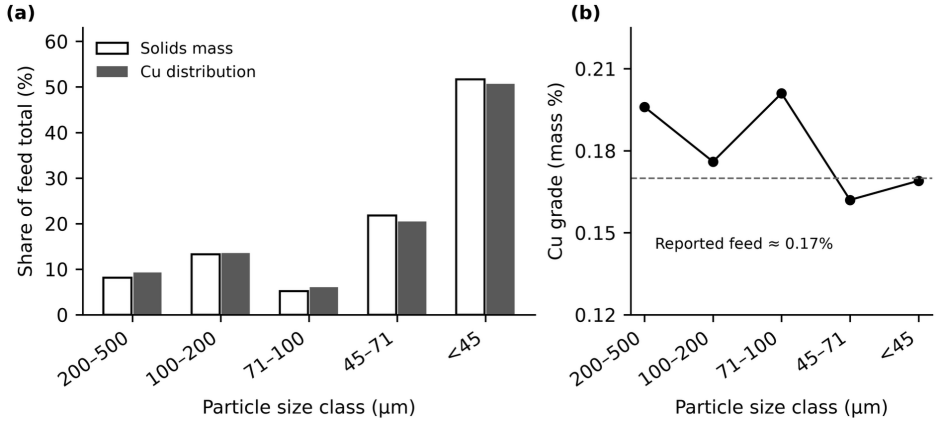


Fig. 2. Solids mass share and copper distribution (a), and copper grade by size class (b), redrawn from Table 4 of Mambetaliyeva et al. (2026). The data concern legacy tailings from Kazakhstan, not KGHM current tailings. Values are reproduced as tabulated; no uncertainty estimates were supplied for these size balance entries.

Grinding decisions should start with the identity and associations of the copper-bearing minerals. Coarse liberated sulphides may be lost because of poor suspension, detachment or froth transport.

Locked particles may benefit from selective regrinding that exposes more sulphide surface. For fine particles with altered surfaces, grinding may renew the surface while also producing more slimes. Mineralogical and surface measurements are needed to distinguish these possibilities before choosing a treatment.

3.2. Preconcentration and copper losses

Sensor-based sorting removes coarse barren material before intensive comminution when accepted and rejected particles have a measurable contrast. Its effectiveness depends on the sensor response, particle presentation, size range and relation between the sensed property and mineral value (Robben and Wotruba, 2019). A higher copper grade in the accepted stream should therefore be reported together with the mass and copper rejected. The accepted feed can become richer even when recovery from the original ore falls.

For a single pass preconcentration step followed by flotation, define L as the fraction of original feed copper rejected upstream and Rf as flotation recovery relative to the accepted copper. If there are no other copper exits within the boundary, recovery to the final concentrate is

$$R_{\text{whole}} = (1 - L)R_{\text{f}} \quad (2)$$

All quantities in Eq. (2) are fractions. This accounting identity can also be used for a larger steady-state boundary if L includes all net upstream copper exits and Rf covers the entire downstream treatment of the accepted material. Applying it to a circulating stream requires closure of the recirculating balance first. The equation contains no flotation kinetics.

Witecki et al. (2026) make the distinction visible in a published KGHM case study. Their reported comparison gives flotation operational recovery increasing from 85.86% to 86.83%, while process recovery relative to the original feed changes from 85.86% to 85.81%. Table 2 preserves these reported values and the separate coarse waste copper distribution. The source also reports 1.12% of original feed copper in coarse sorting waste. Inserting that value into Eq. (2) gives (1 – 0.0112) × 0.8683 = 0.858575, or 85.8575%, about 0.048 percentage points above its reported 85.81% process recovery. The rounded summaries and complete stream definitions cannot be reconciled from these three numbers alone; Eq. (2) is therefore used only for analytical sensitivity, not as a reconstruction of the published plant balance. The source describes the small process recovery difference as lying within plant balance uncertainty.

Table 2. Published KGHM comparison with recovery denominators retained

Quantity	Reference case	Combined route	Basis
Original dry feed (Tg year^{-1})	8.000	8.000	Original plant feed
Dry feed to flotation (Tg year^{-1})	8.000	7.3512	Accepted material entering flotation
Flotation operational Cu recovery (%)	85.86	86.83	Cu entering the flotation stage
Process Cu recovery (%)	85.86	85.81	Cu in the original plant feed
Cu reporting to coarse waste (%)	–	1.12	Cu in the original plant feed
Final concentrate Cu grade (mass %)	28.84	29.06	Dry final concentrate

Source: Witecki et al. (2026), Table 5, Fig. 6 and discussion. Values are transcribed as reported; 1 Tg = 10^6 Mg. The stage recoveries and coarse waste distribution do not reproduce the published whole-process recovery when used in the two-stream identity; the difference is approximately 0.048 percentage points. The source reports further copper exits. No balance adjustment has been made. The analytical calculation in Fig. 3 uses only the two stage recoveries and varies upstream copper loss.

3.3. Break even copper loss

For baseline recovery R_0 and downstream recovery R_1 after adding preconcentration, the break-even fraction of upstream copper rejection follows directly from Eq. (2):

$$L_{crit} = 1 - \frac{R_0}{R_1} \quad (3)$$

At break-even, $(1 - L_{crit})R_1 = R_0$. Dividing by R_1 gives $1 - L_{crit} = R_0/R_1$, and rearrangement gives Eq. (3). With the published stage recoveries $R_0 = 0.8586$ and $R_1 = 0.8683$, $L_{crit} = 1 - 0.8586/0.8683 = 0.011171254$; hence $100 \times L_{crit} = 1.1171254\%$, or approximately 1.12% of original-feed Cu. The calculation assumes comparable final products, no unaccounted Cu exits and fixed downstream recovery. Fig, 3 varies L under that assumption. It illustrates a standard accounting constraint; changing accepted-feed mineralogy may also change R_1 in an actual plant.

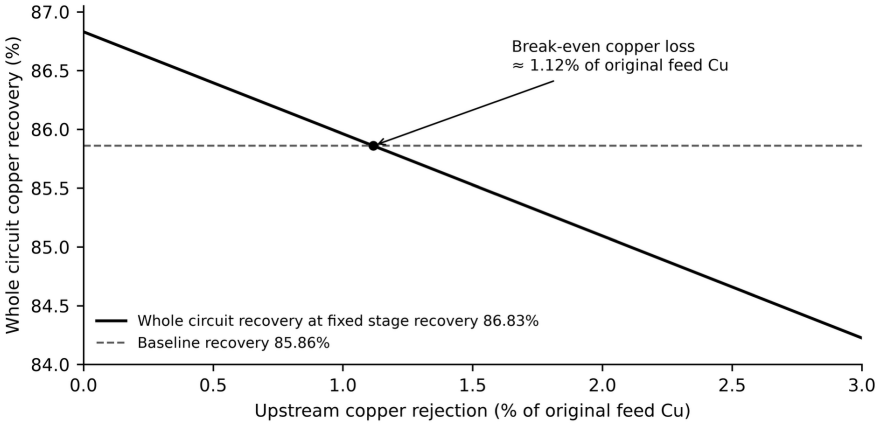


Fig. 3. Analytical sensitivity of whole circuit recovery to upstream copper rejection using Eq. (2). The stage recovery values 85.86% and 86.83% are taken from Witecki et al. (2026); the curve and break-even point are calculated here. Fixed downstream recovery is an explicit assumption. This is not a reconstruction of the reported plant balance

This small threshold explains why seemingly modest rejection losses deserve accurate measurement. At $R_1 = 0.8683$, each additional percentage point of original copper lost upstream reduces whole circuit recovery by 0.8683 percentage points when downstream recovery is held constant: $dR_{whole}/dL = -R_1$. Both percentage-point quantities refer to copper in the original feed. A recovery claim close to the break-even line should consequently be tested with paired balances and uncertainty on the difference. Uncertainty bars cannot be added to Fig. 3 because the required underlying measurements and covariance are not available.

Preconcentration may still be worthwhile when overall copper recovery is unchanged, for example if it reduces grinding demand or tailings production. Energy, water demand and product quality may also offset a recovery gain. These outcomes should be reported separately, using the same process boundary for copper recovery, concentrate quality, dry throughput, specific energy and net freshwater demand.

4. Selectivity in carbonaceous and saline systems

4.1. Carbon rejection and copper selectivity

Preflotation removes a carbon-rich product before sulphide flotation. Segregating flotation instead partitions an existing concentrate. Foszcz and Drzymala (2011) studied dextrin-assisted segregation of final Polish industrial concentrates and measured the partitioning of Cu, organic carbon and associated metals at that position in the circuit. Applying the treatment to run-of-mine ore requires checking the mineral associations, exposed surfaces and existing reagent coverage that determine which particles the depressant can affect.

In the industrial preflotation cases reported by Konieczny et al. (2013), a frother-only treatment sent 28.22% of organic carbon and 8.11% of Cu to the carbon-rich product. The collector-and-frother

case gave 21.14% and 20.37%, respectively. These values illustrate the competing carbon and copper partitions in practice. Because operating conditions differed between the cases, they cannot isolate the collector effect. Whether the Cu in the carbon-rich product becomes a net loss depends on its subsequent treatment.

Surface analysis helps explain why carbon rejection can be difficult. Grano et al. (1990) combined flotation and X-ray photoelectron spectroscopy for Mount Isa copper and lead-zinc ores under different electrochemical conditions. Graphitic coatings contributed to the natural floatability of iron sulphides, while hydroxide and carbonate overlayers altered the exposed sulphide surfaces. Carbon in a froth product can therefore originate from both separate gangue particles and coatings on other minerals. The two forms need to be distinguished when interpreting bulk carbon assays.

Yenial-Arslan et al. (2023) examined five geological domains from Mount Isa and related rock properties to collectorless pyrite recovery and chalcopyrite losses. Their results add an explanation based on feed variability to the Polish studies of stream partitioning. Geological-domain information should therefore be retained in comparative preflotation tests. Any predictive relation would need testing on additional domains before use in mine planning.

Chimonyo et al. (2020a) reviewed starch modification for separating copper sulphides from carbonaceous material. In a controlled chalcopyrite-graphite study, the same authors compared oxidised and native wheat starch and found differential depression (Chimonyo et al., 2020b). This gives a reagent mechanism to investigate in carbon-bearing ore. Such tests should retain the starch preparation, surface state and reagent sequence while measuring both Cu and carbon partitioning.

Drzymala et al. (2016) found that selected frothers made copper-bearing shale and bornite floatable under their test conditions, while chalcocite recovery remained negligible. Copper in a carbon-rich froth may thus include floatable sulphides and composite particles as well as entrained material. Product mineralogy, supported by water-recovery measurements, is needed to identify their relative contributions.

Zheng et al. (2025) used surface chemistry and molecular dynamics to investigate chalcopyrite-pyrrhotite separation. Molecular calculations can help formulate an adsorption hypothesis. Testing that hypothesis in a carbonaceous, saline plant slurry requires corresponding surface and flotation measurements under the relevant water and reagent conditions.

Peng et al. (2014) measured the zeta potential of copper-bearing shale over a range of pH in water and selected frother solutions, finding changes in its isoelectric response. Szyszka and Szczepanski (2015) measured advancing and receding contact angles on polished Rudna shale by sessile-drop and captive-bubble methods at 20 °C. Acetal and pyridine had limited effects on the measured wettability. These are distinct observations: a change in electrokinetic behaviour needs a separate wetting measurement before it can be related to particle hydrophobicity.

Szyszka (2019) compared three glycol-ether frothers in the flotation of copper-bearing carbonaceous shale, expressing their doses both nominally and relative to the critical coalescence concentration (CCC). This links the dose comparison to suppression of bubble coalescence. For copper-carbon separation, measuring bubble size and gas holdup alongside Cu and carbon partitioning would help distinguish changes in the contacting environment from changes in the mineral surfaces being floated.

Organic carbon measurements should report how carbonate carbon was removed or accounted for, together with sample preparation, detection limits and the analytical method. Reagent tests should specify dose, conditioning time, addition order, pH, redox potential and relevant dissolved species. Surface spectroscopy and electrokinetic measurements are most useful when they test a defined explanation for the separation response, such as sulphide depression or altered slime attachment.

4.2. Process water and flotation stage

Process water affects mineral interfaces and gas dispersion through its ionic composition, residual reagents and colloidal material. Similar conductivities can therefore conceal chemically different waters. Characterisation should include major ions, pH, temperature and relevant organic residues alongside conductivity or dry residue. The analysis needs to describe the water used in the test, including any treatment, rather than rely solely on historical plant records.

Paluchniak and Bakalarz (2025) tested Polkowice ore in plant water with a starting dry residue of 54.5 kg m^{-3} and chloride concentration of 23.46 kg m^{-3}. They diluted or concentrated the water to 60–140% of its starting level and tested chloride additions of 5 and 10 kg m^{-3} separately. Under these conditions, higher salinity improved the rougher response but worsened the response during cleaning. Water quality selected for roughing must therefore also be assessed against the final concentrate. Concentrating the whole water and adding chloride should be treated as separate interventions because they change its composition differently.

Zhang et al. (2015) compared tap water and seawater in copper-gold flotation with added bentonite, using rheology, settling and cryogenic scanning electron microscopy to interpret the results. Seawater reduced bentonite swelling and changed the aggregate network, alleviating the adverse flotation response observed in tap water. The study shows how water chemistry can affect separation through the structure of the suspension, alongside direct effects on mineral surfaces.

The Polkowice study concerns the response of different flotation stages to saline plant water. The bentonite study concerns changes in slurry structure in a controlled water comparison. Together, they show why interpreting a salinity response requires information on both ionic composition and gangue mineralogy.

A comparison of water sources should vary reagent conditions separately, using representative splits of the same ore. Fresh reference water, plant water and modified plant water can be compared using final concentrate Cu and organic carbon, copper recovery, water recovery and product mass. If an effect depends on frother dose or froth depth, that interaction should be retained in the next round of tests.

4.3. Slurry rheology

Fines, gangue minerals and water chemistry can change the flow of a flotation slurry and the transport of particles. Apparent viscosity should be reported with shear rate, measuring geometry, temperature, solids concentration and conditioning history. Structured suspensions also need a flow curve and a defined yield-stress protocol. Water comparisons should keep solids loading and particle size constant, since dilution affects both rheology and hydraulic residence.

Zhang and Peng (2015) studied bentonite and kaolinites of different crystallinity in copper-gold flotation. Bentonite increased pulp viscosity more strongly than kaolinite, and higher viscosity corresponded to lower copper recovery. Their results show that gangue identity and structure help explain rheological differences that bulk solids concentration alone cannot describe.

Quiero-Gelmi et al. (2024) measured settling, compression and yield stress in a predominantly chalcocite copper concentrate from northern Chile. Rheological resistance increased sharply at high solids volume fraction. The results are relevant to dewatering and concentrate handling. Their application to flotation requires measurements on the actual aerated feed and water mixture, which operates under a different concentration regime.

Gao et al. (2018) examined pulp density, aggregation and separation in a nickel-copper sulphide system containing fine serpentine. This provides a useful mechanistic comparison, although its feed and gangue differ from those of the copper-ore studies above. Comparative tests should distinguish changes in suspension structure from the accompanying changes in water throughput and reagent action.

Residual polymers in recycled water can affect mineral selectivity as well as slurry rheology. Jimenez et al. (2024) tested an anionic polyacrylamide with chalcopyrite, enargite and bornite and found mineral-dependent flotation responses under the chemical conditions examined. A study of recycled polymers should therefore assess their effects on mineral interfaces alongside flocculation and gas dispersion. Fig, 4 shows the pathways and measurements needed to distinguish them.

4.4. Surface modification

Cheng et al. (2025) compared grinding and nanoparticle-collector treatment of fine chalcopyrite using roughness, wettability and flotation measurements, supported by molecular simulations. Changes in roughness and collector interaction were associated with increased hydrophobicity and flotation

response. Extending these results to an ore slurry would require product mineralogy and measurements of collection or entrainment under the intended hydrodynamic conditions.

Cheng et al. (2023) combined pyrite-surface analyses with closed-circuit tests of nanoparticle collectors for reverse-flotation desulphurisation of high-sulphur bauxite. The study is relevant here as an example of relating surface characterisation to a final separation outcome. Its valuable product, target sulphide and gangue assemblage differ from those of copper flotation, so it provides no copper-recovery estimate.

The studies establish several individual links, but the full coupling remains to be tested. A suitable experiment would measure the surface response, bubble or suspension behaviour and Cu-carbon selectivity on the same split feed. Varying a hydrodynamic parameter separately from water or reagent conditions would reveal any interaction between them. The final product balance should then be tested on independent material or operating conditions.

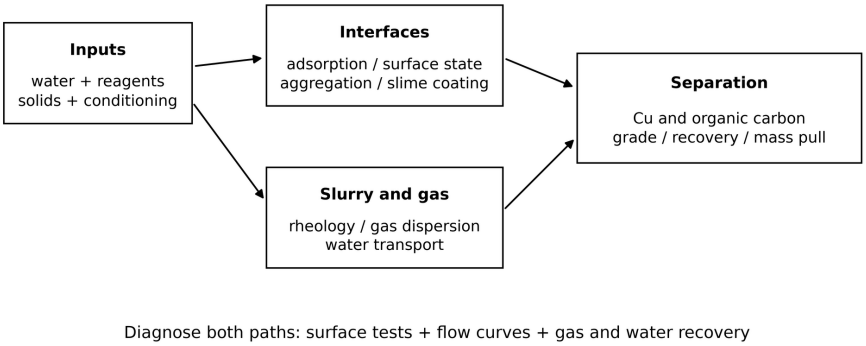


Fig. 4. Conceptual pathways linking water, reagents and solids to flotation response. The same treatment can affect mineral interfaces and hydrodynamics. Original synthesis informed by Gao et al. (2018), Zhang and Peng (2015), Zhang et al. (2015), Jimenez et al. (2024) and Paluchniak and Bakalarz (2025); the arrows identify hypotheses for experimental distinction

5. Equipment performance and scale transfer

5.1. Gas dispersion measurements

Volumetric air rate becomes informative for comparison only when related to the active cross-sectional area and the resulting bubble population. Superficial gas velocity, Jg, and Sauter mean bubble diameter, d_{32}, can be combined to give an idealised bubble surface area flux:

$$S_b = \frac{6J_g}{d_{32}} \tag{4}$$

Sb has units of s^{-1} when Jg and d_{32} use consistent length units. It describes the geometric supply of bubble surface; predicting copper recovery also requires a description of particle collection and subsequent separation. Coalescence and spatial variations in flow can make a single measurement unrepresentative. Reported Sb values should therefore include the sampling locations, aerated cross-section and bubble-sizing method.

Femenias et al. (2022) investigated flotation and gas dispersion with a dual flotation-conductivity cell. Within their system, gas holdup reflected the combined influence of air rate and frother concentration. For saline ore slurries, the conductivity measurement would require calibration for the liquid and solids present. A comparison of gas dispersion should also include froth transport, which gas holdup alone does not describe.

Suazo et al. (2026) measured gas dispersion, residence-time distributions and metallurgical responses in a HydroFloat cell treating industrial copper rougher tailings. Mean bubble diameter remained around 0.5 mm within the conditions studied, showing that this coarse-particle duty did not require large individual bubbles. The value applies to that hydrodynamic regime. Feed size, solids loading, fluidisation and aggregate behaviour must be retained when considering another application.

5.2. Contacting and separation zones

An intense contacting zone followed by a gentler separation zone allows collision and detachment to be controlled in different parts of the apparatus. The contacting zone may occupy only a small fraction of the total volume. Its contact time, and any rate constant based on that time, must therefore be distinguished from residence time in a complete mechanical cell. Equipment comparisons should describe the conditioning, contacting, separation and froth zones and all recycle paths.

Hassanzadeh et al. (2024) compared Imhoflot and mechanical flotation at mini-pilot scale and tested an industrial cell at several positions in a copper circuit. Their assessment distinguishes pre-roughing, cleaner-related duties and tailings treatment, and discusses the limits of volumetric comparison and concentrate upgrading. These details matter when selecting a machine for a particular feed. A promising result at one position provides a reason to test the intended duty under matched conditions.

At Collahuasi, intensified cells were installed on a circulating column-tailings stream after pilot testing, followed by surveys of the cleaning circuit (Vallejos et al., 2025a). They recovered fine material that otherwise circulated and produced a stream suitable for joining the final concentrate. The case shows how circulating load and product routing determine a cell's contribution to the circuit, beyond its recovery when considered in isolation.

5.3. Flotation kinetics and residence time

Vinnett et al. (2025) showed that the collection intervals used in batch flotation affect fitted kinetic parameters. Reported rate constants should therefore be considered with the time resolution, sampling procedure and mass balance of the test. A high coefficient of determination gives limited information about physical mechanism or prediction in an independent experiment. Successive cumulative fractions from one test also need to be distinguished from independent replicates.

For reactor-separator cells with recirculation, elapsed test time, contactor residence time and number of passes describe different exposures. Hassanzadeh and Hoang (2026) discuss the consequences for scale-up. Laboratory tests need to record flow paths and recycle so that these exposures can be related to those expected at the intended operating scale.

Vallejos et al. (2025b) represented collection, separation and froth transport separately in an intensified-cell model, including water recovery and gangue entrainment. The model was calibrated in the laboratory and then used for industrial scenarios; industrial validation was identified as future work. Those scenarios can guide pilot testing, but their predictions have yet to be demonstrated in plant operation.

Table 3 defines the time quantities used to compare conventional and reactor-separator cells, drawing on Vinnett et al. (2025) and Hassanzadeh and Hoang (2026). Nominal hydraulic time, measured phase residence and cumulative contact exposure use different bases. Recycle contributes to contactor throughput while remaining an internal stream in the whole-circuit Cu balance.

A fitted rate constant should be reported with its time basis, apparatus boundary and kinetic model. The definitions do not provide a universal conversion between different machines.

Table 3. Time and recycle quantities for flotation comparisons

Quantity	Unit	Definition	Required distinction
Single-pass contact time	s	Elapsed time in the defined contacting zone for one passage	Report contacting volume, phase and total contactor flow, including recycle
Cumulative contact exposure	s	Sum of time spent in the contacting zone over the observed passages	Use a passage history or an explicit model; equal residence per pass must be justified
Nominal hydraulic time	s or min	Active pulp volume divided by the defined pulp throughput	State whether the flow is fresh feed or contactor throughput and report gas-volume treatment

Quantity	Unit	Definition	Required distinction
Measured mean residence time	s or min	First moment of a normalised tracer response for the phase traced	Report tracer recovery, sampling duration, phase and sampling boundary
Number of passages	–	Observed or modelled count of contactor traversals	A flow-ratio estimate is not an individual particle passage history
Froth residence or transport time	s	Time between froth entry and product overflow for a defined tracer or path	State gas, liquid or particle basis; report froth depth and transport distance
Cumulative batch flotation time	s or min	Time from the defined flotation start to the end of each concentrate interval	Report conditioning separately, collection intervals and any volume replacement

6. Connecting CFD to measurable separation outcomes

6.1. Hydrodynamic and metallurgical validation

CFD resolves circulation, gas distribution and local flow conditions that a bulk residence time cannot describe. The phases and closure relations must be chosen for the question being tested. For example, high turbulence may increase bubble-particle collisions while also promoting detachment. A predicted velocity or dissipation field needs comparison with measurements and a separate model relating that field to the separation response. Water-air flow alone does not predict copper recovery.

Salem-Said et al. (2013) modelled a Dorr-Oliver cell using an Euler-Euler gas-liquid description and an SST turbulence closure. They examined unsteady rotor-stator interaction and prescribed bubble diameters against hydrodynamic measurements. The results show how the assumed bubble population affects flow and gas distribution. An application to copper ore must also examine the effects of measured slurry rheology and particle classes, followed by testing of the coupled separation model against independent product assays.

Fig, 5 outlines a sequence for developing a metallurgical prediction from CFD. Conservation, discretisation and solution stability are checked first. Calculated flow and gas dispersion are then compared with independent measurements before particle classes and a flotation model are added. Product grades and recoveries are finally tested on material withheld from calibration. This allows errors in the flow description to be identified before they can be absorbed into fitted separation parameters.

These are proposed validation requirements. Acceptance tolerances must be set for the intended application.

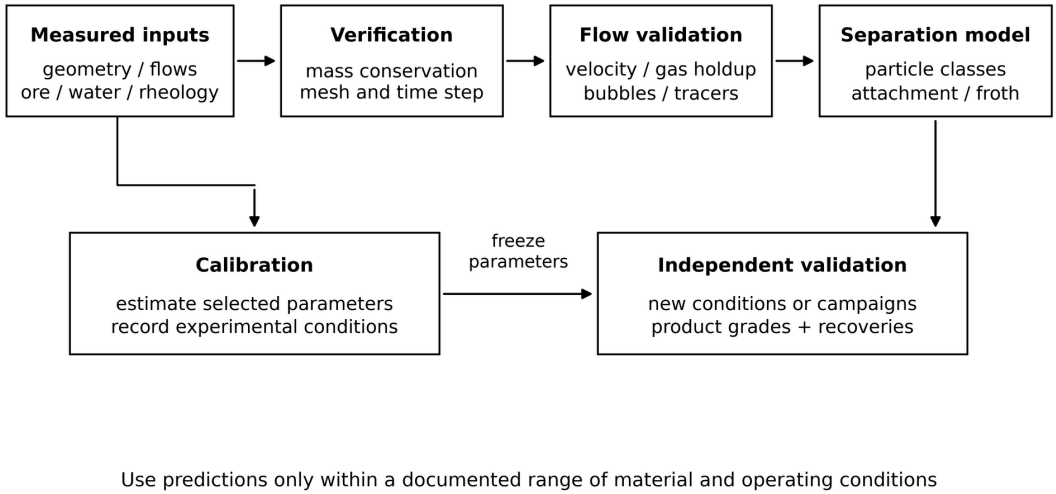


Fig. 5. Proposed sequence for connecting CFD to an independently tested separation model. Numerical verification, hydrodynamic validation and metallurgical prediction are separate steps. Original synthesis informed by Salem-Said et al. (2013), Mesa and Brito-Parada (2019) and Vallejos et al. (2025b)

6.2. CFD model selection

Model detail should follow the physical question. Liquid-only calculations can first examine impeller-driven circulation. Gas can then be added with a measured or predicted bubble-size distribution. Settling, segregation and non-Newtonian flow need to be represented when they affect the duty, or shown to be negligible within the stated operating range.

Table 5 sets out conditional choices for stirred-cell geometry, rotating zones, turbulence, phase coupling, inlets and walls. Where bubble size changes appreciably, a population balance or a justified representation based on measurements is needed. Extended froth transport may require a separate model after pulp flow has been resolved (Salem-Said et al., 2013; Mesa and Brito-Parada, 2019).

Calibration and validation should use separate experimental conditions or campaigns. Randomly dividing points from one time series may retain much of the same information in both sets. Before attributing a predicted gain to geometry, test sensitivity to bubble size, drag, viscosity and turbulence assumptions. Mesh and time-step checks should examine phase distributions, residence time and the outputs on which the conclusion depends. Acceptable errors must be small enough to resolve the treatment effect of interest.

Table 4. Measurements required to evaluate a coupled CFD and flotation model

Model component	Independent observable	Reporting requirements	Failure exposed
Circulation and power	Velocity profiles; torque or shaft power	Sampling position, rotation speed, aerated condition	Incorrect circulation or energy input
Gas dispersion	Gas holdup; bubble size distribution	Measurement method, spatial sampling, water and frother	Wrong gas inventory or assumed bubble population
Mixing and residence time	Tracer response and recovery	Injection, sampling, flow rates, phase traced	Bypass, dead zones or inappropriate mean residence time
Suspension and particle transport	Solids profiles; size dependent exits	Particle density, size classes, slurry flow curve	Settling or segregation hidden by a homogeneous model
Froth and entrainment	Water recovery; froth residence or transport	Froth depth, lip length, transport distance, wash water	Recovery fit masking drainage or entrainment error
Metallurgical prediction	Cu and carbon grades and recoveries	Independent feed batches, product mass, uncertainty	Calibration mistaken for predictive validation

Table 5. Proposed CFD model selection and reporting protocol

Decision	Conditional recommendation	Independent check or report
Phases and slurry properties	Begin with liquid circulation; add gas and size or density classes when required. Represent non-Newtonian behaviour with a measured flow curve.	Report phase fractions, particle classes, rheological law and operating temperature
Turbulence closure	Use a justified RANS baseline, for example SST k-omega or a k-epsilon variant. Test an alternative where swirl or anisotropy controls the result.	Compare velocity and power; test the sensitivity of gas distribution and relevant dissipation estimates

Decision	Conditional recommendation	Independent check or report
Rotating zone	Use multiple reference frames for a mean-flow screening question; use transient sliding or rotating meshes when rotor-stator interaction matters.	Report interfaces and averaging; test rotor-angle resolution, torque and periodic behaviour
Bubble population	Prescribe a measured distribution over a justified envelope, or couple a population balance for breakup and coalescence.	Report kernels and size classes; validate bubble size and gas holdup after changing water or frother
Walls and free surface	Specify no-slip walls, wall roughness and wall treatment compatible with the turbulence model; define gas escape and pulp overflow.	Report near-wall resolution or y-plus and sensitivity to the top-boundary treatment
Phase interaction	State drag and retained lift, dispersion or other interphase-force closures; justify neglected terms for the duty.	Test their effects on gas inventory, circulation and solids profiles
Mesh and time step	Refine rotor gaps, injection regions and strong gradients; assess spatial and temporal convergence separately.	Report changes in torque, phase distribution and residence time as well as conservation
Froth and separation coupling	Use a calibrated attachment-detachment and entrainment description; add a froth model where product transport is consequential.	Validate water recovery, Cu and carbon grades and recoveries on withheld conditions

Where a closure choice controls the conclusion, compare it with an alternative or constrain it with measured inputs. Tuning bubble size and attachment parameters against one recovery curve is calibration. Validation requires hydrodynamic and metallurgical observations withheld from that tuning. The choices in Table 5 are recommendations for testing, not a universally optimal solver setup.

Proposed procedure based on the hydrodynamic study of Salem-Said et al. (2013), the scale-up review of Mesa and Brito-Parada (2019) and the laboratory calibration of Vallejos et al. (2025b). Each choice requires validation for the ore, water and duty under study.

6.3. Patent disclosures and experimental questions

Patent documents describe ways of arranging contact, circulation and measurement in flotation equipment. Table 6 uses three published applications to identify apparatus choices and the experiments needed to assess them for copper flotation. The comparison concerns technical disclosure and does not assess legal validity, territorial protection or freedom to operate.

Table 6. Selected published patent concepts and corresponding test requirements

Published application	Technical concept	Test needed for a copper duty
Jameson (2006) WO2006081611A1	Bubble–particle contacting arrangement with a distinct contacting and separation function	Contact exposure, pressure demand, bubble dispersion, recovery and grade under matched feed conditions
Rinne (2022) US20220258178A1	Fresh feed and lower recirculated feed in a fluidised bed flotation arrangement	Bed stability, size dependent residence, circulating inventory and net copper balance
McNamara et al. (2022) WO2022034512A1	Process data, CFD related estimates and virtual sensing for operating adjustment	Independent gas holdup and bubble size checks, drift detection and product assay validation

Sources are the published applications, including their principal claims and descriptions. Their disclosure does not establish a transferable recovery gain or legal status.

Jameson (2006) describes bubble-particle contacting, Rinne (2022) describes separate fresh and recirculated slurry feeds to a fluidised bed, and McNamara et al. (2022) combine process data, simulation and virtual sensing. These are different approaches to controlling contact and circulation. For a copper duty, predicted operating conditions and control recommendations need to be tested as feed and water composition change, using independent product assays to assess the result.

7. Testing copper ores and current tailings

7.1. Ore and tailings sampling

Ore, final concentrate, current tailings and deposited tailings have different processing histories. Sampling should record collection point and time, storage, water source and previous reagent exposure. Retaining mineralogical and size information allows changes in flotation response to be related to feed variability. Composite samples improve representativeness, but blending can also obscure a feed component responsible for poor selectivity.

Bakalarz and Duchnowska (2024) examined copper recovery from stratiform-ore flotation tailings. Together with the KGHM balance reported by Witecki et al. (2026), this gives a Polish basis for investigating tailings recovery. The treatment choice still depends on whether the material is a current process stream or has been deposited and altered during storage.

Sampling current tailings before disposal allows losses to be related to the operating circuit. The copper may occur in fine liberated sulphides, coarse locked particles, or material lost during collection or froth transport. Deposited tailings introduce further variation through oxidation, weathering and handling. Processing tests and the economic assessment of Chilean tailings by Drobe et al. (2021) illustrate why both material properties and treatment costs matter. Their results inform the assessment of another deposit without establishing its economics.

Mambetaliyeva et al. (2026) related regrinding of legacy sulphide tailings to liberation and surface renewal. Both effects should be measured when interpreting the response to grinding. Fresh tailings may have a different surface history and may not need the same treatment. Comparative tests should therefore control storage and air exposure and retain untreated material as the reference for each regrinding or conditioning route.

7.2. Comparative tests and mass balances

The choice of treatment should follow the observed copper loss. Locked particles need liberation and mineral-association measurements; liberated sulphides with poor flotation response need surface and reagent tests. Coarse liberated particles require examination of suspension, residence and detachment. Where recovery improves in the pulp but not in final concentrate, froth transport and entrainment need to be measured. More than one mechanism may operate in the same feed. Paired tests should link the proposed explanation to the final copper balance.

Table 7 proposes comparative tests and criteria for pilot work. Each test begins with representative splits from the same material, uses the relevant water chemistry and closes the Cu and solids balances. Treatments should be compared at matched product quality or through complete grade-recovery curves. Recoveries measured at different concentrate grades are insufficient for that comparison.

The tests are proposed work. Effect sizes and uncertainty requirements should be set from baseline variability and the intended industrial decision before confirmatory testing.

Experimental replication means repeating the treatment on independent material, rather than reassaying one product or collecting successive concentrate cuts from one test. Randomisation and blocking by feed batch or campaign help account for mineralogical variation. The number of replicates should follow pilot variance and the smallest difference worth detecting. Where representative splits are available, a paired design can compare treatment and baseline within each material batch. The design and uncertainty should be reported with the recovery difference.

Mass closure should include all sampled net streams and, where possible, propagated sampling and assay uncertainty. Closure errors need investigation before balances are adjusted. For circulating systems, inventory and stream measurements should demonstrate steady state, with recycle kept separate from new feed. Carbon-rich side products and material intended for reuse remain in the

accounting until their final destinations are known. Calling a stream a useful product does not establish additional copper recovery.

Table 7. Prospective experimental comparisons and criteria for advancing to pilot evaluation

Test family	Matched comparison	Primary measurements	Reason to advance
Carbon control	Same ore split; baseline versus reagent sequence; defined water	Cu and organic carbon balances; product mineralogy; water recovery	Lower carbon at acceptable Cu loss and matched final product quality
Water and rheology	Water source × reagent condition, blocked by ore batch	Major ions; residual polymer; flow curves; gas dispersion; grade–recovery	Reproducible effect after separating chemistry and hydraulic changes
Equipment and CFD	Same feed duty and chemistry; measured flows and recycle	Residence distribution; bubble size; power; froth transport; Cu balance	Independent prediction and benefit under comparable circuit conditions
Current tailings	Untreated split versus selective regrinding, conditioning or new cell	Size and liberation; surface condition; product quality; specific energy	Additional usable copper product with a closed net balance

7.3. Criteria for pilot testing

Pilot testing should address a benefit large enough to matter under the intended operating conditions. The assessment needs the copper balance alongside product impurities, reagent demand, water use and specific energy. Dewatering or disposal benefits can be included when measured or clearly identified as estimates. Environmental claims need a corresponding system boundary and inventory; reducing one solids stream alone does not establish an overall environmental benefit.

The studies leave several uncertainties. Mechanistic tests simplify mineral mixtures and water histories, while industrial cases often change several conditions together. Hydrodynamic observations alone cannot identify the attachment chemistry, and recovery fits may compensate for an incorrect collection volume. Product definitions and sampling methods also differ between studies. These differences are the reason for the matched tests proposed here and limit the transfer of a reported reagent dose, cell size or recovery to another plant.

This review expands the MEC2026 abstract “Kierunki rozwoju technologii przeróbki rud miedzi” through a fuller comparison of the evidence, a worked recovery balance and proposed tests linking surface and hydrodynamic measurements. It reports no new KGHM trials or validated industrial simulations.

8. Conclusions

Overall recovery must be calculated from the original feed to a defined final product, including every net Cu exit. The preconcentration example shows how a small upstream loss can offset a downstream flotation gain when downstream recovery is held fixed. Product quality, energy and water demand must be assessed alongside that balance.

Copper-shale surfaces, clay structure and saline water affect flotation through different mechanisms. Testing them on matched material, with measurements of electrokinetic behaviour, wettability and bubble dispersion, helps distinguish those mechanisms. A model coupling surface chemistry and hydrodynamics then needs independent tests of both the flow and final separation.

Current and deposited tailings require separate assessments. Fresh losses can be traced to the operating feed and water history; stored material also reflects weathering, surface alteration and

spatial variation. Regrinding or conditioning should proceed when tests identify the limiting mechanism and demonstrate additional Cu in a usable product from that material.

References

BAKALARZ, A., DUCHNOWSKA, M., 2024. *Analysis of the Possibility of Copper Recovery from Flotation Stratiform Copper Ore Tailings*. Miner. Process. Extr. Metall. Rev. 45, 943–949. doi: 10.1080/08827508.2024.2316060

CHENG, G., PENG, Y., XIONG, L., LU, Y., LI, E., GAO, J., QIN, Y., WANG, X., LAU, E.V., 2025. *New insights into enhancing sustainable flotation performance of fine chalcopyrite via surface modification*. Particuology 105, 155–164. doi: 10.1016/j.partic.2025.08.001

CHENG, G., ZHANG, J., SU, H., ZHANG, Z., 2023. *Synthesis and characterization of a novel collector for the desulfurization of fine high-sulfur bauxite via reverse flotation*. Particuology 79, 64–77. doi: 10.1016/j.partic.2022.11.012

CHIMONYO, W., FLETCHER, B., PENG, Y., 2020a. *Starch chemical modification for selective flotation of copper sulphide minerals from carbonaceous material: A critical review*. Miner. Eng. 156, 106522. doi: 10.1016/j.mineng.2020.106522

CHIMONYO, W., FLETCHER, B., PENG, Y., 2020b. *The differential depression of an oxidized starch on the flotation of chalcopyrite and graphite.* Miner. Eng. 146, 106114. doi: 10.1016/j.mineng.2019.106114

DROBE, M., HAUBRICH, F., GAJARDO, M., MARBLER, H., 2021. *Processing Tests, Adjusted Cost Models and the Economies of Reprocessing Copper Mine Tailings in Chile.* Metals 11, 103. doi: 10.3390/met11010103

DRZYMALA, J., SWEBODZINSKA, A., DUCHNOWSKA, M., BAKALARZ, A., LUSZCZKIEWICZ, A., KOWALCZUK, P.B., 2016. *Preliminary study on collectorless flotation of chalcocite, bornite and copper-bearing shale in the presence of selected frothers*. E3S Web Conf. 8, 01031. doi: 10.1051/e3sconf/20160801031

FEMENIAS, F., MALDONADO, M., MIRANDA, N., GUTIERREZ, L., 2022. *Flotation Performance and Gas Dispersion Properties in a Laboratory Flotation Cell.* Minerals 12, 1351. doi: 10.3390/min12111351

FOSZCZ, D., DRZYMALA, J., 2011. *Differentiation of organic carbon, copper and other metals contents by segregating flotation of final Polish industrial copper concentrates in the presence of dextrin*. Physicochem. Probl. Miner. Process. 47, 17–26.

GAO, Y., ZHANG, G., WANG, M., LIU, D., 2018. *The Critical Role of Pulp Density on Flotation Separation of Nickel-Copper Sulfide from Fine Serpentine.* Minerals 8, 317. doi: 10.3390/min8080317

GERSON, A., NAPIER-MUNN, T., 2013. *Integrated Approaches for the Study of Real Mineral Flotation Systems.* Minerals 3, 1–15. doi: 10.3390/min3010001

GRANO, S.R., RALSTON, J., SMART, R.St.C., 1990. *Influence of electrochemical environment on the flotation behaviour of Mt. Isa copper and lead-zinc ore.* Int. J. Miner. Process. 30, 69–97. doi: 10.1016/0301-7516(90)90067-9

HASSANZADEH, A., GUNGOR, E., SAMET, E., DURUNESIL, D., HOANG, D.H., VINNETT, L., 2024. *Imhoflot™ Flotation Cell Performance in Mini-Pilot and Industrial Scales on the Acacia Copper Ore.* Minerals 14, 590. doi: 10.3390/min14060590

HASSANZADEH, A., HOANG, D.H., 2026. *First Insights into Scale-Up Procedures for Reactor–Separator Flotation Cells.* Minerals 16, 733. doi: 10.3390/min16070733

JAMESON, G.J., 2006. *Method and apparatus for contacting bubbles and particles in a flotation separation system. Published patent application* WO2006081611A1, 10 August 2006. https://patents.google.com/patent/WO2006081611A1/en (accessed 23 September 2026)

JIMENEZ, G., CABRERA, P., RODRIGUEZ, A., CUERVO, C., GUTIERREZ, L., 2024. *The Effect of an Anionic Polyacrylamide on the Flotation of Chalcopyrite, Enargite, and Bornite.* Minerals 14, 634. doi: 10.3390/min14070634

KONIECZNY, A., PAWLOS, W., KRZEMINSKA, M., KALETA, R., KURZYDLO, P., 2013. *Evaluation of organic carbon separation from copper ore by pre-flotation.* Physicochem. Probl. Miner. Process. 49, 189–201. doi: 10.5277/ppmp130117

MAMBETALIYEVA, A., TUSSUPBEKOVA, T., SABIROVA, L., MAKASHEVA, G., YELEUSSIZ, S., BARMENSHINOVA, M., KALIASKAR, S., 2026. *Grinding-Induced Surface Renewal of Legacy Sulfide Minerals and Its Impact on Tailings Reprocessing*. Minerals 16, 741. doi: 10.3390/min16070741

MCNAMARA, H., LEON GATICA, M., HORNUNG, B., LABORDE, C., 2022. Method for optimizing mineral recovery process. Published patent application WO2022034512A1, 17 February 2022. https://patents.google.com/patent/WO2022034512A1/en (accessed 23 September 2026)

MESA, D., BRITO-PARADA, P.R., 2019. *Scale-up in froth flotation: A state-of-the-art review*. Sep. Purif. Technol. 210, 950–962. doi: 10.1016/j.seppur.2018.08.076

PALUCHNIAK, T., BAKALARZ, A., 2025. *Flotation of sulfide copper ore from Legnica-Glogow Copper Basin (Poland) in process water of different salinities*. Mining Sci. 32, 87–104. doi: 10.37190/msc/207432

PENG, M., RATAJCZAK, T., DRZYMALA, J., 2014. Zeta potential of Polish copper-bearing shale in the absence and presence of flotation frothers. Mining Sci. 21, 57–63. doi: 10.5277/ms142105

QUIERO-GELMI, A., OLCAY-BARREDA, R., MAMANI-APALA, P., 2024. Thickener design for a copper concentrate using rheology, sedimentation and compression parameters. Mining Sci. 31, 103–118. doi: 10.37190/msc243106

RINNE, A., 2022. Flotation cell. Published patent application US20220258178A1, 18 August 2022. https://patents.google.com/patent/US20220258178A1/en (accessed 23 September 2026)

ROBBEN, C., WOTRUBA, H., 2019. *Sensor-Based Ore Sorting Technology in Mining: Past, Present and Future*. Minerals 9, 523. doi: 10.3390/min9090523

SALEM-SAID, A.H., FAYED, H., RAGAB, S., 2013. *Numerical Simulations of Two-Phase Flow in a Dorr-Oliver Flotation Cell Model*. Minerals 3, 284–303. doi: 10.3390/min3030284

SUAZO, C., KRACHT, W., VALDES, F., 2026. *Characterization of Hydrodynamics and Mixing Regime of a HydroFloat ® Cell*. Minerals 16, 699. doi: 10.3390/min16070699

SZYSZKA, D., 2019. *Frother critical coalescence concentration and dose in flotation of copper-bearing carbonaceous shale*. Mining Sci. 26, 289–295. doi: 10.37190/msc192620

SZYSZKA, D., SZCZEPANSKI, W., 2015. Contact angle of copper-bearing shales using the sessile drop and captive bubble methods in the presence of selected frothers. Mining Sci. 22, 191–199. doi: 10.5277/msc152216

VALLEJOS, P., YIANATOS, J., BENÍTEZ, M., SHERRELL, I., YÁÑEZ, A., BETANCOURT, D., 2025b. *Modelling and Simulation of Intensified Flotation Cells for Fine Particles Flotation*. Minerals 15, 1270. doi: 10.3390/min15121270

VALLEJOS, P., YIANATOS, J., RODRÍGUEZ, M., CORTÍNEZ, J., 2025a. *Using Intensified Flotation Cells to Improve Cleaning Circuit Performance*. Minerals 15, 453. doi: 10.3390/min15050453

VINNETT, L., ESTEBAN, A., ORELLANA, F., RIVERA, M., BENÍTEZ, M., 2025. *On the Sensitivity of Kinetic Modeling to the Selection of Flotation Intervals in Batch Tests*. Minerals 15, 583. doi: 10.3390/min15060583

WITECKI, K., JAKUBCEWICZ, A., KRUSZWICKA, I., 2026. *Waste Stream Reduction by Combining Coarse Waste Preconcentration and Fine Tailings Utilization Technologies in a Copper Concentration Plant: The KGHM Polska Miedź S.A. Case Study*. Minerals 16, 651. doi: 10.3390/min16060651

YENIAL-ARSLAN, U., JEFFERSON, M., CURTIS-MORAR, C., FORBES, E., 2023. *Pathway to Prediction of Pyrite Floatability from Copper Ore Geological Domain Data*. Minerals 13, 801. doi: 10.3390/min13060801

ZHANG, M., PENG, Y., 2015. *Effect of clay minerals on pulp rheology and the flotation of copper and gold minerals*. Miner. Eng. 70, 8–13. doi: 10.1016/j.mineng.2014.08.014

ZHANG, M., PENG, Y., XU, N., 2015. *The effect of sea water on copper and gold flotation in the presence of bentonite*. Miner. Eng. 77, 93–98. doi: 10.1016/j.mineng.2015.03.006

ZHENG, Q., SHEN, P., SU, C., DONG, L., LIU, D., 2025. *Selective depression mechanism: Surface chemistry and molecular dynamics study on the flotation separation of chalcopyrite and pyrrhotite*. J. Environ. Chem. Eng. 13, 119856. doi: 10.1016/j.jece.2025.119856