

MINISTRY OF EDUCATION AND TRAINING
HANOI UNIVERSITY OF MINING AND GEOLOGY

DO THI NHU QUYNH

**DEVELOPMENT OF A TECHNOLOGICAL REGIME
TO IMPROVE THE FLOTATION PERFORMANCE OF
ZINC OXIDE ORES FROM THE BAC KAN REGION**

**SUMMARY OF DOCTORAL DISSERTATION
FIELD: MINERAL PROCESSING ENGINEERING**

Hanoi – 2026

The dissertation was completed at the Department of Mineral Processing, Faculty of Mining, Hanoi University of Mining and Geology.

Scientific supervisor:

Assoc. Prof. Dr. Pham Van Luan

Hanoi University of Mining and Geology

Reviewer 1: **Assoc. Prof. Dr. Tran Van Lung**

Vietnam Mineral Processing Association

Reviewer 2: **Dr. Nguyen Van Hanh**

Vietnam Mineral Processing Association

Reviewer 3: **Dr. Tran Trung Toi**

Hanoi University of Mining and Geology

The dissertation will be defended before the University-level Doctoral Dissertation Evaluation Council at Hanoi University of Mining and Geology at hours, on 2026.

The dissertation may be consulted at:

National Library of Vietnam

Library of Hanoi University of Mining and Geology

INTRODUCTION

1. Rationale and significance of the dissertation

Zinc is an important non-ferrous metal for industry, while high-grade zinc sulfide ore resources are progressively declining. In the Bắc Kạn region, a significant proportion of lead-zinc resources occurs as weathered zinc oxide ores of low grade, complex mineralogical composition and fine dissemination, with abundant clay slimes and common associations with iron-manganese oxides and silicate minerals. These characteristics make beneficiation by conventional methods difficult and result in unstable flotation performance.

Research and industrial practice indicate that zinc oxide flotation performance depends not only on the collector but is also strongly affected by fine slimes, dissolved ions, mineral-surface condition and the modifier system. It is therefore necessary to investigate simultaneously the material characteristics, dissolved-ion environment, reagent-action mechanisms and process modelling in order to establish an appropriate technological regime for zinc oxide ores from Bắc Kạn.

2. Research objectives

To establish the scientific basis and a technological regime for improving the flotation performance of zinc oxide ores from the Bắc Kạn region through investigation of material characteristics, the effects of the dissolved-ion environment and optimisation of the modifier system.

The specific objectives are to clarify the material characteristics of the ore samples; determine the influence of the dissolved-ion environment and optimise the modifier system

using response surface methodology; and develop and verify appropriate flotation regimes for two representative low-grade zinc oxide ore types from Chợ Đồn.

3. Research objects, scope and methods

The research objects comprise the high-grade zinc oxide ore sample C17 and two low-grade zinc oxide ore samples, KN and KĐ, from Chợ Đồn, Bắc Kạn, together with fatty-acid-collector flotation in the presence of dissolved ions and modifier reagents.

The dissertation employs mineralogical and chemical analytical methods (XRD, multi-element chemical analysis and ICP), laboratory flotation testing, chemical and surface-mechanism analysis, experimental design and mathematical modelling using Design-Expert 11 with Response Surface Methodology (RSM) and Box-Behnken Design (BBD), combined with statistical data processing.

4. Scientific and practical significance

Scientifically, the dissertation clarifies the relationships among material characteristics, the dissolved-ion environment and flotation performance, and establishes a basis for selecting and optimising the modifier system by mathematical modelling.

Practically, the results provide a basis for selecting reagent regimes and developing flotation flowsheets suited to the different zinc oxide ore types in the Bắc Kạn region.

5. Theses defended

Thesis 1: Material-characterisation studies clarified the occurrence of zinc minerals in two low-grade zinc oxide ore types from Chợ Đồn, Bắc Kạn. In sample KN, zinc occurs mainly as hemimorphite and smithsonite in relatively discrete,

medium-to-fine, porous particles, which favours liberation and direct flotation. In sample KĐ, zinc occurs by isomorphous substitution or in close intergrowth with chalcophanite and Fe-Mn oxide minerals; the texture is dense and compact, making liberation and flotation difficult. These material characteristics govern flotation response and provide the scientific basis for selecting modifier systems and developing a separate process flowsheet for each ore type.

Thesis 2: By applying Box-Behnken experimental design in combination with Response Surface Methodology (RSM), the dissertation determined the magnitude of the effects and interactions of a modifier combination comprising Na_2S as the sulfidising agent, Tan-X as a surface-cleaning reagent and Sep-X as a depressant/dispersant in zinc oxide ore flotation. Results obtained on the high-grade C17 sample established the scientific basis for reagent-system and reagent-regime selection and provided direction for optimising flotation of the two representative low-grade zinc oxide ore types from Chợ Đồn, Bắc Kạn.

Thesis 3: Based on material characteristics and optimisation of the reagent regime, suitable flotation flowsheets were established for the two low-grade zinc oxide ore types from Chợ Đồn, Bắc Kạn. Sample KN uses the Na_2S –Tan-X–Sep-X system combined with a fatty-acid-based collector, whereas sample KĐ uses Na_2S –starch–SHMP. Closed-circuit verification on TankCell equipment produced a KN concentrate grading 21.05% Zn at 66.70% Zn recovery after one cleaning stage, while KĐ produced a concentrate grading 16.10% Zn at

60.19% Zn recovery after two cleaning stages, demonstrating the technical feasibility of the proposed flowsheets.

6. Novel contributions of the dissertation

- The dissertation substantially clarifies the effects of several multivalent cations in the flotation environment of low-grade zinc oxide ores from Chợ Đồn, Bắc Kạn. Excessive accumulation of dissolved cations in recirculated water is identified as a major reason why some previously applied zinc oxide flotation schemes did not achieve the expected performance. Effective reagent combinations were therefore established to control the adverse effects of dissolved ions during flotation.

- RSM and Box-Behnken experimental design were applied to model and optimise the reagent regime for zinc oxide flotation. Ellipsoidal representations were additionally used to evaluate metallurgical responses as the modifier system varied within the investigated domain.

- Experimental work established modifier combinations adapted to two zinc oxide ore types of different mineralogical composition: Tan-X/Sep-X for the silicate-carbonate ore type (KN) and starch/SHMP for the Fe-Mn-rich zinc oxide ore type (KĐ). Suitable flotation flowsheets were proposed, achieving a zinc concentrate grade of 21.05% Zn at 66.70% Zn recovery for KN and 16.10% Zn at 60.19% Zn recovery for KĐ.

7. Dissertation structure and research logic

The dissertation is organised into four chapters, progressing from scientific fundamentals to technological verification.

Chapter 1 – Overview of technology and physicochemical fundamentals of zinc oxide ore flotation. This chapter reviews

zinc oxide beneficiation technologies, the physicochemical basis of sulfidisation–fatty-acid flotation and the influence of dissolved ions, thereby identifying the research gap.

Chapter 2 – Material-characterisation studies. Samples C17, KN and KĐ are characterised with emphasis on chemical and mineralogical composition, modes of zinc occurrence and features likely to govern flotation behaviour.

Chapter 3 – Optimisation of the modifier system by Response Surface Methodology. Sample C17 is used to systematically investigate the effects of pH, Na_2S and modifiers. Na_2S , Tan-X and Sep-X are incorporated into the BBD/RSM model to identify an appropriate operating domain and verify predictive capability.

Chapter 4 – Beneficiation technology for low-grade zinc oxide ores from the Chợ Đồn mining area. The research findings are transferred to the low-grade KN and KĐ samples to establish grinding conditions, pulp solids concentration, slime-treatment strategy and ore-specific reagent systems, followed by open- and closed-circuit verification in a mechanical flotation machine and TankCell.

This structure ensures that each technological conclusion is supported by corresponding material characteristics and experimental evidence. The summary presents only the results directly supporting the defended theses and proposed technological regimes; detailed datasets, regression equations, response-surface plots and complete analytical results are provided in the full dissertation.

Throughout data processing and evaluation, the two principal metallurgical criteria are Zn grade in the products and

Zn recovery. Condition tests are compared according to the simultaneous trends of these two responses rather than by selecting the maximum of only one response. Model adequacy is assessed by analysis of variance, significance of regression coefficients, Lack of Fit and agreement between predicted and validation values. In process development, results from the mechanical flotation machine are used as a reference against TankCell; the number of cleaning stages, concentrate quality and recovery are considered simultaneously when selecting a flowsheet. This approach supports development of an ore-specific technological regime and avoids generalising a single test condition to all zinc oxide ores in the study area.

CHAPTER 1. OVERVIEW OF TECHNOLOGY AND PHYSICOCHEMICAL FUNDAMENTALS OF ZINC OXIDE ORE FLOTATION

1.1 Overview of zinc oxide ore flotation technology

Beneficiation routes widely used by researchers worldwide include: (1) sulfidisation followed by flotation with cationic collectors such as amines; (2) flotation with fatty-acid collectors; (3) sulfidisation and activation with metal ions (Cu^{2+}), followed by flotation with sulfhydryl collectors such as xanthates or with mixed cationic/anionic collectors; and (4) flotation with mercaptan and chelating collectors.

Domestic studies have mainly focused on flotation, gravity separation, magnetic separation and hydrometallurgical/chemical beneficiation. The major obstacles to stable industrial application, particularly for flotation, are: (1) high losses in fine size fractions; and (2) inadequate control of

the dissolved-ion environment, causing high reagent consumption and low recovery when process water is recycled. This creates an urgent need for zinc oxide flotation research grounded in advanced surface and solution chemistry.

1.2 Scientific basis of fatty-acid flotation of zinc oxide ores

Fatty-acid flotation of zinc oxide ores is simultaneously affected by mineral-surface condition, the dissolved-ion environment, sulfidisation and the reagent regime. Dissolved Ca, Mg, Fe and other ions can alter mineral-surface properties and affect flotation selectivity. Control of the ionic environment and use of an appropriate modifier system are therefore important.

For zinc oxide minerals, sulfidisation with Na_2S modifies the surface and facilitates collector–mineral interaction. In addition, combining a fatty-acid-based collector with kerosene can increase hydrophobicity and improve floatability under suitable conditions.

Accordingly, the dissertation focuses on the relationships among the dissolved-ion environment, sulfidisation and the modifier system in order to establish a basis for selecting a suitable reagent regime for zinc oxide ores from Chợ Đồn, Bắc Kạn.

1.3 Effects of dissolved ions on fatty-acid flotation of zinc oxide ores

In fatty-acid flotation of zinc oxide ores, recovery is not simply an independent reaction between two components, mineral and collector, but a complex thermodynamic system comprising three mutually interacting components: solution (dissolved-ion system) – mineral surface – collector.

Competitive adsorption between inorganic ions and collector species includes competition on mineral surfaces, competition within the pulp and indirect competition through disruption of sulfidisation. This competition demonstrates that the dissolved-ion environment can significantly affect hemimorphite sulfidisation and flotation.

The influence of dissolved ions is not entirely adverse; it depends on concentration, chemical conditions and reagent-addition sequence. Consequently, controlling the ionic system in the pulp, sequestering harmful ions and selecting the correct reagent-addition sequence are important for improving fatty-acid flotation of zinc oxide ores. The proposed three-level linear control sequence comprises: Level 1 – pulp control; Level 2 – pretreatment and liquid-phase cleaning, followed by sulfidisation and surface restructuring ($\text{Tan-X} \rightarrow \text{Na}_2\text{S} \rightarrow \text{Sep-X}$); Level 3 – formation of a stable hydrophobic layer using an oleate collector blend plus kerosene.

1.4 Box-Behnken experimental design

The model describes the quantitative relationships and interactions among three process variables: Na_2S , Sep-X and Tan-X dosages. Response Surface Methodology (RSM) with a Box-Behnken Design (BBD) is implemented in Design-Expert. The second-order polynomial regression for recovery and zinc grade in the concentrate is:

$$Y = \beta_0 + \sum_{i=1}^3 \beta_i X_i + \sum_{i=1}^3 \beta_{ii} X_i^2 + \sum_{i < j} \beta_{ij} X_i X_j + \varepsilon \quad (1.6)$$

where:

- Y is the response to be optimised (Zn recovery or Zn grade);

- X_i and X_{ij} are coded control variables (Na_2S , Sep-X and Tan-X);
- β_0 is the intercept;
- β_i are first-order regression coefficients describing the independent linear effect of each reagent;
- β_{ii} are quadratic coefficients describing response-surface curvature (non-linearity);
- β_{ij} are cross-interaction coefficients used to assess synergistic or antagonistic interactions between reagents (e.g. the supporting effect of Tan-X on Na_2S);
- ε is the residual error.

CHAPTER 2. MATERIAL CHARACTERISATION OF THE ORE SAMPLES

2.1 Material characterisation of the process samples

The process samples used in the dissertation are low-grade zinc oxide ores from the Chợ Đồn mining area: a brown zinc oxide ore (hereafter the brown ore, sample code KN) and a black zinc oxide ore (hereafter the black ore, sample code KĐ).

The characteristics of the investigated samples are presented in Figures 2.3–2.6.

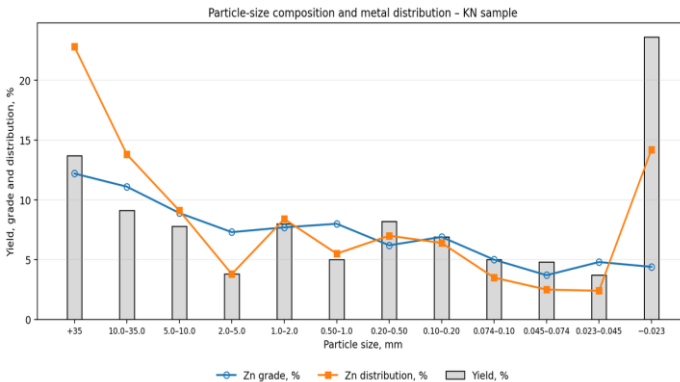


Figure 2.3. Particle-size composition and metal distribution of the KN sample

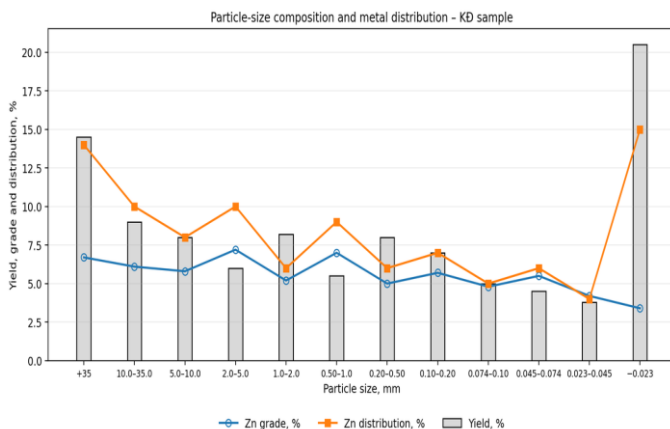


Figure 2.4. Particle-size composition and metal distribution of the KD sample

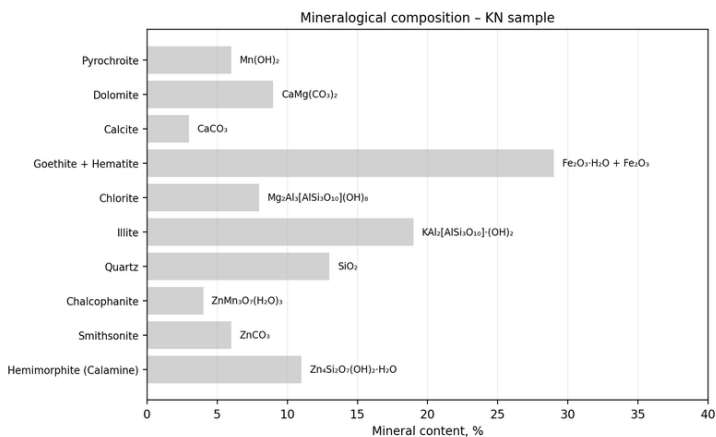


Figure 2.5. Mineralogical composition of the KN ore sample

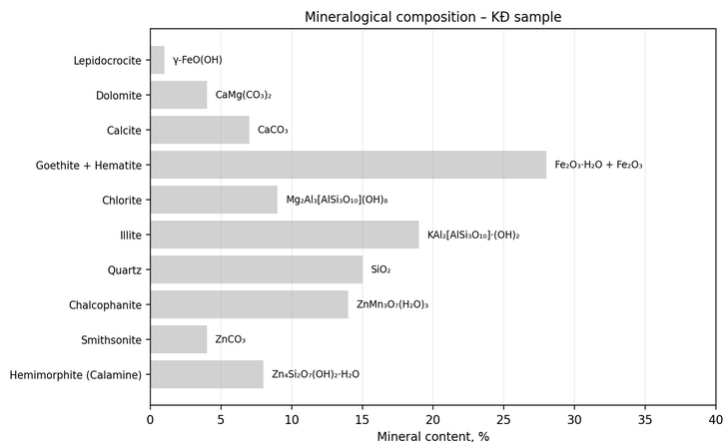


Figure 2.6. Mineralogical composition of the KĐ ore sample

Material-characterisation results indicate that sample KN is more amenable to flotation than sample KĐ. In water, some mineral components of the two samples may dissolve and generate $\text{Fe}^{2+}/\text{Fe}^{3+}$, Al^{3+} , Ca^{2+} , Mg^{2+} and Zn^{2+} ions that can affect flotation. The influence of these ions therefore requires further investigation.

Characteristic	KN sample	KĐ sample
Head Zn grade	7.40%	6.57%
Main Zn-bearing minerals	Hemimorphite (9–11%); smithsonite (4–6%)	Chalcophanite (12–14%); hemimorphite (6–8%)
Notable associated minerals	Dolomite and clay minerals	Calcite and Fe–Mn phases
Processing characteristics	More favourable for activation and flotation	More difficult to liberate and upgrade

2.2 Sample used to investigate ionic effects on flotation

The ore sample coded C17 was collected from the weathered zone of zinc oxide ore at the Chợ Điền mine. Mineralogical analysis shows that smithsonite (30–32%) and hemimorphite (15–17%) are the principal zinc-bearing minerals. Gangue consists mainly of goethite (34–36%), hematite (5–7%), quartz (3–5%) and illite (2–4%), while other minerals such as calcite and kaolinite–chlorite occur only in minor amounts. Chemical analysis gives a total zinc grade of 17.94% Zn. The sample was dry-ground to 100% passing 0.1 mm for ion-composition determination and flotation testing.

CHAPTER 3. OPTIMISATION OF THE MODIFIER SYSTEM FOR A HIGH-GRADE ZINC OXIDE ORE FROM BẮC KẠN USING RESPONSE SURFACE METHODOLOGY

3.1 Research objective

The objective of this chapter is to determine the effects of the modifier system on flotation of a high-grade zinc oxide ore from Bắc Kạn and to optimise the reagent regime using Box-Behnken experimental design combined with Response Surface Methodology (RSM). The work aims to identify a suitable reagent-operating region and establish a scientific basis for selecting reagent systems for flotation studies on the two low-grade zinc oxide ores from Chợ Đồn, Bắc Kạn.

3.2 Research method

Box-Behnken experimental design combined with Response Surface Methodology (RSM) was applied. The three variables incorporated into the BBD were Tan-X, Sep-X and Na₂S. The

optimisation result is used as a reference operating region for experimental verification rather than as a fixed dosage prescription applicable to every ore type.

Box-Behnken experimental design combined with Response Surface Methodology (RSM) was applied. The three variables incorporated into the BBD were Tan-X, Sep-X and Na_2S . The optimisation result is used as a reference operating region for experimental verification rather than as a fixed dosage prescription applicable to every ore type.

3.3 Tests for selection of the modifier system

Modifier-selection tests were divided into nine groups to investigate, respectively: (1) pH regulators, (2) pH value, (3) Na_2S dosage, (4) Tan-X, (5) Na_2SiO_3 , (6) Sep-X, (7) SHMP, (8) starch and (9) the three-variable Tan-X–Sep-X– Na_2S matrix. Test conditions were as follows:

- Tests in group (1) evaluated only the effects of pH and the pH regulators Na_2CO_3 and NaOH ; no other reagents were added.
- Tests in groups (2)–(8) were conducted at fixed pH 9.5, adjusted with Na_2CO_3 , without other additional reagents, so that only the reagent under investigation was evaluated.
- Tests in group (9) varied Tan-X, Sep-X and Na_2S , while fixing Na_2SiO_3 at 500 g/t and pH at 9.5 using Na_2CO_3 .
- All flotation tests were carried out on undeslimed material with a fixed collector-blend dosage of 800 g/t, using twice-distilled water and a 1-L mechanical flotation cell. Flotation performance was evaluated by Zn grade and Zn recovery in the froth product.

Based on modifier-selection results for the weathered silicate-carbonate zinc oxide ore system, Tan-X and Sep-X were selected as control variables for the RSM model, while SHMP and starch were temporarily excluded from the experimental matrix. The integrated modelling approach was: (1) use Na_2CO_3 to control pH and contribute to reducing Ca/Mg concentrations in the liquid phase; and (2) use Na_2SiO_3 together with Sep-X and Tan-X to disperse fine slimes and limit the effects of Fe-bearing components. This combination was selected to control the pulp environment and facilitate sulfidisation and the action of the oleate collector.

3.4 Box-Behnken experimental design

Na_2S , Tan-X and Sep-X were selected as the three variables for the Box-Behnken Design (BBD) and Response Surface Methodology (RSM) models for the two responses, Zn grade and Zn recovery, as expressed in Equations 3.11 and 3.12. Analysis of variance (ANOVA) and the second-order regression model enable assessment of individual effects, variable interactions and the suitable reagent-operating region.

Zn grade:

$$Y_1 = -183.7654 + 0.09628X_1 + 0.36029X_2 + 0.01701X_3 \\ + 0.0001275X_1X_2 - 1.33 \times 10^{-6}X_1X_3 - 6 \times 10^{-6}X_2X_3 \\ - 0.0001420X_1^2 - 0.0003543X_2^2 - 5.50 \times 10^{-7}X_3^2 \quad (3.11)$$

Zn recovery:

$$Y_2 = -666.0647 + 2.54860X_1 + 0.10621X_2 + 0.01949X_3 \\ - 0.0002375X_1X_2 + 6.46 \times 10^{-6}X_1X_3 + 2.28 \times 10^{-5}X_2X_3 \\ - 0.0024999X_1^2 - 0.0002130X_2^2 - 1.844 \times 10^{-6}X_3^2 \quad (3.12)$$

Multi-response optimisation using the desirability function identified a suitable parameter set at Tan-X $\approx$ 510 g/t, Sep-X $\approx$

495 g/t and $\text{Na}_2\text{S} \approx 10,200$ g/t, with an overall desirability $D \approx 0.92$. Under these conditions, the model predicted a concentrate grade of approximately 30.5% Zn at approximately 79% recovery. Three validation tests gave mean values of 29.5% Zn and 75.4% recovery. The experimental-to-predicted deviations were 3.2% and 4.6%, respectively, both below 5%, demonstrating adequate predictive capability within the investigated domain.

Response-surface analysis and ellipsoidal representation show that the magnitude of influence and sensitivity of the two responses to the three variables differ within the investigated domain. These results support definition of a suitable reagent-dosage region around the optimum and indicate the priority order for dosage control as $\text{Tan-X} \rightarrow \text{Na}_2\text{S} \rightarrow \text{Sep-X}$.

The RSM study using BBD therefore identified and experimentally verified a suitable reagent-operating region for sample C17, providing a reference basis for studying the flotation regimes of the low-grade KN and KĐ samples.

CHAPTER 4. BENEFICIATION TECHNOLOGY FOR LOW-GRADE ZINC OXIDE ORES FROM THE CHỢ ĐỒN MINING AREA

4.1 Research objective

The objective of Chapter 4 is to establish suitable flotation flowsheets for the two low-grade zinc oxide ore samples KN and KĐ from Chợ Đồn, Bắc Kạn, based on the material characteristics of each sample and the modifier-system results obtained in Chapter 3.

4.2 Research method

The study was conducted through flotation process experiments progressing from condition tests to flowsheet tests. Within each test group, one parameter was varied while the remaining parameters were held constant at the conditions selected in the preceding stage.

4.3 Process-development strategy for KN and KD

Although both samples belong to the weathered zinc oxide ore group from the Chợ Đồn mining area, Chapters 2 and 3 demonstrate clear differences in mineralogical composition and in the factors affecting flotation. Applying one common technological regime to both samples may therefore not provide optimum performance. Subsequent work accordingly evaluates individual process parameters to establish a suitable flotation regime for each ore type.

4.4 Establishment of flotation conditions

The dissertation investigated the effects of grind size, slimes, pulp solids concentration and modifier reagents. The principal findings are as follows.

Grind size affects both Zn grade and Zn recovery. Within the investigated range, increasing mineral liberation clearly improves flotation performance. However, excessive fine grinding, although continuing to increase liberation, generates more fine particles and reduces flotation selectivity. This trend is consistent with the mineralogical characteristics of the weathered zinc oxide ores described in Chapter 2.

Desliming provides some improvement in concentrate Zn grade but simultaneously causes Zn loss to the slime product and reduces overall Zn recovery relative to the head feed. Under

the test conditions of the dissertation, the improvement in concentrate grade did not compensate for the loss in Zn recovery. An undeslimed flowsheet was therefore selected for subsequent studies to prioritise Zn retention in the feed and simplify the process flowsheet. This conclusion applies to the investigated samples, reagent regimes and test conditions; cumulative effects of fine slimes and dissolved ions under repeated water recycle were not evaluated in this study.

The effectiveness of the modifier system clearly depends on ore characteristics. For sample KN, the Tan-X-Sep-X system produced more suitable flotation indices than the starch-SHMP system within the investigated range. Conversely, for sample KĐ, starch-SHMP gave more suitable Zn grade and recovery. These two systems were therefore selected for KN and KĐ, respectively, for further Na_2S optimisation and flowsheet development.

4.5 Flotation tests using a mechanical flotation machine and TankCell

Under the investigated conditions, TankCell provided better values for some flotation indices and greater stability than the mechanical flotation machine. Tests in the 75-L TankCell indicated that a suitable collector-blend dosage was approximately 900–1,000 g/t. The results also show that TankCell is suitable for further verification of the flotation regimes for KN and KĐ, particularly for the undeslimed option.

4.6 Open-circuit flotation tests

The flotation flowsheets and reagent regimes for KN and KĐ are presented in Figures 4.18 and 4.19. Open-circuit results are given in Tables 4.4 and 4.5.

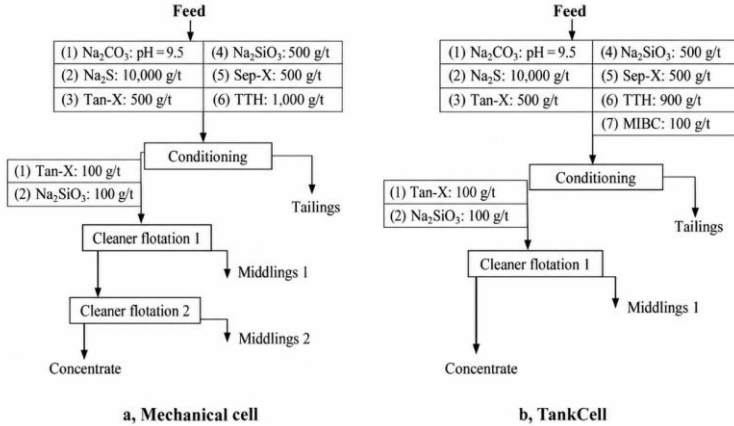


Figure 4.18. Open-circuit flotation flowsheet and reagent regime for the KN sample

Table 4.4. Open-circuit flotation results for the KN sample

Product	Mechanical flotation cell			TankCell		
	Yield, %	Zn grade, %	Zn recovery, %	Yield, %	Zn grade, %	Zn recovery, %
Concentrate	21.87	21.18	62.51	21.46	21.75	62.99
Middlings 1	9.12	5.80	7.14	17.07	8.07	18.59
Middlings 2	7.76	10.59	11.09			
Tailings	61.25	2.33	19.26	61.47	2.22	18.42
Head feed	100	7.41	100	100	7.41	100

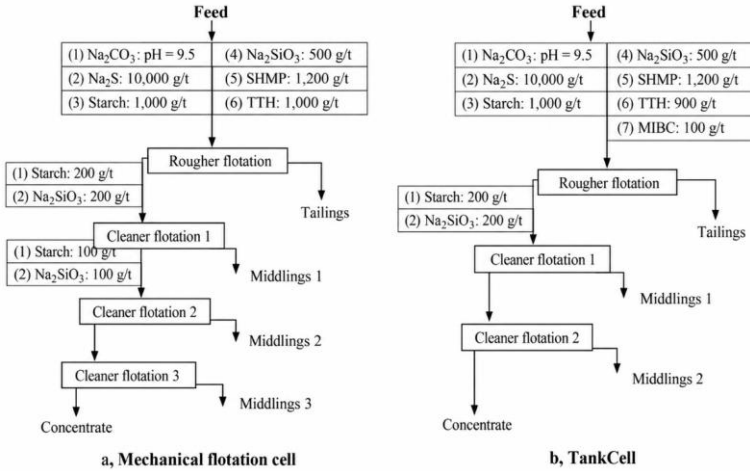


Figure 4.19. Open-circuit flotation flowsheet and reagent regime for the KĐ sample

Table 4.5. Open-circuit flotation results for the KĐ sample

Product	Mechanical flotation cell			TankCell		
	Yield, %	Zn grade, %	Zn recovery, %	Yield, %	Zn grade, %	Zn recovery, %
Concentrate	23.27	16.08	56.87	22.86	16.63	57.78
Middlings 1	11.81	4.90	8.79	17.03	5.18	13.41
Middlings 2	8.46	7.97	10.25	6.94	10.85	11.44
Middlings 3	4.00	9.19	5.59			
Tailings	52.46	2.32	18.50	53.17	2.15	17.37
Head feed	100	6.58	100	100	6.58	100

4.7 Closed-circuit flotation tests

The closed-circuit flotation flowsheets and reagent regimes for KN and KĐ are presented in Figures 4.20 and 4.21. The corresponding results are given in Tables 4.6 and 4.7.

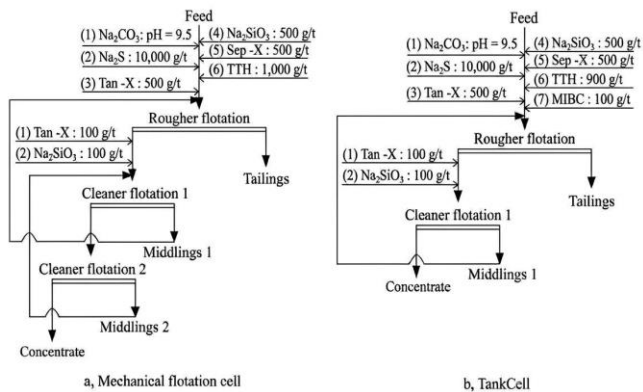


Figure 4.20. Closed-circuit flotation flowsheet and reagent regime for the KN sample

Table 4.6. Closed-circuit flotation results for the KN sample

Product	Mechanical flotation cell			TankCell		
	Yield, %	Zn grade, %	Zn recovery, %	Yield, %	Zn grade, %	Zn recovery, %
Concentrate	24.55	20.32	67.32	23.48	21.05	66.70
Tailings	75.45	2.94	32.68	76.52	2.91	33.30
Head feed	100	7.41	100	100	7.41	100

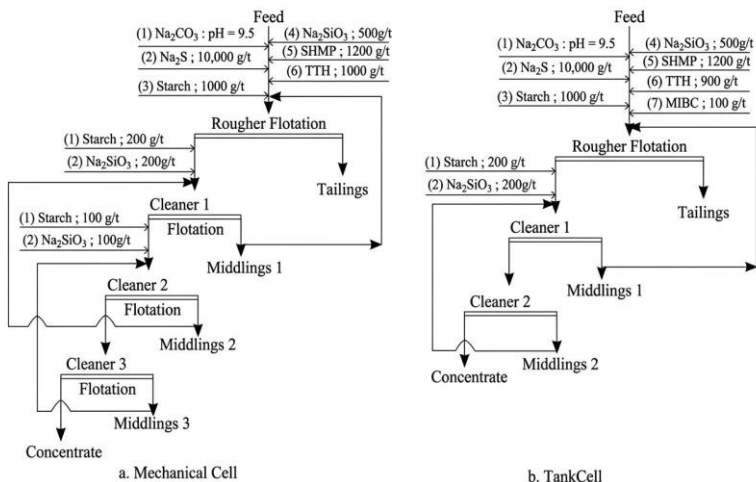


Figure 4.21. Closed-circuit flotation flowsheet and reagent regime for the KĐ sample

Table 4.7. Closed-circuit flotation results for the KĐ sample

Product	Mechanical flotation cell			TankCell		
	Yield, %	Zn grade, %	Zn recovery, %	Yield, %	Zn grade, %	Zn recovery, %
Concentrate	25.23	15.60	59.82	24.60	16.10	60.19
Tailings	74.77	3.54	40.18	75.40	3.47	39.81
Head feed	100.00	6.58	100.00	100	6.58	100.00

CONCLUSIONS AND RECOMMENDATIONS

1. Conclusions

On the basis of the research, the dissertation achieved the following results:

1. The material characteristics and differences in zinc occurrence among the investigated ores were clarified, providing the basis for selecting flotation regimes. Sample C17

has a higher Zn grade and was selected to investigate dissolved-ion effects and optimise the reagent system. Of the two low-grade samples, KN is a silicate-carbonate ore in which zinc occurs mainly as hemimorphite and smithsonite and is more readily liberated. KĐ contains abundant Fe-Mn phases; zinc occurs mainly in chalcophanite and in close association with Fe-Mn oxide minerals, with a dense texture and difficult liberation. These differences govern flotation behaviour and justify separate reagent regimes and flowsheets for the two ore types.

2. The effects of the dissolved-ion environment and the role of modifiers in sulfidisation–flotation of zinc oxide ore with fatty-acid-based collectors were established. Results for C17 show that flotation performance depends simultaneously on ionic conditions in the liquid phase, degree of sulfidisation and the modifier system. Na_2S plays a key role in sulfidising zinc-mineral surfaces; Tan-X, Sep-X, SHMP, Na_2SiO_3 and starch exert different effects depending on material composition and flotation environment. These findings provided the basis for selecting Na_2S , Tan-X and Sep-X as optimisation variables and for choosing suitable reagent systems for KN and KĐ.

3. A quantitative model and a suitable reagent-operating region were developed using RSM with a Box-Behnken Design. The three-variable model of Na_2S , Tan-X and Sep-X identified individual and interaction effects on Zn grade and recovery. At the validation condition of approximately 510 g/t Tan-X, 495 g/t Sep-X and 10,200 g/t Na_2S , the concentrate assayed 29.5% Zn at 75.4% recovery. Deviations between experimental and predicted results were 3.2% and 4.6%, respectively, both below

5%. The model therefore defines an appropriate process-parameter region for subsequent studies on the low-grade KN and KĐ ores.

4. The principal operating conditions and ore-specific modifier systems were established for KN and KĐ. Studies of grind size, pulp solids concentration, slimes and reagent regime showed that the undeslimed option was suitable for both samples under the investigated conditions, helping to limit Zn losses in the fine fraction and simplify the flowsheet. For KN, the Na_2S –Tan–X–Sep–X system is appropriate for the silicate-carbonate ore characteristics; for KĐ, Na_2S –starch–SHMP is more suitable for the Fe-Mn-rich ore. Separate reagent regimes were thereby established according to the material characteristics and floatability of each ore.

5. Separate flotation regimes were developed and verified for the two low-grade zinc oxide ores using TankCell equipment. For KN, a closed circuit comprising one rougher stage and one cleaning stage treated a 7.41% Zn head feed to produce a 21.05% Zn concentrate at 66.70% Zn recovery. For the more difficult KĐ ore, one rougher stage and two cleaning stages treated a 6.57% Zn head feed to produce a 16.10% Zn concentrate at 60.19% recovery. The closed-circuit results confirm the need for ore-specific reagent regimes and cleaning-stage configurations.

6. Based on the established operating conditions and closed-circuit verification, separate practical flowsheets were proposed for KN and KĐ. The flowsheets include ore preparation, grinding–classification, rougher flotation, cleaning, scavenging and middlings recycle, with reagent regimes and the number of

flotation stages arranged according to ore characteristics and beneficiation difficulty. These proposed flowsheets provide a basis for further verification and refinement at semi-industrial scale.

2. Recommendations

The dissertation has established the scientific basis and flotation regimes for zinc oxide ores from Chợ Đồn within the scope of this study. To clarify the remaining issues and further develop the scientific and technological basis, the following research directions are recommended:

1. Continue investigating the effects of slimes, desliming cut size and dissolved ions under multiple cycles of process-water recycle in order to assess the accumulation of fine slimes and ions in the liquid phase and thereby provide a stronger basis for selecting the appropriate slime-treatment strategy and modifier regime.

2. Investigate in greater depth the interaction mechanisms among flotation reagents, dissolved ions and zinc-mineral surfaces, particularly hemimorphite, smithsonite and chalcophanite, using surface-chemistry methods such as zeta-potential measurement, contact-angle measurement, FTIR, XPS and SEM-EDS. This work should clarify the scientific basis of sulfidisation and the actions of Tan-X, Sep-X, starch and SHMP for each ore type.

3. Continue verification of the proposed flowsheets and technological regimes at semi-industrial scale to evaluate the stability of metallurgical performance, middlings-recycle arrangements and flotation-water recycle before considering scale-up.

LIST OF THE AUTHOR'S PUBLISHED PAPERS AND SCIENTIFIC WORKS

In English

1. Luan Van Pham, Thanh Hai Pham, Nhu Quynh Thi Do, Ha Viet Le (2025), "Research to Determine the Appropriate Flotation Reagents for Zinc Oxide Ore Beneficiation: Case Study at Cho-Dien Mine, Vietnam", *Inzynieria Mineralna WMCEES*, 1(2), DOI: 10.29227/IM-2025-02-17.<https://doi.org/10.29227/IM-2025-02-17>

In Vietnamese (titles translated into English)

2. Đỗ Thị Như Quỳnh, Phạm Văn Luận, Lê Việt Hà (2024), "Study to Determine an Appropriate Reagent Regime for Flotation of Zinc Oxide Ore from Chợ Điền Mine, Bắc Kạn", *Proceedings of the National Conference on Earth Sciences and Resources for Sustainable Development*, Transport Publishing House, p. 1024.
3. Đỗ Thị Như Quỳnh, Phạm Văn Luận, Lê Việt Hà (2026), "Research and Proposal of a Flotation Technology Solution for Zinc Oxide Ore from Chợ Điền Mine", *Journal of Mining and Earth Sciences*, 67(1), pp. 18–30.
4. Đỗ Thị Như Quỳnh, Phạm Văn Luận, Lê Việt Hà (2026), "Optimisation of the Reagent Regime in Flotation of Zinc Oxide Ore from Chợ Điền Mine Using Response Surface Methodology (RSM) and Box-Behnken Design", *Journal of Mining and Earth Sciences*, 67(3), pp. 54–65.