

Article

Computational and Experimental Research on Dense Medium Separation of Low-Grade Spodumene

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Abstract: Due to the increasing demand for lithium resources, the efficient exploitation and utilization of low-grade hard-rock deposits has become an inevitable trend. This study conducted comprehensive heavy liquid separation (HLS), numerical simulation, and dense medium separation (DMS) tests using a laboratory dense medium cyclone (DMC) on a low-grade spodumene ore to demonstrate the potential role of DMS technology in this task. HLS tests verified the feasibility of directly producing qualified concentrate and rejecting waste under different separation densities. A two-stage DMS circuit was then proposed, with the influence of key parameters investigated by numerical simulations using the two-fluid model and dispersed model. The optimized set of structural and operational parameters was finally identified by DMS tests. A continuously operated test conducted on $-8 + 0.5$ mm ore produced a spodumene concentrate grading 5.68% Li_2O with over 80% lithium recovery while rejecting 0.13% Li_2O waste to tailings with ~70% disposal rate but only 7.44% lithium losses. The middling with a yield of 12.66% can be further subjected to a traditional grinding-flotation process. The findings underscore the importance of parameter matching in the DMS and demonstrate the application potential of DMS in the development of low-grade spodumene from other hard-rock occurrences.

Keywords: lithium; spodumene; dense medium separation; dense medium cyclone; numerical simulation



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1. Introduction

In the contemporary era of rapid technological advancements, lithium has gained immense importance and emerged as one of the strategic key metals [1–3]. As renewable energy technology and electric vehicles advance, over 87% of lithium production now goes to battery applications [4,5], aside from its traditional use in ceramics, glass, alloys, and medicine [6]. This has led to a surge in global demand for lithium, and a “lithium rush” is currently happening worldwide [7]. The average lithium content of the Earth’s crust is about 0.007%, and mainly occurs in brine lake deposits (about 0.1% Li_2O), hard-rock pegmatite deposits (0.4%~4%), and lithium-rich clays [8–10]. Therefore, the beneficiation of lithium-bearing minerals is crucial for its extensive utilization. Historically, brine lake deposits developed relatively early, while hard-rock pegmatite deposits were halted because of cost and other reasons [11]. Nowadays, the successful application of lithium in the clean energy field has made hard-rock pegmatite deposits the main source of lithium.

Lithium-bearing minerals in hard-rock deposits include spodumene, lepidolite, petalite, amblygonite, zinnwaldite, triphylite, and eucryptite, which are associated with gangue

minerals of primarily quartz, feldspar, and mica [11–13]. With a high theoretical lithium content of about 8.1% Li_2O , spodumene ($\text{LiAlSi}_2\text{O}_6$) stands out as a prime source of lithium. As reviewed by Oliazadeh, et al. [14], Tadesse, et al. [7], and more recently Sahoo, et al. [12], spodumene beneficiation is a multistage process, complicated by similarities in the physicochemical properties of the ore and gangue minerals. Depending on the mineralogy of the deposit and product expectations, the traditional flowsheet may include a mix of dense medium separation (DMS), magnetic separation, de-sliming, and flotation [15–17]. Among these technologies, DMS is the most commonly used pre-concentration technique for treating spodumene liberated at coarse particle sizes, as the specific gravity (S.G.) of spodumene (3.1–3.2) is generally larger than that of associated gangue minerals (2.6–2.8). Depending on the spodumene grain sizes, DMS offers not only the potential for primary lithium concentrate production but also the rejection of silicate gangue prior to further concentration by flotation [18].

Although the first reported utilization of DMS for pegmatite ore was at the Edison mine in 1949 [19], there are only limited studies investigating spodumene beneficiation through DMS. Similar applications have been documented for the spodumene pegmatite deposits in North Carolina, USA, by Redeker [20] and Bikita, Zimbabwe, by Tadesse, Makuei, et al. [7]. Amarante, et al. [21] reported that a heavy liquid, bromoform (S.G. 2.89), can separate spodumene from feldspar, quartz, and muscovite. However, this has not seen industrial implementation. Recently, Gibson, Aghamirian, Grammatikopoulos, Smith and Bottomer [18] performed heavy liquid tests (HLS) and dense medium drum separation tests of Hidden Lake pegmatite ore, Canada. By applying two-stage DMS with a mixed medium of ferrosilicon and magnetite, a concentrate grade of 6.11% Li_2O was obtained, with a 50% lithium recovery from a feed grade of 1.38%. The above studies emphasize the superiority of DMS in pre-concentrating spodumene. Nevertheless, most of them are limited to static DMS vessels like separatory cones, baths, or drums, and very few [22] involve dynamic devices such as dense medium cyclones (DMCs), probably due to reasons like poor stability, severe wear and difficulty in density control [15,23]. Over the past decades, the density-control technology and liner materials have been greatly improved, making it possible and necessary to use DMCs with a larger processing capacity to treat low-grade or fine-grained spodumene. Nonetheless, the optimal performance of a dense medium cyclone (DMC) operation remains heavily contingent on aligning the physical properties of the separating medium and flow field dynamics with key mineralogical characteristics—including particle size distribution, liberation degree, etc. [24].

Undoubtedly, physical trials are the most straightforward way to identify the best parameters. However, the testing process is typically time-consuming and resource-intensive. It is widely accepted that the results of physical experiments are difficult to extend to different operating systems. Thus, the empirical models proposed by the Dutch State Mines [25], Collins, et al. [26], Davis [27], and Wood [28], exhibit restricted applicability—primarily to coal-based materials or narrowly defined ore types. In contrast, recent developments in computational fluid dynamics (CFD) and discrete element (DEM) technologies have made it much easier to study the internal flow field and separation process of separation devices [29–31], as well as reveal parameter influence laws [32,33]. Given the intrinsic turbulence anisotropy within DMCs, turbulence modeling necessitates the application of the Reynolds stress model (RSM) and large eddy simulation (LES) [34]. For the multiphase flow, both Eulerian-Eulerian and Eulerian-Lagrangian approaches can be employed depending on the properties of solid phases. Two-fluid model (TFM) is commonly used for the simulation of dense medium bulk flow based on kinetic theory for granular flows (KTGF) or empirical viscosity models [35–38]. Institutions like JKMR [26,39] and PESCO [40] demonstrated through empirical studies that these suspensions exhibit instability and

non-Newtonian fluid characteristics—including yield stress and shear-thinning behavior. As a result, while the viscosity correction method improved the prediction of the density field, its underlying assumption that the dense medium is a Newtonian fluid remains problematic in various applications [35]. A recent method of TFM coupled with a turbulent dispersion model (TDM) was successfully applied for the prediction of hydrocyclone classifiers [41,42], which offered an alternative approach for medium flow simulation. When focusing on the motion of individual particles, the CFD-DEM coupling method is more accurate and efficient, but it requires more computational resources. To improve model robustness and reduce computing load, coarse-grained DEM [43–45] or Lagrangian particle tracking (LPT) [37,46,47] models are increasingly used. These studies revealed that both particle and fluid medium dynamics are highly responsive to mineral characteristics such as particle size distribution—largely because particles of diverse sizes traverse distinct flow trajectories, substantially altering the overall particle-fluid interactions at the bulk scale. However, prior numerical studies [37,38,44,48,49] mainly focused on low-density DMS processes for coal, leaving out high-density DMS, particularly for spodumene beneficiation utilizing DMC.

This work intends to illustrate the potential of DMC in the pre-concentration of spodumene from hard rocks by conducting a comprehensive investigation on low-grade spodumene pegmatites in Nasarawa, Nigeria. Heavy-liquid float-sink tests were used to assess gravity concentration feasibility based on the ore's mineralogy parameters. Following the determination of the estimated cut density, a TFM-LPT model was used to study the effect of key geometric parameters and medium qualities on dense medium segregation and ore particle separation performance. Finally, two-stage DMC tests, including lithium concentration and gangue rejection, were performed on the actual samples using a laboratory DMC to identify the optimal process parameters based on product quality analysis. By resolving these issues, a procedure that is both economically viable and environmentally friendly in the Nigerian context was created. The study's findings can serve as references for the development and use of similar low-grade spodumene deposits.

2. Materials and Methods

2.1. The Avatar Spodumene Ore and Mineralogy

Nigeria is exceptionally rich in lithium resources, with lithium deposits forming a visible broad band inside an ancient pegmatite belt. Pegmatite is the primary ore-bearing host rock with the majority found in Plateau, Nasarawa, Kogi, Ekiti, Kwara, and Oyo [50,51]. The spodumene pegmatite samples used in this study were sourced from a low-grade spodumene mine owned by Avatar New Energy Materials Co., Ltd. in Nasarawa State, Nigeria.

Understanding the mineralogy of lithium ore is the initial step in selecting possible beneficiation strategies. As shown in Figure 1, mineralogy study indicates that lithium minerals in raw ore are primarily spodumene with a relatively coarse structure and complete development, predominantly in columnar shape, with a tiny percentage scattered in lepidolite and petalite. Gangue minerals are primarily quartz, albite, and potassium feldspar, followed by muscovite, and include clay minerals such as kaolinite.

2.2. Sample Preparation and Characterization

The sample with a total mass of 2 tons was transported to Haiwang Hydrocyclone Co., Ltd., Weihai, China. After the raw ore was crushed to -8 mm by a jaw crusher (manufactured by Wuhan exploration machinery Co., Ltd., Wuhan, China), subsamples were collected using a riffle splitter (provided by Wuhan exploration machinery Co., Ltd., Wuhan, China) to ensure representativeness. A small portion (6 kg) was used for

sieve analysis, and another fraction (1 kg) was split out and powdered for elemental analysis using X-Ray fluorescence (XRF) and inductively coupled plasma atomic emission spectrometry (ICP-AES). As the DMC has a relatively low separation sharpness when processing particles smaller than 0.5 mm, the remainder sample was de-slimed using a standard sieve with a sieve opening size of 0.5 mm to obtain the $-8 + 0.5$ mm size fraction for HLS and DMS tests. The results of chemical multi-element analysis and particle size distribution (PSD) of the ore are shown in Tables 1 and 2, respectively.

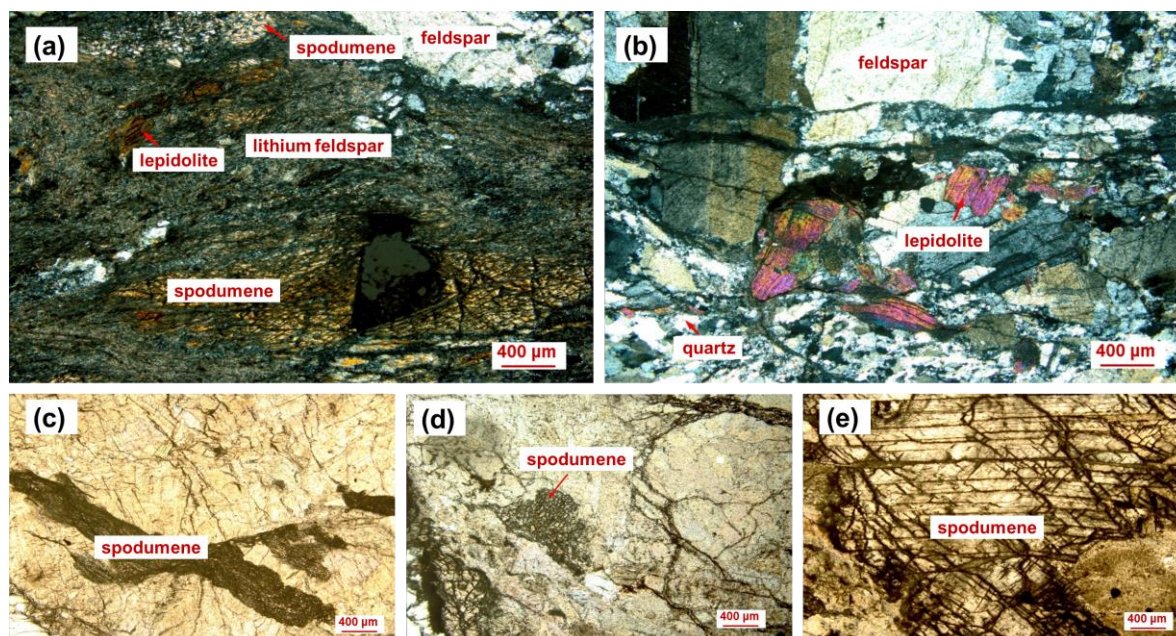


Figure 1. Occurrence state of main minerals: (a) various lithium minerals distributed between feldspar particles; (b) lepidolite and feldspar; (c) columnar spodumene aggregate; (d) allotriomorphic spodumene; (e) large columnar crystals of spodumene.

Table 1. Chemical components analysis of the raw ore.

Element	Li ₂ O	BeO	K ₂ O	Na ₂ O	SiO ₂	Al ₂ O ₃
Assay/%	1.08	0.01	2.69	4.67	72.60	15.91
Element	MgO	TFe	MnO	P ₂ O ₅	S	
Assay/%	0.59	0.33	0.11	0.02	0.01	

Table 2. Size analysis of the raw ore.

Size Fraction/mm	Yield/%	Li ₂ O Grade/%	Li ₂ O Distribution/%
−8 + 6	5.15	2.16	10.26
−6 + 4	17.28	1.75	27.88
−4 + 2	13.64	1.19	14.97
−2 + 0.5	40.12	0.90	33.29
−0.5	23.80	0.62	13.60
Total	100.00	1.08	100.00

Table 1 shows that the Li₂O content in the ore is only 1.08%, demonstrating a low-grade lithium ore. The gangue mineral components are mainly SiO₂ and Al₂O₃, accounting for a total of 88.51%. The contents of K₂O and Na₂O are relatively high, reaching 4.67% and 2.69%, respectively. Table 2 reveals that Li₂O is predominantly distributed in the +0.5 mm size fraction, with yield and distribution rates of 76.20% and 86.40%, respectively.

Furthermore, the grade steadily increases with increasing particle size, indicating that the dissemination size of spodumene is rather coarse and thus suitable for DMS.

2.3. Heavy Liquid Separation Test

Heavy liquid separation or float-sink tests served as a diagnostic tool to assess the viability of a sample-to-gravity separation using DMS. It is conducted using a small portion of the sample and, if successful, can aid in determining the optimal S.G. cut-points for the DMS test and to benchmark the DMS performance. In this study, HLS tests were performed using LST heavy liquid, supplied by Central Chemical Consulting Pty Ltd., Australia. It is a concentrated solution of lithium heteropolytungstates in water and can reach a density up to 2.90 g/mL at 25 °C, and a density of 3.6 g/mL at elevated temperatures. In addition, it is less poisonous and has a lower viscosity than previous polytungstates like SPT.

The test was carried out with heavy liquid densities ranging from S.G. 2.50 to 2.85 in increments of S.G. 0.10, as per the flowsheet presented in Figure 2. The test started with about 2 kg of $-8 + 0.5$ mm feed material at the maximum liquid density of S.G. 2.85. A separatory funnel was employed to help separate heavy and light materials if necessary. Following the initial separation, the dense medium was diluted with deionized water to achieve lower target densities, and the floated material from the preceding step was re-tested at each reduced density level. This procedure was systematically repeated for all densities in the predefined series. To ensure consistency, the heavy liquid density was measured both before and after each test, verifying that the desired specific gravity was maintained throughout the process. All products underwent thorough rinsing with deionized water to eliminate residual heavy liquid, followed by drying under controlled conditions. The final sink-and-float fractions were then weighed and chemically analyzed to determine yield, grade, and lithium recovery under various S.G. cut-points. The HLS test was repeated three times, and the average results were represented.

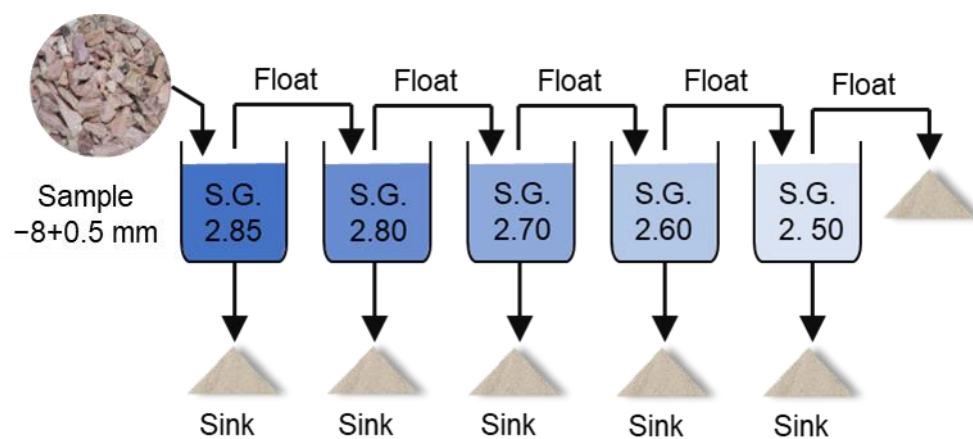


Figure 2. Heavy liquid separation testing procedure.

2.4. Numerical Simulation

2.4.1. Model Strategy

In a DMC, the ore-slurry mixture is fed tangentially into the cyclone. The centrifugal force pushes heavier particles to travel toward the wall and then downwards through the spigot (underflow). Meanwhile, lighter particles travel upwards through the vortex finder (overflow). Direct numerical solutions for gas-liquid-solid multiphase flows often face convergence challenges. Therefore, the study adopted a systematic modeling framework outlined in Figure 3 to progressively investigate ferrosilicon classification and ore separation dynamics in stages.

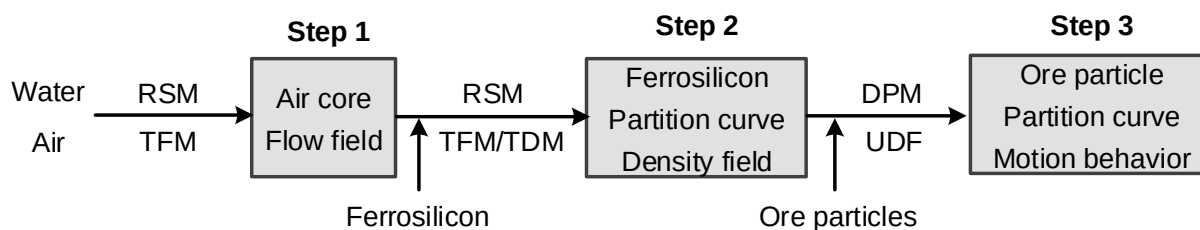


Figure 3. Modeling strategy used in this study.

Initially, the RSM-TFM model simulated a preliminary water-air two-phase flow field. Subsequently, ferrosilicon particles of varying sizes were introduced into the domain, and their spatial distribution was analyzed using the RSM-TFM model, thereby establishing the density field within the DMC. The turbulent dispersion model (TDM) was incorporated to quantify turbulence-induced particle redistribution. Finally, leveraging the time-averaged gas-liquid-solid flow solution, the LPT model tracked the trajectory of individual ore particles in the slurry and evaluated separation efficiency. More information regarding these models can be found in previous works on hydrocyclones [41,42] as well as in the Supplementary File.

2.4.2. Geometry and Mesh

The numerical tests primarily focus on a $\Phi 250$ mm DMC (cylinder diameter = 250 mm), which is the same as the laboratory equipment described in the next section. The geometry and computational mesh are shown in Figure 4.

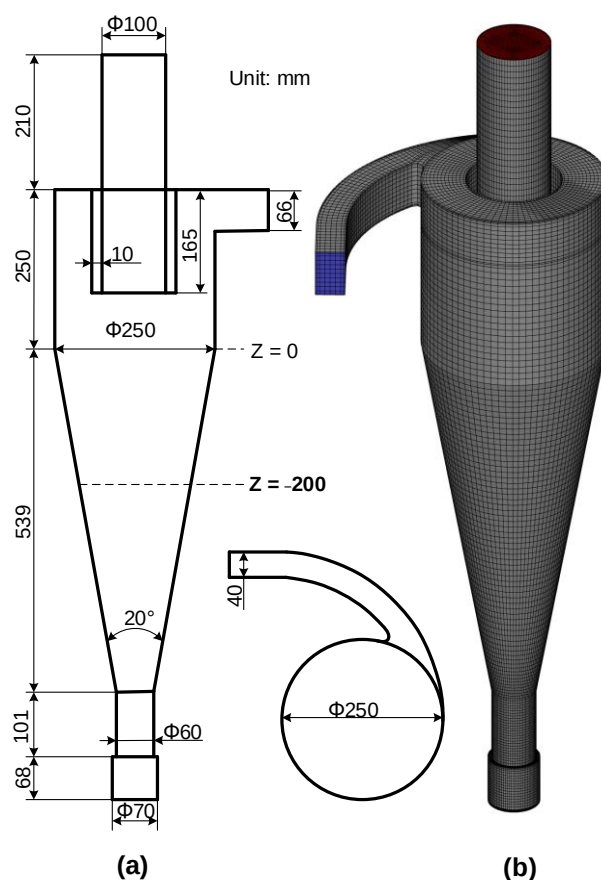


Figure 4. (a) Geometric parameters and (b) computational mesh of $\Phi 250$ mm DMC.

The grid type and resolution are key determinants of computational efficiency and accuracy in numerical simulations. To this end, the ICEM meshing tool was employed with

a multi-block O-grid meshing technique to generate high-quality hexahedral grids, with local refinement applied to the vortex finder's bottom and wall regions. This ensured that the first grid layer resided within the turbulent logarithmic region, maintaining Y^+ values between 30 and 300 for appropriate wall-function applicability.

Grid independence tests were conducted using grid counts of 100 k, 193 k, 410 k, and 830 k. Tangential and axial velocity profiles at the $Z = 0$ mm plane were used to evaluate the optimal grid configuration, with detailed results provided in Figure S1 in the Supplementary File. Analysis showed that beyond a grid count of ~400 k, further increases in grid density had minimal impact on solution convergence. Thus, the optimal grid count for the $\Phi 250$ mm DMC was established as 400 k, balancing computational efficiency and numerical precision.

2.4.3. Simulation Conditions

The dense medium used in the DMC is a suspension made of ferrosilicon particles and water. According to the separation principle of the DMC, the medium particles will settle and classify. Thus, the feed medium density is typically significantly lower than the final cut-point. Furthermore, this process is impacted by not only the structural and operational parameters but also the physical properties of dense medium particles. Based on earlier research, this study sorted out four primary factors, including aspect ratio (AR), inlet pressure (P), feed medium density (FMD), and ferrosilicon fineness (FF), as listed in Table 3. As a result, a total of 17 runs of numerical simulations were completed.

Table 3. Primary parameters of the DMS considered in the simulations.

Run	Factor	Symbol and Unit	Value
1–5	Aspect ratio	AR	0.4, 0.5, 0.6 *, 0.7, 0.8
6–9	Inlet pressure	P, MPa	0.1, 0.12, 0.14 *, 0.16, 0.18
10–13	Feed medium density	FMD, S.G.	1.8, 1.94 *, 2.0, 2.2, 2.4, 2.6
14–17	Ferrosilicon fineness	FF, $-45 \mu\text{m}$ content, %	95%, 90% *, 85%, 80%, 75%

Note that the asterisk (*) represents the default value of each factor.

For each test, a “velocity inlet” boundary condition was applied at the inlet, while “pressure outlet” conditions were specified for the two outflow boundaries. Inlet velocity was dynamically determined based on the inlet pressure parameters listed in Table 3. Static pressure at both outlets was set to 1 atm, mimicking ambient atmospheric conditions. The air backflow coefficient was adjusted to 1.0 to promote air core formation. Turbulence intensity at the outlets was generally set at 5% [42], and a “no-slip” condition was applied to all wall boundaries. These boundary specifications were consistently extended to the solid particle phases.

Analogous to experimental setups, the feed medium density was defined by introducing a specified volume fraction of ferrosilicon particles. The continuous particle size distribution (PSD) was segmented into discrete size fractions, each assigned to distinct phases within the computational domain. For instance, the 270D ferrosilicon sample with a density of 6900 kg/m^3 was divided into six fractions, as shown in Table 4. Each fraction was allocated to new phases with median particle sizes and respective volume fractions within each interval.

Numerical simulations were conducted using ANSYS Fluent 2018 software. A transient solver was used for simulations, and the SIMPLE (phase-coupled semi-implicit method for pressure-linked equations) algorithm was used to iteratively resolve pressure-velocity coupling in multiphase flow simulations. The equations of momentum, turbulent kinetic energy, turbulent dissipation rate, and Reynolds stress were discretized using the QUICK (quadratic upstream interpolation for convective kinematics) scheme. All simula-

tions used a fixed timestep of 5×10^{-4} s, which was chosen based on the calculation speed and Courant number. Converged results were produced in 20–30 s of physical time. The findings displayed here were averaged over the last three seconds of the simulation unless otherwise noted. The model validation part is provided in the Supplementary File as it was covered in detail in a previous study [52].

Table 4. Size distribution of 270D ferrosilicon used in numerical simulations.

Size Fraction/ μm	Mean Size/ μm	Yield/%	Cumulative Yield/%	Volume Fraction/%
–12.75	6.40	15.13	15.13	2.37
–21.25 + 12.75	17.00	24.32	39.45	3.81
–29.75 + 21.25	25.50	22.64	62.09	3.55
–38.25 + 29.75	34.00	17.01	79.10	2.67
–46.75 + 38.25	42.50	11.07	90.17	1.74
–85 + 46.75	65.90	9.83	100.00	1.54

2.5. Laboratory Experimental Work

This section details the laboratory test rig's construction, material properties, and operating conditions used in this study.

2.5.1. Test Rig

The physical experiments were designed and conducted in the laboratory of Weihai Haiwang Hydrocyclone Co., Ltd. (Weihai, China). Figure 5 illustrates the schematic diagram and implementation of the laboratory test rig, which consists of a measurement and control system, a feed system, and a separation system. A Kfj-80 centrifugal pump (made by Nanfang Pump Industry Co., Ltd., Hangzhou, China) regulates the feed flow rate, which is then measured by an MGG-50 magnetic flowmeter (provided by Azbil Corporation, Osaka, Japan). Feed pressure is monitored using a Y-100 pressure transmitter (provided by North Huaqing Instrument Co., Ltd., Tianjin, China). A custom-built 1200 L mechanical agitation tank integrated with a frequency converter is employed to prepare and stabilize the slurry mixture. An electric cabinet receives signals from each of these electronic components. A bypass pipe is installed on the main pipe to ensure pulp circulation and feed sampling. A $\Phi 250$ mm DMC with various accessories is integrated into the test platform.

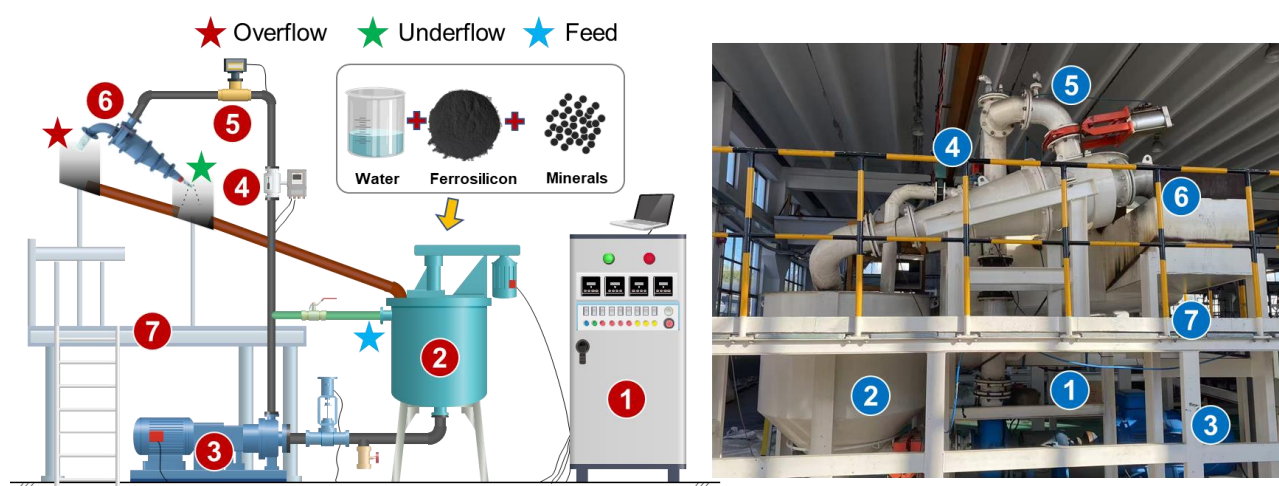


Figure 5. Schematic illustration and development of the laboratory test rig: 1—Electric cabinet; 2—Mixing tank; 3—Centrifugal pump; 4—Magnetic flowmeter; 5—Pressure transmitter; 6— $\Phi 250$ mm DMC; 7—Platform.

2.5.2. Properties of Dense Medium

For physical experiments, 270D ferrosilicon with a silicon composition of 14%–16% was employed. This grade has been validated by [26] to provide optimal corrosion resistance while maintaining particle density within acceptable limits. A combination of a DMA 4200M powder densimeter (provided by Anton Paar Company, Graz, Austria) and a Malvern 3000 laser diffractometer (provided by Malvern Panalytical, Malvern, UK) was utilized to characterize the material's density and particle size distribution, respectively. Measurement results revealed an average ferrosilicon density of 6900 kg/m^3 , with a measurement uncertainty of $\pm 15 \text{ kg/m}^3$. As depicted in Figure 6, the actual particle size distribution (PSD) of the 270D ferrosilicon used in tests exhibits a fineness of approximately 88%, with most particles within the 20–30 μm size fraction.

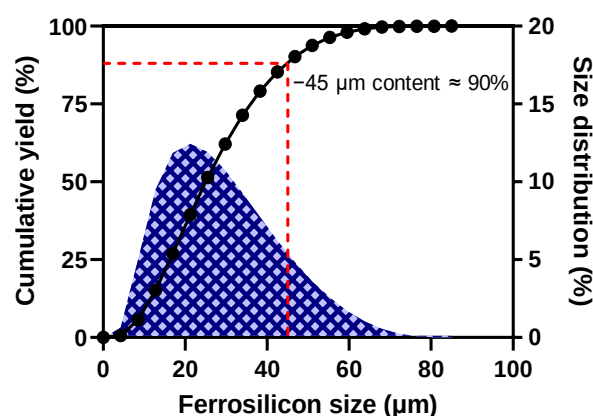


Figure 6. Particle size distribution of 270D ferrosilicon: the blue region denotes its probability density function and the dash line represents its cumulative distribution.

2.5.3. Test Procedure and Data Collection

According to the mineralogy of the Avatar spodumene ore and the results of HLS tests, two-stage separation tests under various FMDs, including lithium concentration and gangue rejection, were designed to guarantee the recovery of lithium and rejection rate of gangue minerals simultaneously. Based on the outcomes of the numerical simulation tests, physical separation tests were conducted to ascertain the ideal parameters for the two-stage DMS. A typical test procedure includes three stages:

(1) Material preparation

To create dense medium suspensions with the required densities, 400 L of tap water was first added to a stirring tank, and then a specific mass of 270D ferrosilicon powder, as indicated in Table 3. Following 10 min of vigorous stirring, the centrifugal pump was activated at a 30 Hz frequency, with the bypass line opened to facilitate additional mixing. Continuous recirculation routed all slurry flows back to the agitation tank, ensuring uniform feed properties throughout the process.

(2) Sampling

Gradually raise the pump frequency to get the desired feed pressure readings. When a quasi-steady state was reached, 10 kg of ore samples were added to the tank. After 10 min, samples from the underflow, overflow, and feed streams were taken with minimal time differences. Note that the sampling locations are shown in Figure 5. For each operating condition, three parallel tests were taken.

(3) Product processing

Each sample's wet mass was recorded before undergoing sequential filtration, drying, and gravimetric analysis to establish mass flux ratios. For ore separation experiments,

following dense medium recovery, the heavy product and light product were collected. Sample masses were measured to calculate the tailings rejection rate, quantifying the separation efficiency. A small portion (50–100 g) of the samples was further ground and assayed to determine the grade and recovery of lithium in the concentrate, middling, and tailings.

3. Results and Discussion

3.1. Heavy Liquid Separation Performance

HLS test was performed on 2 kg of $-0.5 + 8$ mm sample to evaluate the availability of DMS. Figure 7 shows both discrete and cumulative HLS results of sink samples in terms of yield, grade, and recovery. As shown in Figure 7a, the studied density range can be roughly divided into three intervals based on two critical densities at S.G. 2.7 and 2.85. As the S.G. of spodumene is 3.1–3.2, the Li_2O grade of the product at S.G. 2.85 is significantly higher than those of other density grades, reaching up to 5.90%. In contrast, the Li_2O grades of products in other density grades are all below 1.00%. Hence, Li_2O is predominantly distributed in sink products at S.G. 2.85, with a distribution rate of 86.42%, as shown in Figure 7b. It is indicated that the gravity-separation selectivity of this spodumene ore is favorable, making it relatively easy to obtain high-grade spodumene concentrate directly through DMS.

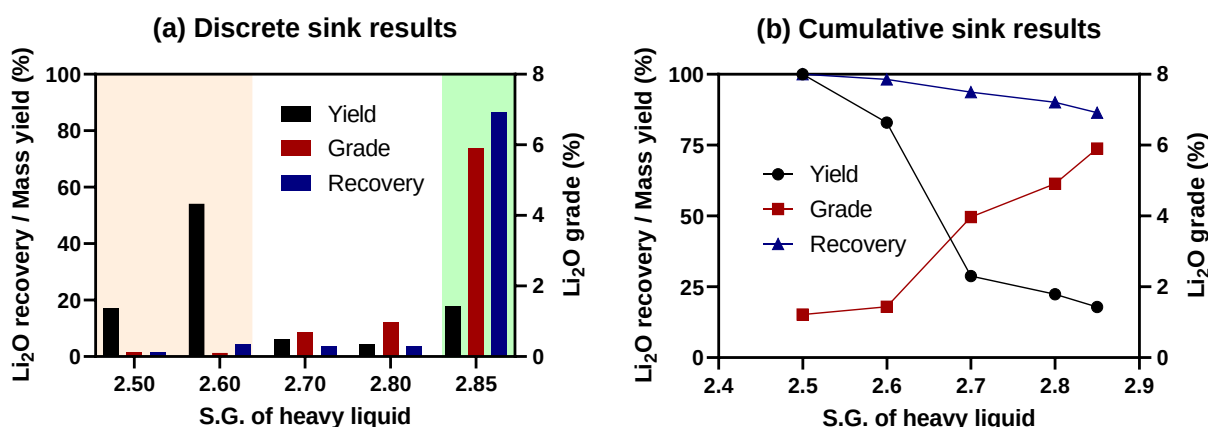


Figure 7. HLS results of sink samples: (a) discrete results and (b) cumulative results.

As the liquid S.G. drops, the Li_2O content in the ore gradually declines. The Li_2O grades of sink products at S.G. 2.70 and 2.60 are merely 0.13% and 0.10%, respectively, yet their yields are as high as 71.21% and 17.08%, respectively. The feasibility and value of tailings rejection during HLS of this spodumene ore are relatively high.

Inspired by the above results, the DMS process of this spodumene ore should consist of two-stage separations. In particular, the “concentrate collecting” operation takes place in the first stage, and the “tailings discarding” action takes place in the second. Moreover, the theoretical or suggested S.G. cut-points for the two stages can be set as 2.85 and 2.70, respectively.

3.2. Effect of Primary Factors on Medium Stability Obtained from CFD Tests

The movement dynamics of ore particles are governed by the density field properties, notably its density and homogeneity. From a theoretical perspective, a homogeneous dense medium is conducive to enhancing separation accuracy [53]. However, ferrosilicon particles undergo size-based separation within the DMC under the influence of centrifugal forces—finer particles accumulate in the overflow stream, while coarser fractions report to the underflow. According to CFD simulation results, Figures 8–12 depict the dynamic

stability of the dense medium as influenced by geometric aspect ratio, feed pressure, medium density, and ferrosilicon fineness. This was assessed by using partition curves and density differentials.

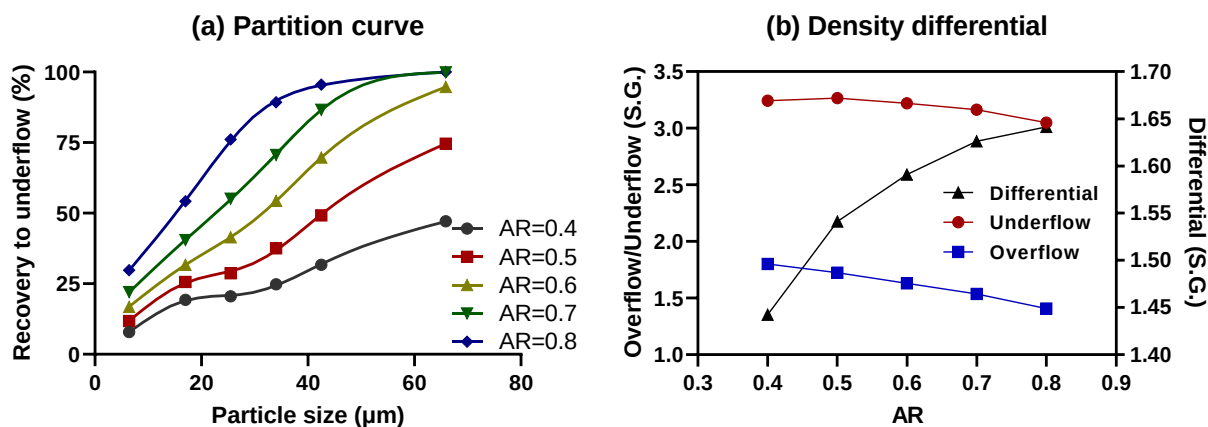


Figure 8. Effect of aspect ratio on dense medium stability obtained from CFD tests: (a) partition curve and (b) density differential.

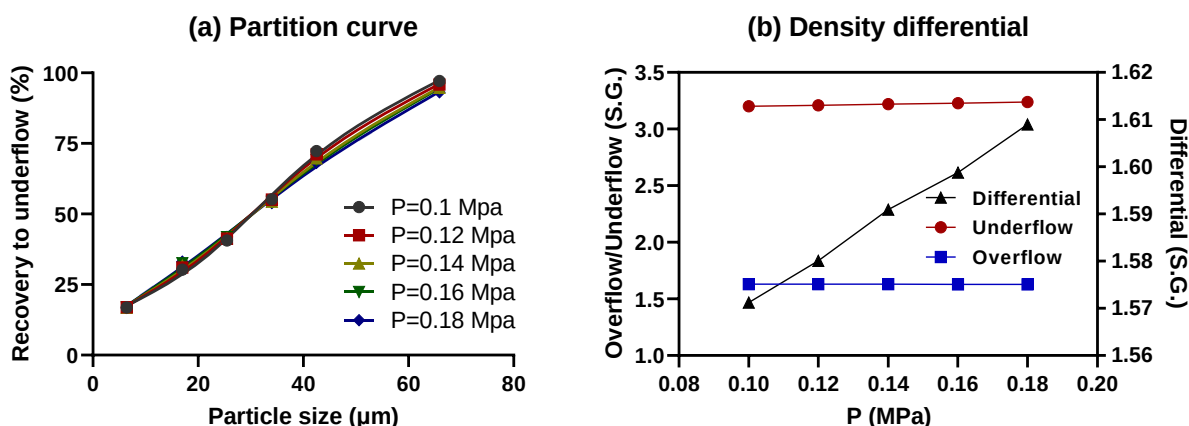


Figure 9. Effect of inlet pressure on dense medium stability obtained from CFD tests: (a) partition curve and (b) density differential.

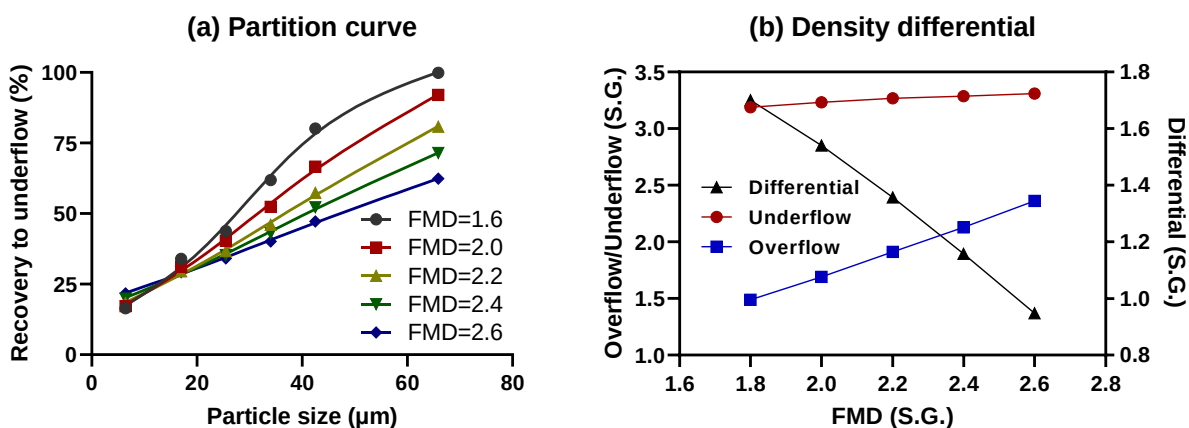


Figure 10. Effect of feed medium density on dense medium stability obtained from CFD tests: (a) partition curve and (b) density differential.

As shown in Figure 8, the underflow S.G. is about 3.0, while the overflow S.G. is around 1.5. As the aspect ratio gradually increases, the partition curve of ferrosilicon particles gradually moves to the upper left, indicating that more and more particles enter

the underflow, and the classification accuracy (seen from curve steepness) is also improved. The increase in aspect ratio will also increase the water split ratio to the underflow, which can be seen from the grade efficiency (close to water split) of the minimum particle size in Figure 8a. As a result, the densities of the underflow and overflow gradually decrease, but the differential S.G. between them gradually increases from 1.44 to 1.64. The distribution of ore particles in the sink and float products must also be considered when determining the aspect ratio in production practice.

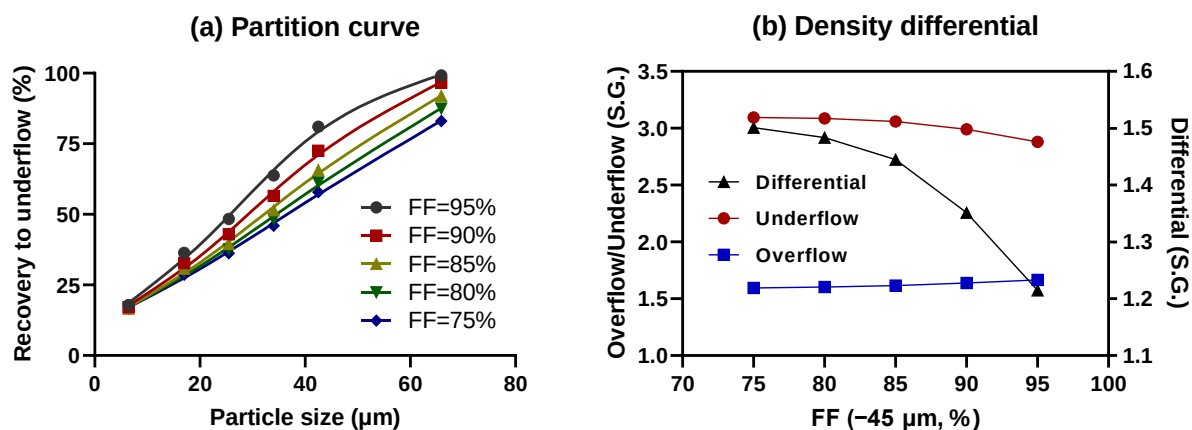


Figure 11. Effect of ferrosilicon fineness on dense medium stability obtained from CFD tests: (a) partition curve and (b) density differential.

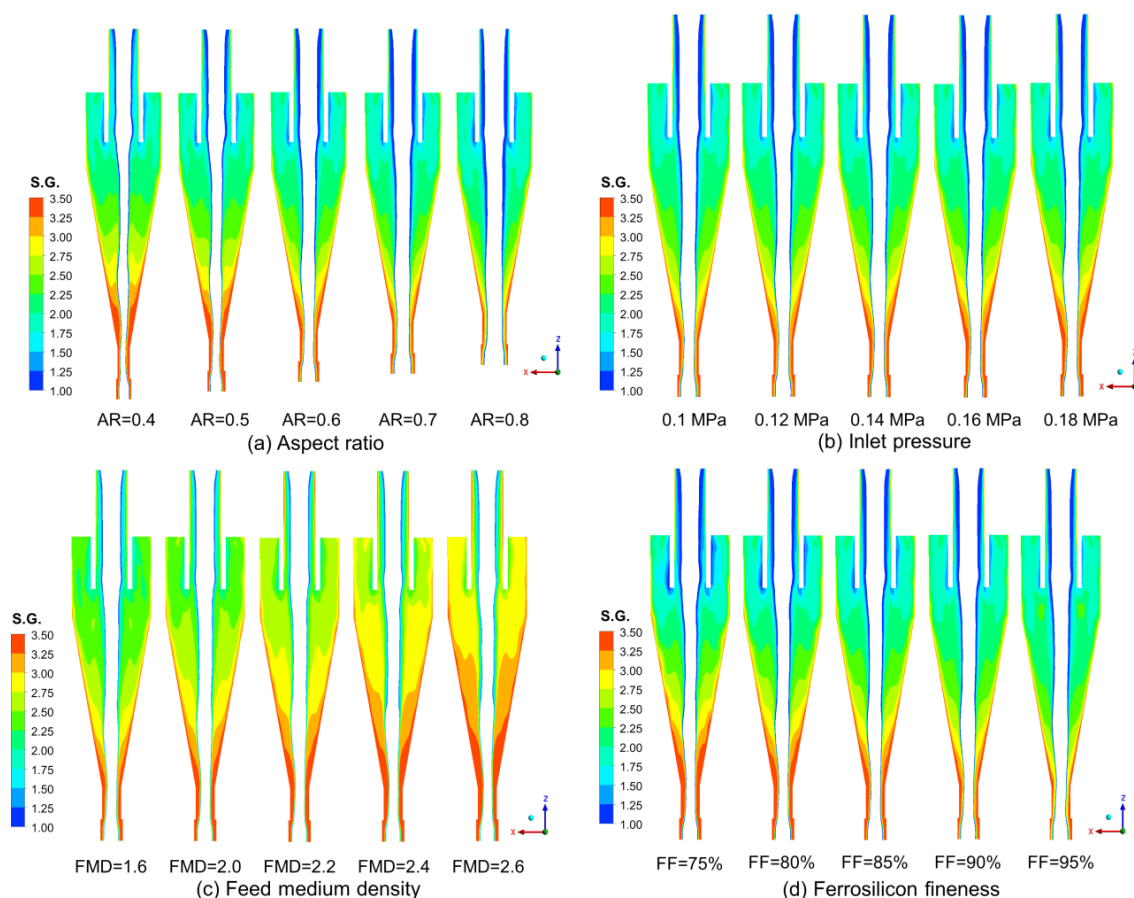


Figure 12. Effects of (a) aspect ratio, (b) inlet pressure, (c) feed medium density, and (d) ferrosilicon fineness on density field obtained from CFD tests.

Figure 9 shows that under the current feed medium density (S.G. = 1.94), the influence of feed pressure on the partition curve of ferrosilicon is negligible. Correspondingly, the changes in the medium density of overflow and underflow are also basically unchanged, although their differential increases from S.G. 1.57 to 1.61.

Figure 10 shows that as the feed medium S.G. increases, the partition curve of the ferrosilicon gradually tilts to the lower right. This indicates that an increasing number of ferrosilicon particles enter the overflow, reducing classification accuracy. The increase in feed medium density will cause a more noticeable crowding effect near the spigot, and the volume fraction of ferrosilicon gradually increases, but the water split ratio increases slightly, as can be seen from the efficiency of minimum particle size in Figure 10a. As a result, the densities of the underflow and overflow gradually increase, with the overflow increasing more rapidly. Therefore, the differential between them gradually reduces from S.G. 1.70 to 0.95.

Figure 11 illustrates the effect of ferrosilicon fineness on its classification behavior. As the fineness of ferrosilicon increases, the partition curve exhibits a leftward shift, signifying higher underflow recovery for each particle size fraction. This phenomenon is primarily attributed to reduced coarse particle content in finer ferrosilicon, which alleviates congestion at the spigot and facilitates coarse particle passage into the bottom stream. However, this does not directly translate to a higher overall ferrosilicon yield in the underflow. The total yield is contingent not only on the grade efficiency of individual size classes but also on the material's particle size distribution (PSD), as described by the following equation:

$$\gamma_u = \sum_{i=0}^n G_i \times \gamma_{f,i} \quad (1)$$

where G_i and $\gamma_{f,i}$ denote the grade efficiency of each size ferrosilicon and its yield in the feed. As shown in Figure 11b, the underflow density gradually decreases, while the overflow density increases as the ferrosilicon fineness increases. Therefore, the differential between the two products gradually narrows, and the effect becomes more noticeable as fine particle content increases. This shows that the finer the ferrosilicon particles are, the better the stability and homogeneity of the medium are, which is consistent with the literature [24,53]. However, it does not imply that the ore separation effect is better, as an increase in fine particle content will significantly increase the medium viscosity.

To express the influence of various factors on the medium stability more vividly, Figure 12 depicts the density field distribution on the X-Z plane. The medium density in the cylindrical section is close to that of the feed. Under the action of centrifugal force, ferrosilicon particles begin to settle toward the wall, and the maximum density is near the lower part of the cone and the spigot. The iso-density lines have varying shapes depending on the parameter conditions. Except for feed pressure, which has negligible influence, the other three parameters all influence the overall density field by influencing the accumulation condition of ferrosilicon particles at the spigot. In general, a higher cone angle ratio, a higher separation density, and finer ferrosilicon all improve the medium's stability and homogeneity, but they also affect separation density, which will be discussed in depth in the following section.

3.3. Effects of Primary Factors on Ore Separation Obtained from CFD Tests

After crushing, lithium and gangue minerals typically have densities of 2000–3200 kg/m³ and diameters ranging from 0.5 to 8 mm. LPT simulations were carried out by injecting and tracking particles of various S.G. and sizes. Each simulation was replicated three times, with 800 particles introduced per trial. Particles directed to the underflow stream were logged and

used to generate partition curves as functions of particle density and size. Figure 13 illustrates the partition curves derived under a feed specific gravity of 1.94.

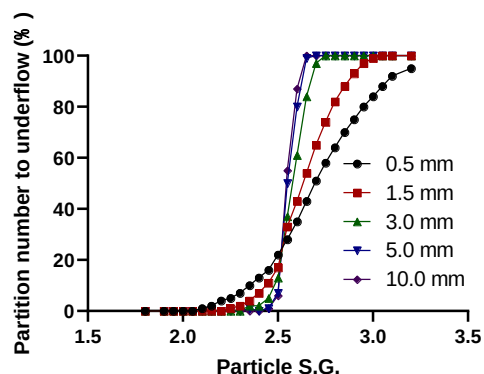


Figure 13. Partition curves as a function of particle size derived from CFD tests.

As depicted in Figure 13, the partition number exhibits a progressive rise with increasing particle density across all ore size fractions. The cut-point decreases markedly with growing particle size, indicating that larger particles enhance separation precision. The simulated results successfully capture the pivot phenomenon, where partition curves for different ore sizes intersect at a common point. Predicted pivot parameters show minor deviations from the feed medium's specific gravity, a behavior well-documented in high-density dense medium separation (DMS) systems [54].

It is possible but time-consuming to investigate the interaction of the four factors and ore sizes. Hence, this study focuses on the separation behavior of 3 mm particles as an example. Figure 14 shows the individual effect of these factors on the ore partition curves. Overall, the separation effect is in excellent accordance with the variation of the distribution characteristics within the density field.

The cut-point gradually decreases as the aspect ratio grows; however, the cut precision improves as the aspect ratio ranges from 0.4 to 0.6. The two fluctuations correlate to the drop in underflow density and the density difference, as seen in Figure 8. This implies that an excessively large aspect ratio will considerably lower separation density, necessitating a greater feed medium density to satisfy the original specifications. An overly tiny aspect ratio produces a huge density differential, diminishing separation sharpness.

Given that the feed pressure exerts a minor influence on the medium stability and density field, its impact on the separation effect is also limited. The cut-point progressively rises with the slow increase in the underflow density, whereas the separation sharpness slightly drops with the increase in the density difference. The results indicate that the inlet pressure is more suitable for fine-tuning the cut density.

It is expected that a higher feed medium density leads to a higher cut density. Although the density differential gradually decreases (see Figure 10), the separation sharpness is reduced with the elevation of the separation density. This is because the separation sharpness of the DMC is related not only to the density difference but also to the overall medium viscosity. An increase in the feed medium density will augment the medium viscosity throughout the entire separation space, thereby resulting in a reduction in separation precision. In the actual separation process, the cut-point is affected by the ore-to-medium ratio in addition to the feed medium density [44,45,55]. Therefore, physical experiments are usually required to optimise this value.

As ferrosilicon fineness increases, the cut-point initially demonstrates a gradual decline followed by a more rapid decrease, while separation sharpness exhibits a trend of increasing up to 85% fineness before declining. An analysis of Figures 11, 12 and 14 reveals a strong correlation between the cut-point and density field distribution. This indicates that a homoge-

nous density field formed by finer ferrosilicon enhances high-precision separation, whereas a pronounced density gradient from coarser ferrosilicon enables high-density separation even at lower feed densities. It is important to note, however, that the latter effect diminishes gradually and significantly impairs the separation efficiency of fine ore particles. Additionally, excessive ferrosilicon fineness increases the apparent viscosity of the dense medium, elevating flow resistance and inevitably reducing separation sharpness—an effect more pronounced for finer particles. Consequently, 270D ferrosilicon with 90% – 45 μm content remained a relatively optimal choice for subsequent investigations.

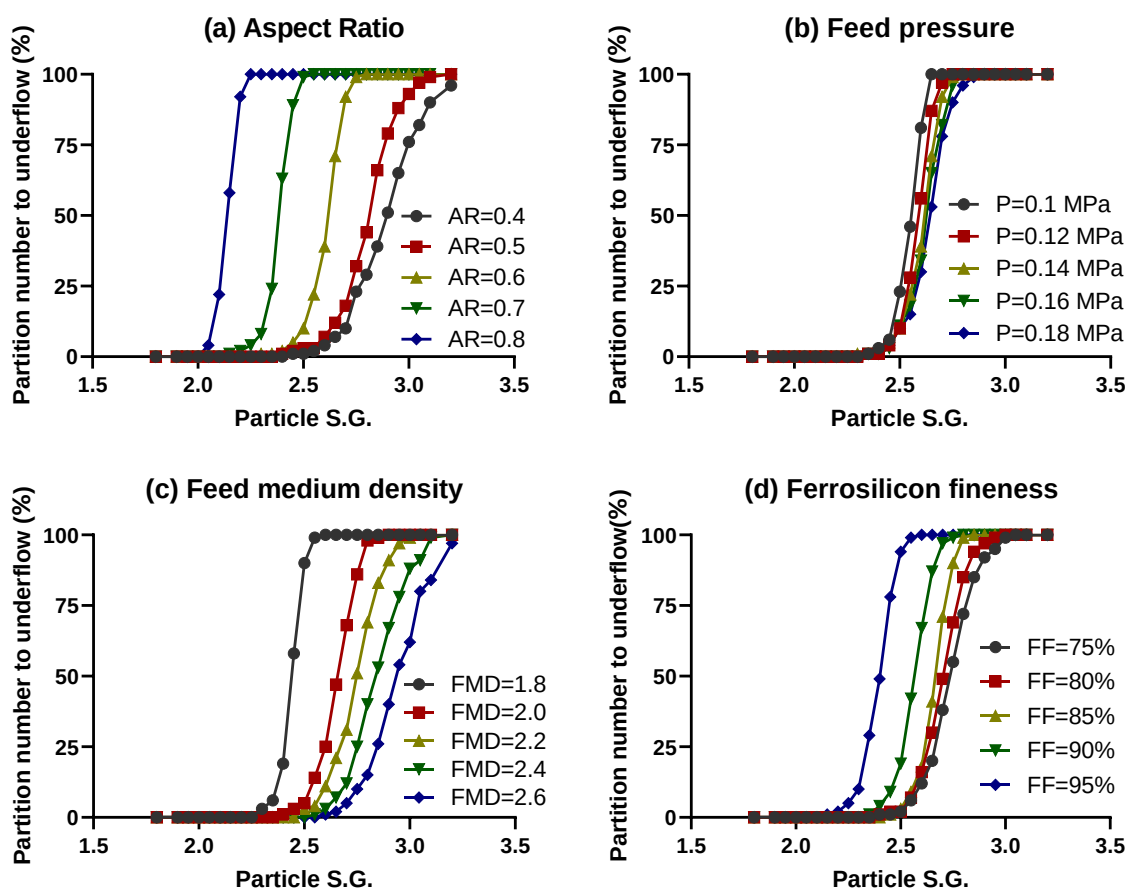


Figure 14. Effects of (a) aspect ratio, (b) inlet pressure, (c) feed medium density, and (d) ferrosilicon fineness on ore partition curves obtained from CFD tests.

Based on the above analyses, the aspect ratio and feed medium density are the main factors controlling the cut-point and must be first determined. Meanwhile, due to the classification effect of ferrosilicon, the cut-point is always larger than the S.G. of the feed medium. Hence, an “offset” is inevitable for DMC separation. Figure 15 shows the effects of aspect ratio and feed medium density on cut-points and offsets. Under a fixed feed medium S.G. at 1.94, both the cut-point and offset decrease with increasing aspect ratio. The offset can vary from 0.96 to 0.20. This indicates that a higher cut-point can also be achieved with a smaller cone-angle ratio and a lower feed medium density. When the aspect ratio is set to 0.6, the cut-point increases, and the offset gradually decreases as feed medium density increases. This suggested that to obtain a higher cut-point, the benefit of simply increasing the feed medium density becomes less significant. Hence, matching aspect ratio and feed medium density remains a difficult blend of art and science that must ultimately be decided through physical testing.

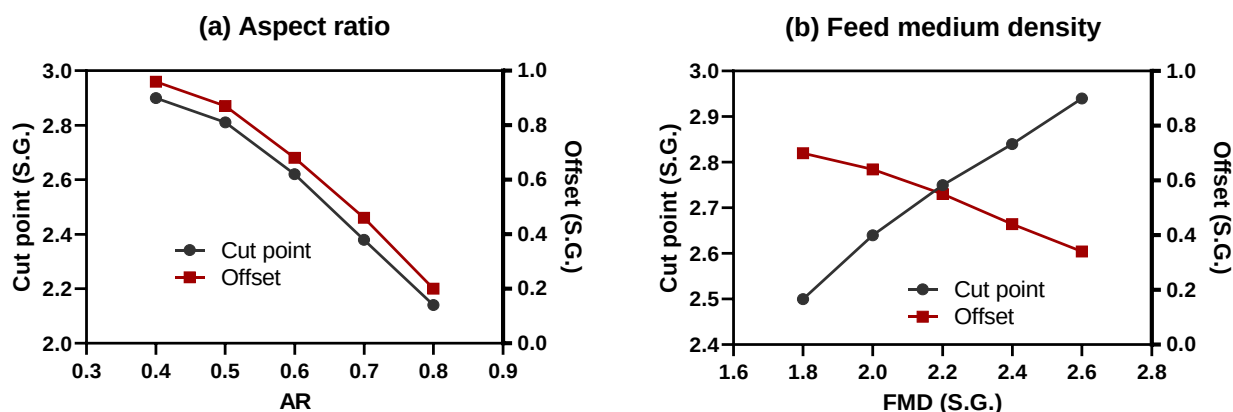


Figure 15. Effects of (a) aspect ratio and (b) feed medium density on cut-points and offsets obtained from CFD tests.

3.4. Laboratory DMC Physical Tests

Guided by the results of HLS and numerical simulation, laboratory physical tests were conducted to optimize parameters for achieving optimal cut-points of S.G. 2.85 for the first stage and S.G. 2.70 for the second stage.

3.4.1. First-Stage DMS Tests

The first-stage separation is a high-density separation, and the theoretical yield of spodumene concentrate is relatively low. Therefore, in this paper, a reduced aspect ratio (0.55) combined with an appropriate feed medium density was more practical. An appropriate range of feed medium density can be determined as S.G. 2.2–2.5 according to Figure 15. The effect of feed medium density on physical separation is shown in Figure 16.

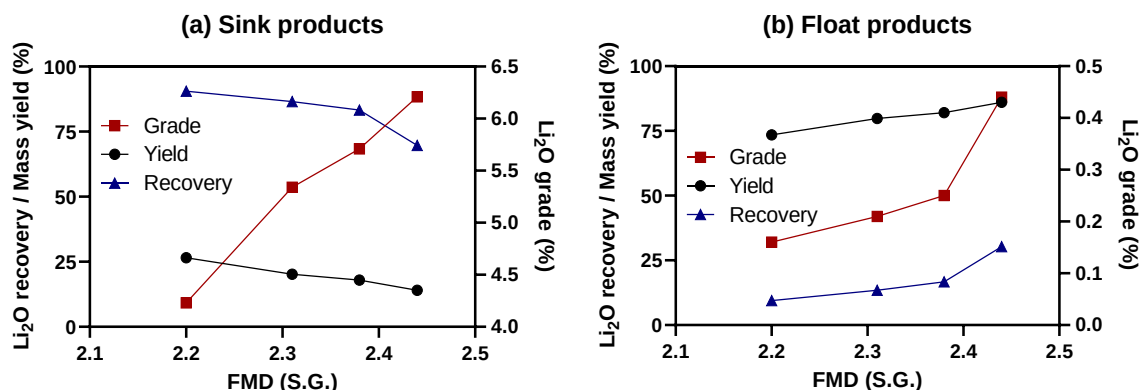


Figure 16. First-stage DMS results: (a) sink products and (b) float products.

As can be seen from Figure 16, the feed medium density has a significant impact on the concentration of spodumene. With the increase in feed medium density, more intergrown particles of spodumene and gangue minerals in the intermediate density grade entered the overflow and thus became tailings. As a result, the Li₂O grade of the first-stage sink product gradually increased, while its operating yield and Li₂O recovery continuously decreased. When the feed S.G. was 2.38, the Li₂O grade of the sink product was 5.71%, meeting the requirement of chemical-2 grade (>5.50%) [56]. Its operating yield and Li₂O recovery were 17.92% and 83.30%, respectively. On the other hand, the Li₂O grade of the tailings in the first stage was 0.25%, indicating potential for recovery.

3.4.2. Second-Stage DMS Tests

The second-stage DMS aims to improve overall lithium recovery while removing as much monomer-liberated waste rock as possible. Before selecting the aspect ratio and feed medium density of the second-stage DMC, a heavy liquid test was performed on the first-stage tailings, as illustrated in Figure 17. It can be seen from Figure 17a that the S.G. of gangue minerals is mainly located between 2.50 and 2.70. In addition, there were some high-grade particles with a yield of 6% existing in the first-stage float product, demonstrating the imperfect separation of DMC. However, these particles can be easily recovered in this stage by setting a low cut-point. Figure 17b indicates that an appropriate cut-point should be set at 2.65, when the sink product's yield, grade, and recovery were 14.14%, 0.44%, and 77.73%, respectively.

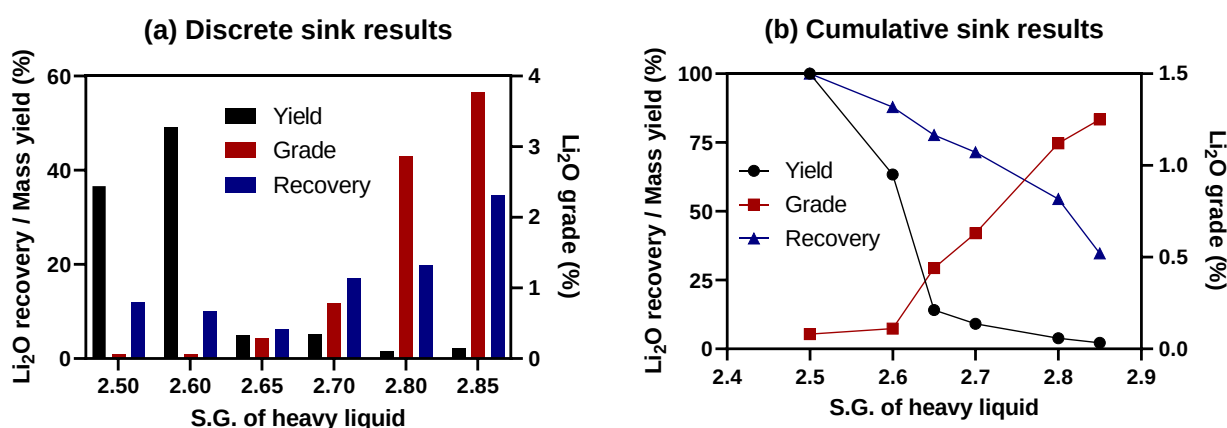


Figure 17. HLS of first-stage sink product: (a) discrete results and (b) cumulative results.

The separation sharpness in the second stage is more crucial for the final lithium loss. Therefore, a larger aspect ratio (0.65) combined with an appropriate feed medium density was adopted. According to Figure 15, the cut-point was 2.66 when the aspect ratio was 0.6 at feed S.G. 2.00. Hence, fine-tuning of the feed medium density was conducted, with results shown in Figure 18.

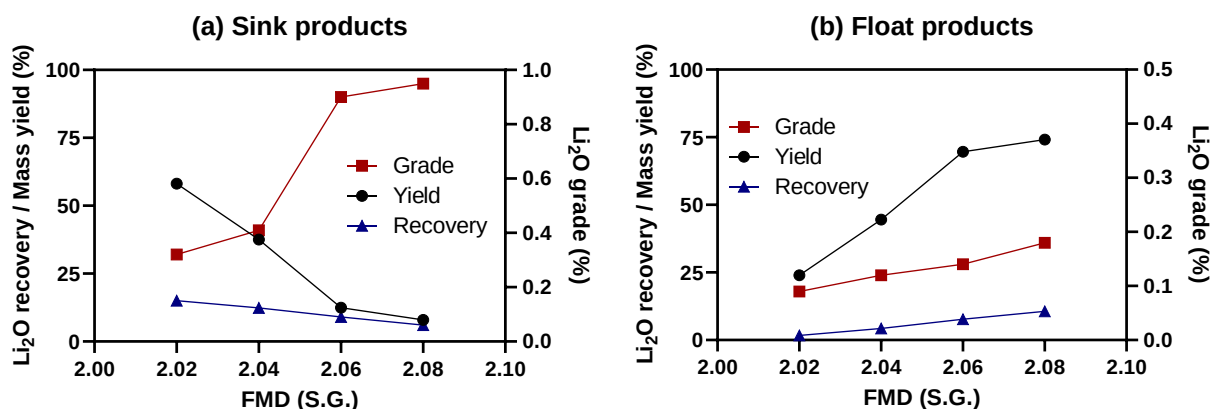


Figure 18. Second-stage DMS results: (a) sink products and (b) float products.

As shown in Figure 18, as the feed medium density increases, the Li_2O grade of the second-stage sink product gradually rises with a decreasing recovery. When the feed S.G. was 2.06, there was an obvious increase in both the Li_2O grade of the sink product and the discarding rate of the float product. Under these conditions, the Li_2O grade and recovery of the sink product were 0.90% and 9.23%, respectively. This meets the flotation feed requirements of spodumene. Meanwhile, a qualified float product with a Li_2O grade of

0.13% (<0.15%) can be rejected. The operating waste-discarding rate was close to 70.00%, and its loss rate was only 7.48%, indicating a remarkable waste-discarding effect.

3.4.3. Continuous Two-Stage DMS

Based on the results of “lithium concentrating” and “waste discarding” tests, a continuous separation test of low-grade spodumene ore (500 kg) was carried out according to the two-stage DMS flowsheet shown in Figure 19. The feed S.G. for the two stages was set to 2.38 and 2.08, respectively. The separation results are shown in Table 5.

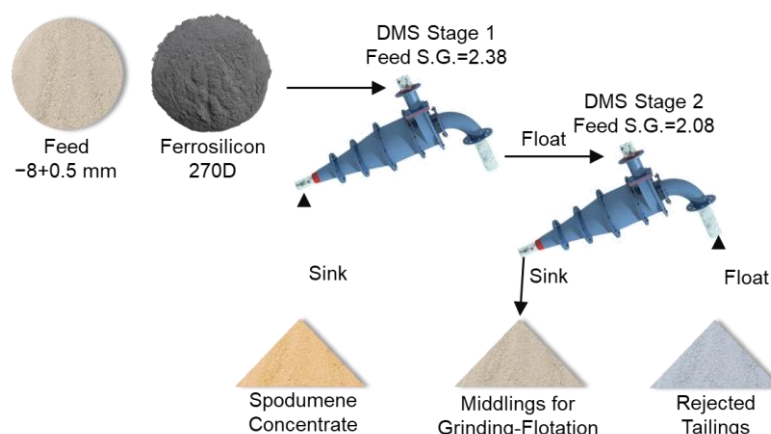


Figure 19. Continuous two-stage DMS circuit flowsheet.

Table 5. Results of continuous two-stage DMS.

Products	Yield/%	Li ₂ O Grade/%	TFe/%	Li ₂ O Recovery/%
Concentrate	17.88	5.68	0.43	83.60
Middling	12.66	0.86	0.31	8.96
Tailings	69.46	0.13	0.15	7.44
Feed	100.00	1.21	0.25	100.00

Table 5 indicates that the Li₂O grade of spodumene concentrate obtained by the continuous two-stage DMS was 5.68%, which reached chemical-2 grade according to YS/T 261-2011 [56]. The concentration yield from continuous DMS was just close to that of HLS, while the Li₂O recovery was as high as 83.60%, demonstrating an excellent performance of two-stage DMS. The waste discarding rate was nearly 70% with a Li₂O loss of 7.44%. In addition, only 12.66% of middlings with an average Li₂O grade of 0.86% were produced and subjected to the subsequent grinding-flotation circuit. Therefore, for this type of low-grade spodumene mine, the DMS technology, along with the above flowsheet, not only can produce a qualified spodumene concentrate but also discard most of the tailings in advance. One can expect that the overall beneficiation costs, including grinding, flotation, and tailings treatment, will be greatly reduced, promoting the long-term development of low-grade spodumene mines.

Before referencing these parameters for industrial applications, one should know that the above separation indicators were obtained under the condition of a relatively large medium-to-ore ratio (about 20:1) and relatively stable working conditions in the laboratory. At the production site, indicators such as the comprehensive concentrate yield and recovery may be reduced to some extent, subject to the performance of the density control system, and fluctuations in feed properties.

4. Conclusions

This study examines the feasibility of DMS technology for low-grade spodumene using HLS tests, numerical simulations, and laboratory experiments. A two-stage DMS process is proposed to produce qualified spodumene concentrate while simultaneously rejecting most of the gangue minerals. The main findings can be summarized as follows:

(1) A low-grade spodumene mine in Nigeria has a Li_2O grade of 1.08%. The target mineral is predominantly spodumene, whereas the gangue minerals consist of quartz and feldspar. The Li element in the sample is mainly distributed in the +0.5 mm size fraction with a rate of 86.4%. Heavy liquid separation tests have demonstrated that the fraction with a S.G. >2.85 achieved a Li_2O recovery of 86.42%, while another fraction with a S.G. <2.7 had a yield of 71.21%.

(2) The numerical test method (RSM-TFM-TDM) can predict the medium-grading behavior and density field within the DMC, and the LPT model can be utilized to forecast the ore-separation performance. All factors modified the density field by influencing the spatial distribution of ferrosilicon particles of varying sizes, particularly near the cone and spigot, thereby further influencing the ore separation process. Within the studied range of factors, the density difference between the overflow and underflow typically ranged from S.G. 1.0 to 1.6, the cut-point lay between S.G. 2.20 and 2.95, and the offset was within S.G. 0.2~0.95. An increase in the aspect ratio reduced the density, cut-point, and offset. The feed pressure showed a negligible impact on these indexes. An increase in the feed medium density boosted the underflow density but reduced the density differential, causing the cut-point to rise as the offset decreases. An increase in the ferrosilicon fineness minimized density differentials and cut-points. However, increasing the medium viscosity will reduce the separation sharpness. For this sort of mine, the ideal medium fineness was 270D, and the aspect ratio and feed medium density should be chosen based on the expected cut-points in each stage.

(3) In the “concentrate collection” DMS test, when the feed medium density was S.G. 2.38, a qualified spodumene concentrate with Li_2O grade of 5.71%, yield of 17.92%, and Li_2O recovery of 83.30% was produced. In the “tailings discarding” test, the optimal feed medium density was S.G. 1.86, and the waste discarding effect is remarkable. The sink product meets flotation standards with a grade and Li_2O recovery of 0.90% and 9.23%, respectively. The tailings had a Li_2O grade of only 0.13%, with a discarding rate close to 70.00% and a Li_2O loss of 7.44%.

(4) For this type of low-grade spodumene mine, adopting the two-stage DMS flowsheet can result in qualifying spodumene concentrate products prior to the grinding operation, while the majority of gangue minerals can be discarded to tailings in advance. This technology has the potential to significantly cut beneficiation expenses such as grinding, flotation, and tailings treatment, boost enterprise economic benefits, and effectively promote the long-term growth of Nigerian mines.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/min15050434/s1>, Figure S1: Grid-independence tests on the $\Phi 250$ mm DMC: (a) tangential velocity and (b) axial velocity; Figure S2: Water-air system validation: (a) pressure drop and (b) R_f ; Table S1: Laboratory test scheme and results; Table S2: Comparison of measured and predicted separation performance. References [29,41,42,57–65] are cited in the Supplementary Materials.

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References

1. Moss, R.; Tzimas, E.; Kara, H.; Willis, P.; Kooroshy, J. *Critical Metals in Strategic Energy Technologies*; Publications Office of the European Union: Luxembourg, 2011.
2. Gu, S.; Zhang, L.; Fu, B.; Wang, X.; Ahn, J.W. Feasible route for the recovery of strategic metals from mixed lithium-ion batteries cathode materials by precipitation and carbonation. *Chem. Eng. J.* **2021**, *420*, 127561. [CrossRef]
3. Dorn, F.M.; Peyré, F.R. Lithium as a Strategic Resource. *J. Lat. Am. Geogr.* **2020**, *19*, 68–90. [CrossRef]
4. Liu, J.; Zhang, Y.; Zhou, J.; Wang, Z.; Zhu, P.; Cao, Y.; Zheng, Y.; Zhou, X.; Yan, C.; Qian, T. Advances and prospects in improving the utilization efficiency of lithium for high energy density lithium batteries. *Adv. Funct. Mater.* **2023**, *33*, 2302055. [CrossRef]
5. Jaskula, B. *Lithium Statistics and Information*; United States Geological Survey: Reston, VA, USA, 2024. Available online: <https://pubs.usgs.gov/periodicals/mcs2024/mcs2024-lithium.pdf> (accessed on 1 February 2025).
6. Seefurth, R.N.; Sharma, R.A. Investigation of lithium utilization from a lithium-silicon electrode. *J. Electrochem. Soc.* **1977**, *124*, 1207. [CrossRef]
7. Tadesse, B.; Makuei, F.; Albijanic, B.; Dyer, L. The beneficiation of lithium minerals from hard rock ores: A review. *Miner. Eng.* **2019**, *131*, 170–184. [CrossRef]
8. Xie, R.; Zhao, Z.; Tong, X.; Xie, X.; Song, Q.; Fan, P. Review of the research on the development and utilization of clay-type lithium resources. *Particuology* **2024**, *87*, 46–53. [CrossRef]
9. Kesler, S.E.; Gruber, P.W.; Medina, P.A.; Keoleian, G.A.; Everson, M.P.; Wallington, T.J. Global lithium resources: Relative importance of pegmatite, brine and other deposits. *Ore Geol. Rev.* **2012**, *48*, 55–69. [CrossRef]
10. Howell, R.J.; Lagos, L.; de los Hoyos, C.R.; Declercq, J. Classification and characteristics of natural lithium resources. *Elements* **2020**, *16*, 259–264. [CrossRef]
11. Gourcerol, B.; Gloaguen, E.; Melleton, J.; Tuduri, J.; Galiege, X. Re-assessing the European lithium resource potential—A review of hard-rock resources and metallogeny. *Ore Geol. Rev.* **2019**, *109*, 494–519. [CrossRef]
12. Sahoo, S.K.; Tripathy, S.K.; Nayak, A.; Hembrom, K.C.; Dey, S.; Rath, R.K.; Mohanta, M.K. Beneficiation of lithium bearing pegmatite rock: A review. *Miner. Process. Extr. Metall. Rev.* **2024**, *45*, 1–27. [CrossRef]
13. Kundu, T.; Rath, S.S.; Das, S.K.; Parhi, P.K.; Angadi, S.I. Recovery of lithium from spodumene-bearing pegmatites: A comprehensive review on geological reserves, beneficiation, and extraction. *Powder Technol.* **2023**, *415*, 118142. [CrossRef]
14. Oliazadeh, M.; Aghamirian, M.; Ali, S.; Legault, E.; Gibson, C. Flowsheet development for beneficiation of lithium minerals from hard rock deposits. In *Extraction 2018, Proceedings of the First Global Conference on Extractive Metallurgy*; Springer: Cham, Switzerland, 2018; pp. 2293–2307.
15. Legault-Seguin, E.; Mohns, C.; Rylatt, M.; Lakefield, O. Dense Medium Separation—An Effective and Robust Preconcentration Technology. In *Proceedings of the 48th Annual Canadian Mineral Processors Operators Conference*, Ottawa, ON, Canada, 19–21 January 2016; pp. 19–21.
16. Xie, R.; Zhu, Y.; Liu, J.; Li, Y.; Wang, X.; Shumin, Z. Research status of spodumene flotation: A review. *Miner. Process. Extr. Metall. Rev.* **2021**, *42*, 321–334. [CrossRef]
17. Leißner, T.; Bachmann, K.; Gutzmer, J.; Peuker, U.A. MLA-based partition curves for magnetic separation. *Miner. Eng.* **2016**, *94*, 94–103. [CrossRef]
18. Gibson, C.E.; Aghamirian, M.; Grammatikopoulos, T.; Smith, D.L.; Bottomer, L. The recovery and concentration of spodumene using dense media separation. *Minerals* **2021**, *11*, 649. [CrossRef]
19. Munson, G.A.; Clarke, F.F. Mining and concentrating spodumene in the Black Hills, South Dakota. *AIIME Trans.* **1955**, *202*, 1041.
20. Redeker, I.H. Concentration of spodumene from North Carolina pegmatite ores. In *Proceedings of the SME Fall Meeting and Exhibit*, St. Louis, MI, USA, 4 January 1979; pp. 11–13.
21. Amarante, M.; de Sousa, A.; Leite, M. Processing a spodumene ore to obtain lithium concentrates for addition to glass and ceramic bodies. *Miner. Eng.* **1999**, *12*, 433–436. [CrossRef]
22. Bradley, K.; Liu, J.; Anguelov, R.; Hadley, T. The beneficiation and metallurgical process for the production of mixed REE Product from the nechalacho deposit. In *Conference of Metallurgists*; Springer: Cham, Switzerland, 2022; pp. 681–698.

23. Ferrara, G. State-of-the-art and New developments in dense medium separation processes. In *Mineral Processing, Proceedings of a Conference Honouring Professor P. C. Kapur on His 60th Birthday, New Delhi, India*; Allied Publishers Ltd.: New Delhi, India, 1995; pp. 311–331.
24. He, Y.; Laskowski, J. Effect of dense medium properties on the separation performance of a dense medium cyclone. *Miner. Eng.* **1994**, *7*, 209–221. [\[CrossRef\]](#)
25. Scott, I.A.; Napier-Munn, T.J.; Timothy, J. A dense medium cyclone model for simulation. In Proceedings of the 4th Samancor Symposium on Dense Media Separation: Dense Media 90, Cairns, Australia, 22–23 February 1990.
26. Collins, B.; Napier-Munn, T.J.; Sciarone, M. The production, properties, and selection of ferrosilicon powders for heavy-medium separation. *J. South Afr. Inst. Min. Metall.* **1974**, *75*, 103–115.
27. Davis, J. A Study of Coal Washing Dense Medium Cyclones. Ph.D. Thesis, University of Queensland, Brisbane, Australia, 1987.
28. Wood, C.J. A Performance Model for Coal-Washing Dense Medium Cyclones. Ph.D. Thesis, University of Queensland, Brisbane, Australia, 1990.
29. Zhao, Q.; Cui, B.; Shen, Y.; Liu, W.; Zhao, S.; Feng, Y. Understanding the characteristics and functions of axial velocity fluctuation zone in hydrocyclones: Part 1 flow pattern. *Chem. Eng. Sci.* **2024**, *283*, 119368. [\[CrossRef\]](#)
30. Narasimha, M.; Brennan, M.; Holtham, P.N. A review of CFD modelling for performance predictions of hydrocyclone. *Eng. Appl. Comp. Fluid Mech.* **2007**, *1*, 109–125. [\[CrossRef\]](#)
31. Yao, Y.; Shang, M.; Huang, Z.; Zhou, T.; Zhang, M.; Yang, H.; Lyu, J. Effects of the inlet duct length on the performance of a dense medium cyclone: An experimental and numerical study. *Chem. Eng. Res. Des.* **2022**, *187*, 41–50. [\[CrossRef\]](#)
32. Tian, J.Y.; Ni, L.; Song, T.; Olson, J.; Zhao, J.N. An overview of operating parameters and conditions in hydrocyclones for enhanced separations. *Sep. Purif. Technol.* **2018**, *206*, 268–285. [\[CrossRef\]](#)
33. Ni, L.; Tian, J.Y.; Song, T.; Jong, Y.; Zhao, J.N. Optimizing geometric parameters in hydrocyclones for enhanced separations: A review and perspective. *Sep. Purif. Rev.* **2018**, *48*, 30–51. [\[CrossRef\]](#)
34. Vakamalla, T.R.; Mangadoddy, N. Numerical simulation of industrial hydrocyclones performance: Role of turbulence modelling. *Sep. Purif. Technol.* **2017**, *176*, 23–39. [\[CrossRef\]](#)
35. Vakamalla, T.R.; Mangadoddy, N. Rheology-based CFD modeling of magnetite medium segregation in a dense medium cyclone. *Powder Technol.* **2015**, *277*, 275–286. [\[CrossRef\]](#)
36. Vakamalla, T.R.; Mangadoddy, N. Comprehensive dense slurry CFD model for performance evaluation of industrial hydrocyclones. *Ind. Eng. Chem. Res.* **2021**, *60*, 12403–12418. [\[CrossRef\]](#)
37. Narasimha, M.; Brennan, M.S.; Holtham, P.N.; Napier-Munn, T.J. A comprehensive CFD model of dense medium cyclone performance. *Miner. Eng.* **2007**, *20*, 414–426. [\[CrossRef\]](#)
38. Kuang, S.B.; Qi, Z.; Yu, A.B.; Vince, A.; Barnett, G.D.; Barnett, P.J. CFD modeling and analysis of the multiphase flow and performance of dense medium cyclones. *Miner. Eng.* **2014**, *62*, 43–54. [\[CrossRef\]](#)
39. Dunglison, M.; Napier-Munn, T.; Shi, F. The rheology of ferrosilicon dense medium suspensions. *Miner. Process. Extr. Metall. Rev.* **2000**, *20*, 183–196. [\[CrossRef\]](#)
40. Bosman, J. The art and science of dense medium selection. *J. S. Afr. Inst. Min. Metall.* **2014**, *114*, 529–536.
41. Zhao, Q.; Cui, B.; Shen, Y.; Liu, W.; Zhao, S.; Feng, Y. Understanding the characteristics and functions of axial velocity fluctuation zone in hydrocyclones part 2 particle classification. *Chem. Eng. Sci.* **2024**, *284*, 119444. [\[CrossRef\]](#)
42. Zhao, Q.; Cui, B.; Ji, A.; Song, T.; Shen, Y. Experimental and numerical study of the effect of particle size distribution on hydrocyclone classification. *Adv. Powder Technol.* **2024**, *35*, 104398. [\[CrossRef\]](#)
43. Chu, K.W.; Chen, J.; Yu, A.B. Applicability of a coarse-grained CFD-DEM model on dense medium cyclone. *Miner. Eng.* **2016**, *90*, 43–54. [\[CrossRef\]](#)
44. Chen, J.; Chu, K.; Zou, R.; Yu, A.; Vince, A.; Barnett, G.; Barnett, P. Systematic study of effect of particle size distribution in a dense medium cyclone by Johnson's SB function. *Miner. Eng.* **2016**, *91*, 16–33. [\[CrossRef\]](#)
45. Chen, J.; Chu, K.; Zou, R.; Yu, A.B.; Vince, A.; Barnett, G.D.; Barnett, P.J. Systematic study of the effect of particle density distribution on the flow and performance of a dense medium cyclone. *Powder Technol.* **2017**, *314*, 510–523. [\[CrossRef\]](#)
46. Aketi, V.A.K.; Reddy, V.T.; Mangadoddy, N.; Raparla, S.K.; Kumar, R. Numerical simulation of near-gravity coal particle behavior in a dense medium cyclone using a mixture model coupled with a discrete phase model. *Int. J. Coal Prep. Util.* **2021**, *41*, 554–576. [\[CrossRef\]](#)
47. Narasimha, M.; Brennan, M.S.; Holtham, P.N.; Banerjee, P.K. Prediction of Magnetite Segregation and Coal Partitioning in Dense Medium Cyclone Using Computational Fluid Dynamics Technique. In *Computational Fluid Dynamics*; IntechOpen: London, UK, 2010.
48. Li, Z.; Chu, K.; Zhou, Z.; Feng, Y.; Wang, A. Prediction of medium-to-coal ratio effect in a dense medium cyclone by using both traditional and coarse-grained CFD-DEM models. *Particuology* **2022**, *68*, 44–56. [\[CrossRef\]](#)
49. Kumar, M.; Mangadoddy, N.; Banerjee, R.; Sreedhar, G.E.; Raparla, S.K.; Kumar, R. Hydrodynamic force analysis of magnetite medium inside dense medium cyclone using multiphase GPU parallelized ASM model. *Miner. Eng.* **2021**, *170*, 107061. [\[CrossRef\]](#)

50. Olade, M. Solid mineral deposits and mining in Nigeria: A sector in transitional change. *AJOSR* **2019**, *2*, 1–16.
51. Abdulfattah, F.; Bwala, M.D.; Alabi, O.O.; Sayyadi, M.G.; Hassan, S.B. Characterization and Beneficiation of Nigerian Lithium Ore: An Overview. In *TMS Annual Meeting & Exhibition*; Springer: Cham, Switzerland, 2023; pp. 239–246.
52. Wang, S.; Wang, J.; Qiu, G.; Shen, L. Effects of ferrosilicon fineness on the multiphase flow field and separation performance of dense medium cyclones for low-grade ores. *ACS Omega* **2024**, *9*, 50544–50560. [[CrossRef](#)]
53. Napier-Munn, T. The dense medium cyclone—Past, present and future. *Miner. Eng.* **2018**, *116*, 107–113. [[CrossRef](#)]
54. Scott, I.A.; Napier-Munn, T. A dense medium cyclone model based on the pivot phenomenon. *Trans. Inst. Min. Met. Sec. C* **1992**, *101*, 61–76.
55. Chu, K.W.; Chen, J.; Wang, B.; Yu, A.B.; Vince, A.; Barnett, G.D.; Barnett, P.J. Understand solids loading effects in a dense medium cyclone: Effect of particle size by a CFD-DEM method. *Powder Technol.* **2017**, *320*, 594–609. [[CrossRef](#)]
56. YS/T 261-2011; Non-Ferrous Metal Industry Standard of the People's Republic of China. Spodumene Concentrate. Ministry of Industry and Information Technology of the People's Republic of China: Beijing, China. Available online: <https://www.chinesestandard.net/PDF.aspx/YST261-2011> (accessed on 1 February 2025).
57. Gidaspow, D.; Bezburuah, R.; Ding, J. Hydrodynamics of circulating fluidized beds: Kinetic theory approach. In *Proceedings of the 7th International Conference on Fluidization*, Brisbane, Australia, 3–8 May 1992; pp. 75–82.
58. Schaeffer, D.G. Instability in the evolution equations describing incompressible granular flow. *J. Differ. Equ.* **1987**, *66*, 19–50. [[CrossRef](#)]
59. Lun, C.; Savage, S.B.; Jeffrey, D.; Chepurniy, N. Kinetic theories for granular flow: Inelastic particles in Couette flow and slightly inelastic particles in a general flowfield. *J. Fluid Mech.* **1984**, *140*, 223–256. [[CrossRef](#)]
60. Delgadillo, J.A.; Rajamani, R.K. A comparative study of three turbulence-closure models for the hydrocyclone problem. *Int. J. Miner. Process.* **2005**, *77*, 217–230. [[CrossRef](#)]
61. Kuang, S.B.; Chu, K.W.; Yu, A.B.; Vince, A. Numerical study of liquid-gas-solid flow in classifying hydrocyclones: Effect of feed solids concentration. *Miner. Eng.* **2012**, *31*, 17–31. [[CrossRef](#)]
62. Ghodrat, M.; Kuang, S.B.; Yu, A.B.; Vince, A.; Barnett, G.D.; Barnett, P.J. Numerical analysis of hydrocyclones with different vortex finder configurations. *Miner. Eng.* **2014**, *63*, 125–138. [[CrossRef](#)]
63. Schiller, L.; Naumann, Z. A drag coefficient correlation. *Zeit. Ver. Deutsch. Ing.* **1933**, *77*, 318–320.
64. Burns, A.D.; Frank, T.; Hamill, I.; Shi, J.M. The Favre averaged drag model for turbulent dispersion in Eulerian multi-phase flows. In *Proceedings of the 5th International Conference on Multiphase Flow*, Yokohama, Japan, 30 May 2004; pp. 1–17.
65. Haider, A.; Levenspiel, O. Drag coefficient and terminal velocity of spherical and nonspherical particles. *Powder Technol.* **1989**, *58*, 63–70. [[CrossRef](#)]

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