minerals

MDPI

Article

Dense Medium Cyclone Separation of Fine Coal: A Discussion on the Separation Lower Limit

Chao Ni [1,2], Guangqian Xu [3], Jing Chang [4] and Bo Liu [5,*]

[1] Key Laboratory of Coal Processing and Efficient Utilization (Ministry of Education), China University of Mining & Technology, Xuzhou 221116, China
[2] School of Chemical Engineering and Technology, China University of Mining & Technology, Xuzhou 221116, China
[3] Shandong Energy Xinwen Mining Group Co., Ltd., Tai'an 271000, China
[4] College of Chemistry and Chemical Engineering, Xi'an University of Science and Technology, Yanta Middle Road No. 58 (Jin Saga It Mall), Xi'an 710054, China
[5] Department of Mechanical and Power Engineering, East China University of Science and Technology, No. 130 Meilong Road, Lingyunlu Street, Xuhui District, Shanghai 200237, China
* Correspondence: boliu@ecust.edu.cn

Abstract: The separation of fine coal has been widely discussed in the coal preparation industry due to its high economic potential. Dense medium cyclone (DMC) is the most efficient equipment available for fine coal separation. However, the industrial application of DMC is far from satisfactory due to operational difficulties and maintenance. In this research, particle settling behavior in a dense medium cyclone was analyzed for improved separation. The calculation result about feed pressure and separation lower limit, which fits the experimental data well, might be a guidance for industrial DMC design and operation. According to the calculation result, it is highly recommended that the separation lower limit be set at 0.2 mm rather than 0.1 mm, because the feed pressure head required for the latter (50 D) is three times higher than the former (15 D).

Keywords: dense medium cyclone; fine coal; separation lower limit

check for updates

Citation: Ni, C.; Xu, G.; Chang, J.; Liu, B. Dense Medium Cyclone Separation of Fine Coal: A Discussion on the Separation Lower Limit. *Minerals* **2023**, *13*, 1115. https://doi.org/10.3390/min13091115

Academic Editor: Carlos Hoffmann Sampaio

Received: 2 August 2023
Revised: 17 August 2023
Accepted: 21 August 2023
Published: 24 August 2023

Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Coal preparation plays a crucial role in addressing global climate challenges. The annual global consumption of coal surpasses 8 billion tons, producing nearly 40% of the world's CO_2 emissions [1,2]. In recent years, countries have been trying hard to reduce the consumption of coal. For example, China has built the world's largest solar and wind power installations, with over 15% of its electricity generation coming from renewable sources, and more than 50% of newly developed electrical generation plants now utilizing renewable energy [3]. Despite the significant advancements in renewable energy, eliminating coal from China's energy system remains highly challenging, as it currently constitutes over 50% of the total energy mix and is expected to remain the primary energy source for the next 20 to 30 years. In this context, the significance of coal preparation becomes evident as it enables better utilization of coal resources and contributes to the reduction of overall coal consumption, thereby reducing carbon generation.

The separation between coal and gangue minerals is primarily achieved based on their differences in density or hydrophobicity. Density-based separation techniques, such as jigging and dense medium separation [4,5], rely on the density-dominated particle settling behavior in fluid, utilizing the fact that coal particles are typically lighter than gangue minerals. However, particle size strongly influences particle settling velocity, making density-based separation less efficient for small particles with a negligible density effect. To address this, froth flotation, the hydrophobicity-based separation method was developed for fine particle separation [4,5]. In this approach, hydrophobic coal particles preferentially

attach to air bubbles and rise to the froth region, while hydrophilic particles remain in the pulp [5]. Over decades of development, a two-stage process emerged at the end of last century, wherein particles larger than 0.5 mm are separated using density-based techniques, while particles smaller than 0.5 mm are separated using flotation, effectively combining both methods for improved coal separation (See Figure 1a).

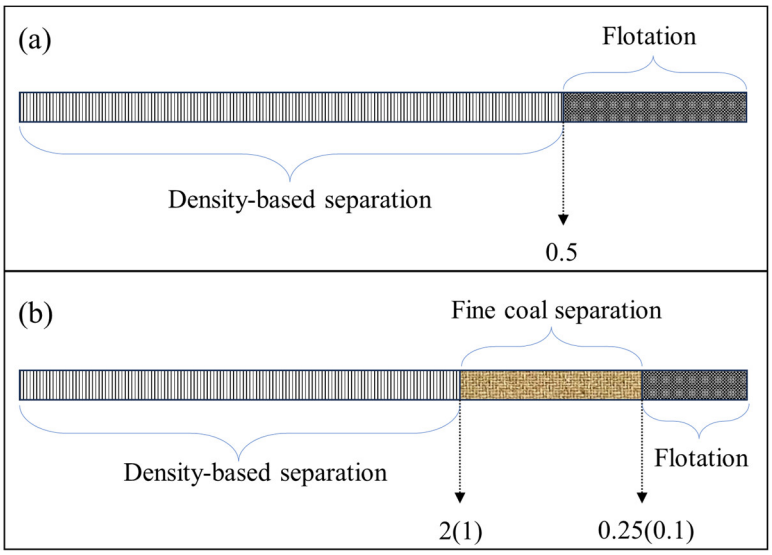


Figure 1. An illustration of the coal preparation process: (**a**) Two-stage separation; (**b**) Three-stage separation, the size range for fine coal separation may vary in different cases.

Soon after its development, the two-stage process revealed limitations in efficiently separating particles in the intermediate size range [6,7]. The industry has seen a trend of the increase of equipment size, which helps to process a larger amount of raw coal using fewer units. However, particles below 1 to 2 mm proved challenging to separate using density-based techniques due to the breakaway effect [8,9], negatively affecting separation density and Ep values. Additionally, flotation struggled to achieve high recovery rates for large particles (typically +0.25 mm for coal particles) due to their easier detachment from bubbles [10–12]. To address this, a three-stage separation process was proposed [6,7], employing specific equipment to separate intermediate particles separately, as depicted in Figure 1b. Techniques such as spiral separators, teetered bed separators, and dense medium cyclones were utilized, with various modifications introduced for improved performance [1,6,13,14]. Nevertheless, effectively separating difficult-to-separate fine coal, characterized by a high content of near-density materials, while maintaining stable separation density, remains a challenge [15,16].

Among all the techniques, the DMC is well acknowledged for high separation precision [1] and should be sufficient to separate difficult-to-separate fine coal in this context. It shows good performance in separation of very fine particles (down to 0.074 mm and 0.045 mm) and difficult to separate fine coal, attributed to the dominant centrifugal force that is much larger than gravitational force and the presence of a medium (typically a mixture of water and magnetite) that enhances separation performance. However, most of the fine coal separation plants with DMC are stopped currently because of operational problems and maintenance [1]. The traditional guidance for designing and operating DMC processes dates back more than 40 years, when the goal was to achieve 'washing to zero' [1], with the hope of replacing flotation, an expensive and difficult-to-use technique at that time. Consequently, in many cases, high feed pressure and fine magnetite were recommended to achieve a small separation lower limit of 0.045 mm [1]. The strict requirement on fine magnetite, used to prepare the dense medium, greatly increases the operation cost. Severe operational and maintenance problems, such as magnetite recovery and pipe wear, have resulted in poor industrial performance.

The advances and wide application of flotation technology have rendered the pursuit of 'washing to zero' unnecessary [1]. The current requirement for DMC in fine coal separation aims to achieve separation within a specific size range, playing a similar role as teetered bed separator and spiral separators. In our previous work, we have demonstrated DMC's high effectiveness in separating fine coal using a 710 mm DMC, which successfully separated fine coal in the range of 0.75 to 0.125 mm [15]. Notably, the working pressure P or head ($\frac{P}{\rho_f g}$) of around 15 D, which interprets the feed pressure head in terms of the DMC diameter D, was slightly higher than the typical 9 D used in coal separation for larger sizes. In the above equation, ρ_f is the fluid density and g is the gravitational acceleration. The separation pressure is much lower than the earlier guidance for 'washing to zero', thereby the industrial challenges on magnetite size and pipe wear can be easily overcome. Moreover, numerous studies have demonstrated that DMC is capable of achieving effective separation within a range of approximately 0.1 mm [1,17]. Embracing the capabilities of DMC in fine coal separation presents a significant opportunity to enhance efficiency and improve recovery in the coal preparation process. However, a systematic discussion on the proper separation lower limit, whether it should be 0.1 mm, 0.2 mm, or 0.3 mm, has not been provided.

In this study, our focus is to explore the separation lower limit for fine coal through the lens of particle settling in a DMC. We will begin by introducing the flow field within the dense medium cyclone and discussing its characteristics. Additionally, we will compare our predictions regarding the separation lower limit with other research in the field to validate our findings and enhance the credibility of our study. Our aim is to provide guidance for DMC operation, particularly in determining feed size, feed pressure, and other relevant parameters, through qualitative discussions. These insights are expected to remove the obstacles in applying DMC technology in fine coal separation.

2. An introduction of the DMC Structure and Flow Field

2.1. The Structure and Flow Pattern of a DMC

The separation process using a DMC is depicted in Figure 2a. This technique effectively separates particles based on their density difference using a dense medium, typically a suspension of magnetite in water [18]. Typically, the DMC consists of a cylinder and a cone region, with the feed (a mixture of coal and dense medium) introduced tangentially at the cylinder region. It has two outlets: the concentrate outlet at the top of the cylinder region and the reject outlet at the bottom of the cone region. Structural modifications, such as the insertion of a vortex finder into the concentrate outlet, can enhance separation performance. The three-product dense medium cyclone, which includes a cylinder cyclone for the first stage separation and a cylinder-cone cyclone for the second stage separation, has also found extensive application in coal separation. However, as it is not the primary focus of this discussion, we will not delve into the details of this technique here [15].

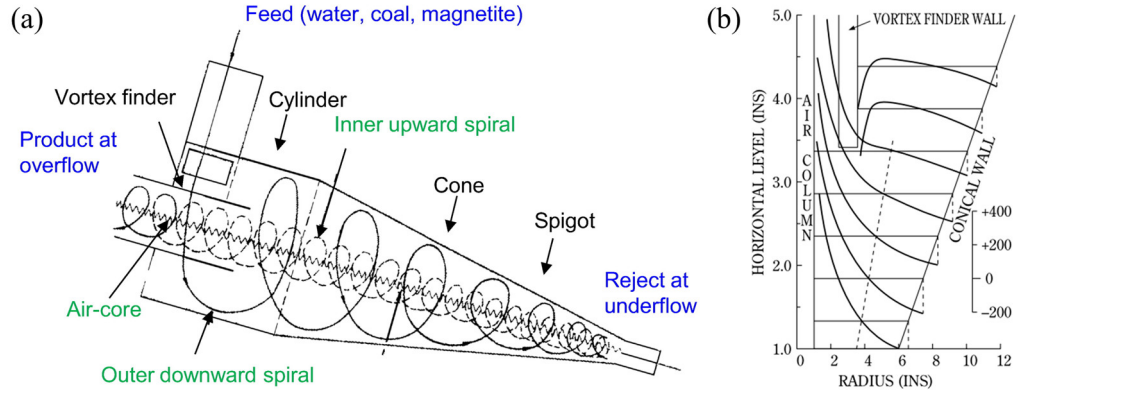


Figure 2. (**a**) Schematic illustration of coal preparation using DMC, adapted from Ref. [18] with permission; (**b**) The tangential velocity in a DMC, adapted from Ref. [19].

In the separation process, the raw coal and dense medium are introduced tangentially into the DMC through the inlet, setting off a swirling motion within the cyclone. An air core can be formed at the center because of the reduced pressure. Furthermore, this swirling action generates significant centrifugal force, compelling the denser particles to migrate towards the outer wall of the cyclone, while the less dense particles are directed toward the center. The effectiveness of this separation greatly relies on the magnitude of the centrifugal force, which can be considerably stronger than the gravitational force. Thus, the centrifugal force plays a pivotal role in achieving superior separation performance within the DMC and is instrumental in determining the separation lower limit [18,19].

The DMC is characterized by its simple structure, yet it exhibits a highly intricate flow pattern. To describe this flow pattern, a cylindrical coordinate system is employed, dividing the velocity into three directions: tangential, axial, and radial. While all these flow directions play significant roles in particle separation, the tangential flow pattern stands out as the most crucial one for discussing the separation lower limit, owing to its direct impact on the centrifugal force [19].

The flow pattern of the tangential velocity in a hydrocyclone is depicted in Figure 2b, which was measured by Kelsall in 1963 [20]. The fluid velocity starts at $v = 0$ at the wall due to the no-slip boundary condition, then undergoes a rapid increase towards the center, reaching a peak of maximum velocity before gradually decreasing towards the air core. This flow pattern can be described as a combination of a free vortex at the outer region and a forced vortex at the center, with a clear separation at the region of maximum velocity. The flow pattern of the free vortex at the outer region assumes a critical role in the particle separation process, given its significant spatial extent compared to the forced vortex.

In this work, our objective is to theoretically examine the settling behavior of particles within the DMC and provide a qualitative guidance on the separation lower limit. Considering the complexity of the flow field and the various operational and structural parameters involved, direct calculations would be impractical. To make the analysis feasible, we have made certain assumptions. While these assumptions might simplify the model, the results obtained are sufficient for gaining a qualitative understanding of fine coal separation and providing operational guidance as intended.

The following key assumptions have been made for the practical calculations:

1. The calculations will only consider the tangential velocity of the outer vortex and will focus solely on the settling of heavy gangue particles within the cyclone's outer vortex. This assumption is based on the dominance of the outer flow in cyclone dynamics [21] and the primary concern for separation is the removal of heavy particles from clean coal.
2. The medium, consisting of a mixture of magnetite, coal, and water, is assumed to be uniform in the radial direction within the outer vortex [21]. Additionally, the medium is treated as a Newtonian fluid, and its viscosity is obtained through calculations.
3. In this calculation, particles are assumed to move at their terminal velocity, as they reach this velocity rapidly in a centrifugal field where acceleration time is negligible.
4. We have not considered particle–particle interactions or the hindered settling condition in this analysis.

Despite these simplifications, the results obtained will provide valuable insights into the particle separation process in the DMC and offer practical guidance for its operation.

2.2. A model for Particle Settling in DMC

The particle separation is achieved by its settling in the DMC. For fine coal particles, the particle settling should be determined by the balance of centrifugal force and viscous force. Therefore, the settling velocity V_s is determined by the force balance as described below:

$$\frac{\pi d^3 \rho_p V^2}{6r} - \frac{\pi d^3 \rho_f V^2}{6r} = \frac{1}{2} C_D A \rho_f {V_s}^2 \quad (1)$$

In this equation, ρ_p is the particle density (kg/m^3), ρ_f is the medium density (kg/m^3), r is the radial distance from the central line (m), V is the tangential velocity of outer vortex (m/s), C_D is the drag coefficient, A is the cross-section area of the particle (m^2).

As introduced in the assumptions section, the tangential velocity in outer flow of a DMC can be described by a vortex equation, which can be described as $Vr^n = C$, where n is a value usually between 0.5 and 1, C is a constant relate to feed condition [22]. Using this equation, we can describe the tangential velocity V using the constant C and the radial location r.

The next question is to determine the drag coefficient C_D, which is heavily affected by the Reynolds number Re. In a DMC, particles experience a strong centrifugal force as they move with the rotating fluid. As a result, the calculation of the Reynolds number differs from traditional methods that consider gravity acceleration. To enhance the reliability of the calculation on Re, one theoretical method and one semi-empirical model, namely the Ar number method and the Zigrang's equation, are adopted [23].

First, Ar number method

$$Ar = \frac{4d^3\rho_m\left(\rho_s - \rho_f\right)\dot{g}}{3{\mu_m}^2} \tag{2}$$

$$Ar = 24Re_p + 3.6{Re_p}^{1.687} \tag{3}$$

Zigrang's equation

$$Re_d = [14.51 + (\frac{\left(\dot{g}\left(\rho_p - \rho_f\right)\rho_f\right)^{0.5}1.83d^{1.5}}{\mu_m})^{0.5} - 3.81]^2 \tag{4}$$

Here, $\dot{g} = v^2/r$ is the centrifugal acceleration, μ_m is the medium viscosity. The viscosity model by Ishii and Mishima is used. This model has been used in DMC simulation with a reasonable result [21].

$$\frac{\mu_m}{\mu_f} = (1 - \frac{C}{0.62})^{-1.55} \tag{5}$$

In this equation, μ_f is water viscosity, C is solid volume fraction.

By employing the above two equations, we obtained consistent Reynolds numbers ranging from 0.1 to 500; the results of the two methods are almost the same, which indicates that replacing gravitational acceleration with centrifugal acceleration is reasonable.

Therefore, the particle terminal settling velocity is:

$$V_S = \sqrt{\frac{4\left(\rho_p - \rho_f\right)C^2}{3\frac{24}{Re_p}\left(1 + 0.15{Re_p}^{0.687}\right)\rho_f r^{2n+1}}} \tag{6}$$

According to Equation (6), the terminal velocity is influenced by material characteristics such as particle density, fluid density, mixture viscosity, and particle diameter, as well as the operation and structure characters which are described by C and n. Table 1 below describes some values we adopted in the calculation.

Notably, we omitted considerations for particle–particle interactions and uneven magnetite distribution in the discussions. While these factors are clearly important and can be examined using advanced techniques such as numerical simulation, their absence does not undermine the qualitative separation lower limit analysis presented here, especially in complex scenarios.

Table 1. Values adopted in the calculation.

Items	Values
n value for outer vortex	0.75 [3]
Cyclone diameter	0.35 m [2]
Calculation zone in radial direction (outer vortex)	0.08–0.15 m [2]
Medium density	1400 kgm^{-3}
Medium viscosity	1.5 mPa·s [2]
C value for outer vortex (for different feed pressure)	0.3, 0.4, 0.51, 0.6, 0.66, 0.72, 0.93

3. Results and Discussion

As mentioned above, we derived a particle settling equation in the outer vortex of a dense medium cyclone by equating the centrifugal force with the viscous drag force. However, before we proceed further, it is crucial to address the applicability of this equation. This consideration is particularly important when discussing particle motion in a DMC, given the complex flow pattern and rapidly evolving pressure field within the cyclone. While forces such as the pressure gradient force are significant factors, they have not been considered in this equation.

The dominance of the viscous drag force can be justified based on the Reynolds number (*Re*) analysis. For instance, in Figure 3, we presented the particle *Re* values for particle sizes ranging from 0.1 mm to 1 mm at pressure heads of 9 D and 50 D. The *Re* value increases from approximately 1 to over 100 and may reach 500 for the 50 D case. Both theoretical and semi-empirical approaches yield nearly identical results. Consequently, particle settling within this range can be categorized as the intermediate regime, where the impact of the viscous drag force decreases with increasing particle size but still plays a significant role.

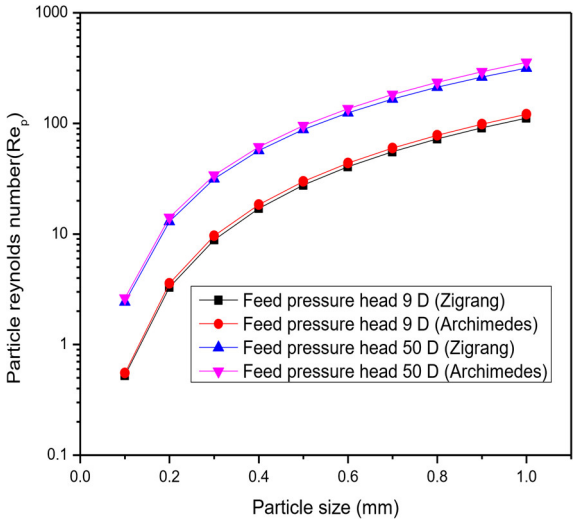


Figure 3. Reynolds number with particle size at different feed pressure head.

As particle size further increases, the *Re* number reaches the Newton's regime, wherein particle settling is barely affected by the viscous force. Instead, the pressure gradient force becomes more influential. This assertion is supported by the findings of Wang et al., who conducted a study on particle separation behavior in a DMC using numerical methods (Figure 4a). For larger particles, particle movement is determined by the balance of centrifugal force and pressure gradient. However, when particle size approaches 2 mm, the viscous drag force becomes non-negligible compared to the centrifugal force. For particle sizes below 1 mm, the viscous drag force becomes the dominating force. Thus, the assumption of a balance between viscous force and centrifugal force is justified, even though the pressure gradient force may come into play for particles close to 1 mm in size. Moreover, the numerical results provided by Wang et al. [24] indicate that the breakaway

size of the dense medium cyclone is around 1 mm (Figure 4b), suggesting that the onset of the viscous force is crucial for determining the lower limit of separation efficiency.

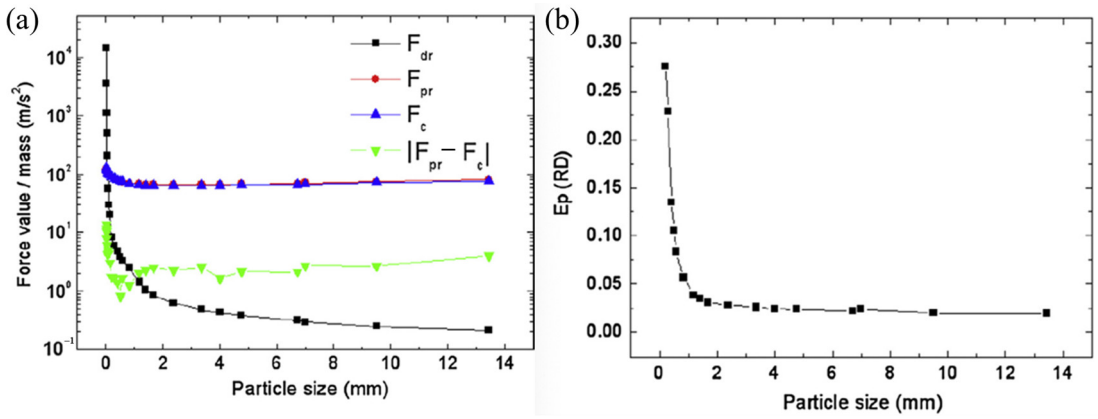


Figure 4. (**a**) Particle size and the breakaway size. (**b**) The force from numerical simulation. Figures are adapted from [24] with permission.

Using the verified model for particle settling in the outer vortex, we can gain a deeper insight into what occurs when using a DMC for fine coal separation. To achieve a clear comparison, the DMC structure parameters introduced by Narasimha et al. are adopted for the calculation [21]. The detailed parameters used in the calculation are shown in Table 1. First, we assume that a dense medium cyclone at a diameter of 0.35 m is used for the separation [21]. Cyclones of similar size are widely used for fine coal separation [1]. Furthermore, the further increase of cyclone diameter should not significantly affect our understanding of the separation lower limit. For this cyclone, the outer vortex occupies a region from 0.08 to 0.15 m away from the centerline. The region that is very close to the wall (0.15 m to 0.175 m) is not considered for the sharp change in velocity, and the region from 0 to 0.08 m is not considered because it is the inner vortex and the air core region. With that information, we compare the impact of particle size and density on the settling velocity.

3.1. Effect of Particle Size and Particle Density

Feed size plays a crucial role in coal preparation, and engineers often aim to separate a wide size fraction of coal using a single piece of equipment to reduce operational and maintenance complexities. However, it is essential to achieve this without significantly sacrificing feed separation precision or incurring substantial additional expenses. Numerous studies have indicated that the breakaway size occurs at around 1 to 2 mm when dealing with a wide size fraction [24]. Below this range, the separation performance deteriorates significantly with decreasing particle size, leading to a substantial difference in separation efficiency. Figure 5a illustrates the settling velocities of particles, highlighting that the settling velocity of 1 mm particles is nearly 5 times that of 0.2 mm particles and 10 times that of 0.1 mm particles. Therefore, it is crucial to exercise caution when determining the feed size range for fine coal. For instance, the experimental requirement on separation 1 mm and 0.1 mm fine may vary significantly.

Raw coal with high content of near density materials is regarded as difficult to separate. In this calculation, the medium density is 1400 kg·m^{-3}, a typical value for coal separation. The separation of particles with a density of 1450 kg·m^{-3} would be more difficult than of particles with a density of 1800 kg·m^{-3}. According to the result of Figure 5b, the settling velocity of 1800 kg·m^{-3} is almost 5 times that of 1450 kg·m^{-3} coal particles, which means that the separation difficulty of the latter is definitely much larger. Therefore, larger feed pressure should be adopted in treating coal with high content of near density materials.

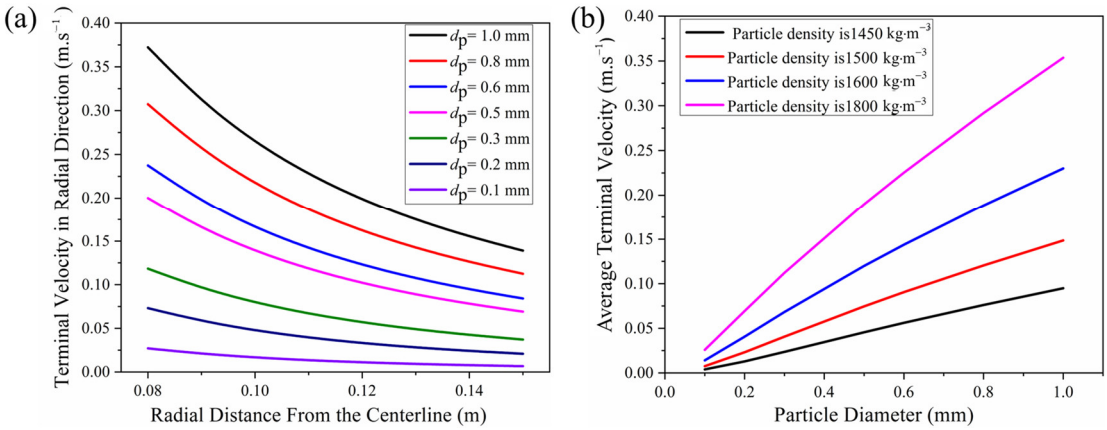


Figure 5. The results for (**a**) particle terminal velocity in radial direction (the average particle, particle density is assumed to be 1800 kg·m^{-3}); (**b**) Average terminal velocity for particles at different size and density.

3.2. Separation Lower Limit and Feed Pressure

The feed pressure head ($H = \frac{p}{\rho_g}$), which is shown in times of cyclone diameter D, is the key parameter for DMC separation and is the most frequently adjustable parameter in operation [1,9]. Figure 6a describes the average settling time in the radial calculation zone. According to the figure, the increases of feed pressure head lead to higher settling velocity and therefore lower settling time in the same radial distance, which is beneficial for separation. It has been proven in an industrial application that high feed pressure contributes to a better separation effect [1].

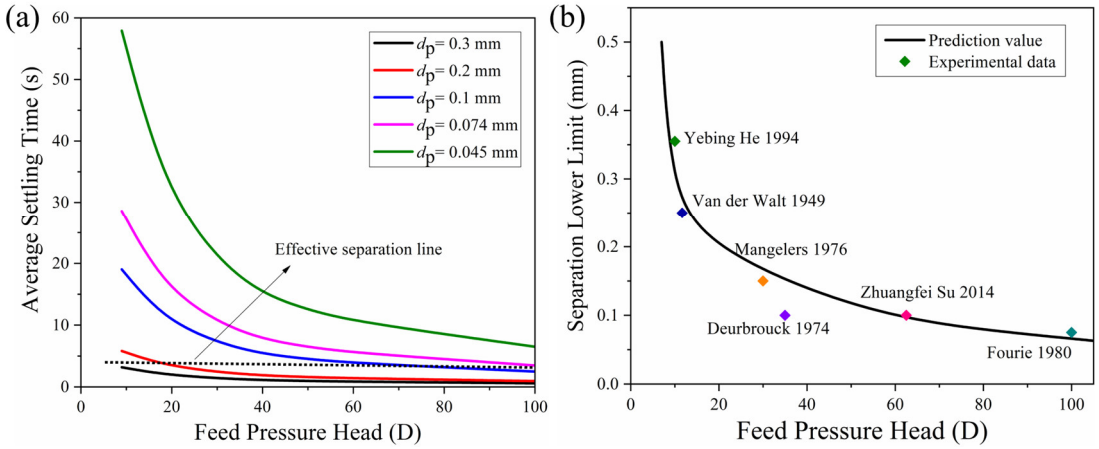


Figure 6. (**a**) Average settling time of particle in the same outer vortex region. (**b**) Comparison of the predicted separation lower limit and the reported results [1,13,17,25–28].

However, at high feed pressure conditions, a challenge may arise concerning magnetite concentration, which can be detrimental to the separation effect. One potential solution to mitigate this issue is by using very fine magnetite, which reduces the settling velocity and, in turn, minimizes over-concentration [1]. However, employing very fine magnetite introduces its own set of challenges. The process of magnetite grinding and recovery becomes difficult and resource-intensive, resulting in substantially higher operating costs.

Additionally, the requirement of high feed pressure poses a hindrance to the application of large cyclones with higher handling capacities. The operational constraints associated with high feed pressure can limit the practicality of implementing large cyclones in various applications. Moreover, the issue of pipe and cyclone wear becomes more pronounced at high feed pressure levels, leading to an increase in maintenance frequency

and associated costs. These wear-related problems can affect the cyclone's efficiency and reliability, further impacting its overall performance.

A prediction value of feed pressure head requirement for different separation lower limits is shown in Figure 6b. The prediction value is obtained by the comparison of average settling time of different size particles with that of 0.25 mm particles separated at a feed pressure head of 9 D. Generally, 0.5 mm is well acknowledged as the finest particle that can be efficiently separated in a DMC at an operation pressure of 9 D. As shown in Figure 4, the prediction fits the experimental data of other researchers well.

The requirement of the feed pressure head increases greatly with the decreases of separation lower limit. It is worth noting that the relationship is not linear, the increase of feed pressure is much larger in the fine size range. As shown in Figure 6b, the feed pressure head requirement is 15 D for the separation lower limit of 0.2 mm, but the requirement increases dramatically to 50–70 D for the separation lower limit of 0.1 mm.

4. Conclusions

In this work, a particle settling equation in the outer vortex of a DMC is derived by balancing the centrifugal force and viscous force. After validating its applicability, we use this model to discuss particle settling behavior in a DMC. The prediction on the separation lower limit of DMC in fine coal separation agrees reasonably well with literature-reported data. Based on the results, the following conclusions about DMC operation can be derived and instruct the further improvement of DMC application in fine coal separation.

- The separation lower limit of DMC would be 0.3 mm around a feed pressure of 10 D, and 0.2 mm around 15 D. However, a feed pressure of 50–70 D would be required to obtain a separation lower limit of 0.1 mm and 100 D for 0.074 mm. Therefore, it is highly recommended to keep the feed pressure at around 20 D and feed particle size should be larger than 0.2 mm.
- The settling velocity of 1 mm particles would be almost 10 times that of 0.1 mm particles at the same feed condition, so it may not be economical to separate a wide size fraction such as 1–0.1 mm with the same DMC.

Since the settling velocity of 1450 $kg \cdot m^{-3}$ particles are much lower than higher density particles, a relatively higher feed pressure would be required when treating feed coal with a high content of near-density materials.

Author Contributions: Writing—original draft preparation, C.N. and J.C.; writing—review and editing, G.X.; supervision, B.L.; funding acquisition, B.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work was financially supported by the National Natural Science Foundation of China (Nos. 22178099), the Open Project of State Key Laboratory of Chemical Engineering (SKL-ChE-22C02), the Shanghai Natural Science Foundation (21ZR1417000), Shanghai Pujiang Program (21PJ1402000), and the Special Project for Peak Carbon Dioxide Emissions-Carbon Neutrality (21DZ1207800) from the Shanghai Municipal Science and Technology Commission.

Data Availability Statement: Data available on request due to restrictions, e.g., privacy or ethical reason. The data presented in this study are available on request from the corresponding author.

Acknowledgments: Bo Liu would like to thank Sean Sanders from the University of Alberta for the fruitful discussion.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. De Korte, G.J.; Engelbrecht, J. Dense Medium Cyclones. *Int. J. Coal Prep. Util.* **2014**, *34*, 49–58. [CrossRef]
2. Agency, I.E. Coal Market Update. July 2023. Available online: https://www.iea.org/ (accessed on 20 August 2023).
3. Editorial, P. China Is World's Largest Investor in Renewable Energy. Available online: https://www.publicfinanceinternational.org/news/2016/03/china-worlds-largest-investor-renewable-energy/ (accessed on 17 January 2022).

4. Constant, M.; Coppin, N.; Dubois, F.; Artoni, R.; Lambrechts, J.; Legat, V. Numerical investigation of the density sorting of grains using water jigging. *Powder Technol.* **2021**, *393*, 705–721. [CrossRef]
5. Bosman, J. The art and science of dense medium selection. *J. South. Afr. Inst. Min. Metall.* **2014**, *114*, 529–536.
6. LI, Y. Study on the Separation Mechanism and Application of Liquid-Solid Fluidized Bed Coarse Slime Separator. Ph.D. Thesis, China University of Mining and Technology, Beijing, China, 2008.
7. Wills, B.A.; Finch, J.A. Chapter 10—Gravity Concentration. In *Wills' Mineral Processing Technology*, 8th ed.; Wills, B.A., Finch, J.A., Eds.; Butterworth-Heinemann: Oxford, UK, 2016; pp. 223–244.
8. Anupam, A.; Bhattacharya, S.; de Korte, G.J. Effect of feed size and size distribution on the performance of dense medium cyclones: A critical review. *Int. J. Coal Prep. Util.* **2020**, *40*, 618–639. [CrossRef]
9. Napier-Munn, T. The dense medium cyclone—Past, present and future. *Miner. Eng.* **2018**, *116*, 107–113. [CrossRef]
10. Ding, S.; Yu, K.; He, Q.; Yin, Q.; Feng, X.; Yong, Y.; Yang, C.; Cao, Y.; Gui, X.; Xing, Y. Bubble-particle detachment in flotation: A comparative study of the tangential and vertical direction. *Powder Technol.* **2023**, *426*, 118655. [CrossRef]
11. Darabi, H.; Koleini, S.M.J.; Deglon, D.; Rezai, B.; Abdollahy, M. Investigation of bubble-particle attachment, detachment and collection efficiencies in a mechanical flotation cell. *Powder Technol.* **2020**, *375*, 109–123. [CrossRef]
12. Ding, S.; Yin, Q.; He, Q.; Feng, X.; Yang, C.; Gui, X.; Xing, Y. Role of hydrophobic fine particles in coarse particle flotation: An analysis of bubble-particle attachment and detachment. *Colloids Surf. A Physicochem. Eng. Asp.* **2023**, *662*, 130980. [CrossRef]
13. Su, Z. Research on the Structure and Process Parameters of Coal Slurry Heavy Medium Cyclone. Master's Thesis, Anhui University of Science and Technology, Huainan, China, 2014.
14. Galvin, K.P.; Zhou, J.; Walton, K. Application of closely spaced inclined channels in gravity separation of fine particles. *Miner. Eng.* **2010**, *23*, 326–338. [CrossRef]
15. Liu, B.; Sha, J.; Liu, Z.; Xie, G.; Peng, Y. Separation of 0.75–0.125 mm Fine Coal Using the Cylindrical Section of a 710/500 mm Three-Product Dense Medium Cyclone. *Int. J. Coal Prep. Util.* **2018**, *38*, 1–12. [CrossRef]
16. Sha, J.; Lei, H.; Wang, M.; Liu, B.; Shao, H. Comparison of Separation Performance of Liquid-Solid Fluidized Bed Separator and Dense Medium Cyclone for Cleaning Coal. *Int. J. Coal Prep. Util.* **2018**, *38*, 106–198. [CrossRef]
17. Fourie, L.; Walt, V.d.; Falcon, P. The beneficiation of fine coal by dense-medium cyclone. *J. S. Afr. Inst. Min. Metall.* **1980**, *80*, 357–361.
18. 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]
19. Concha Arcil, F. Flow Pattern in Hydrocyclones. *KONA Powder Part. J.* **2007**, *25*, 97–132. [CrossRef]
20. Kelsall, D.F. Some applications of hydraulic cyclones in hydrometallurgical processes. *Trans. Soc. Min. Eng. AIME* **1963**, *226*, 225–231.
21. Narasimha, M.; Brennan, M.S.; Holtham, P.N. Numerical simulation of magnetite segregation in a dense medium cyclone. *Miner. Eng.* **2006**, *19*, 1034–1047. [CrossRef]
22. Bradley, D.; Danckwerts, P.V. *The Hydrocyclone: International Series of Monographs in Chemical Engineering*; Elsevier Science: Amsterdam, The Netherlands, 2013.
23. Zigrang, D.J.; Sylvester, N.D. Explicit approximations to the solution of Colebrook's friction factor equation. *AIChE J.* **1982**, *28*, 514–515. [CrossRef]
24. Wang, B.; Chu, K.W.; Yu, A.B.; Vince, A. Computational investigation of the mechanisms of the "breakaway" effect in a dense medium cyclone. *Miner. Eng.* **2014**, *62*, 111–119. [CrossRef]
25. He, Y.B. The Effects of Rheology and Stability of Magnetite Dense Media on the Performance of Dense Medium Cyclones. 1994. Available online: https://open.library.ubc.ca/collections/831/items/1.0081149 (accessed on 20 August 2023).
26. Mengelers, J.; Absil, J.H. Cleaning coal to zero in heavy medium cyclones. *Coal Min. Process.* **1976**, *13*, 62–64.
27. Deurbrouck, A.W. *Washing Fine-Size Coal in a Dense-Medium Cyclone*; Report of investigations; OSTI.GOV: Washington, DC, USA, 1974.
28. Van der Walt, P.J. Recovery of the coking fraction from Witbank fine coal by means of the cyclone washer. *S. Afr. J. Chem.* **1949**, *2*, 29–58.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.