

## Mechanism of Dispersion of Non-Polar Collecting Reagents in Coal Slime Flotation

Anatolii Samoilo<sup>1</sup>, Volodymyr Biletskyi<sup>2</sup>, Natalia Desna<sup>3</sup>

<sup>1</sup> LLC "Preparation plant "Sviato-Varvarynska", 85333, Sergiivka, Donetsk Reg, Ukraine

<sup>2</sup> National Technical University "Kharkiv Polytechnic Institute" (NTU HPI), 61002, Kharkiv, 21 Kyrpychova Str., Ukraine

<sup>3</sup> State University of Economics and Technology, 50005, Kryvyi Rih, 16 Medychna Str., Ukraine

Received November 8, 2024; Accepted March 10, 2025

---

### Abstract

The article investigates the conditions under which non-polar reagents interact with coal slimes during the enrichment process. This is important for determining the mechanism of their dispersion in turbulent flows in the presence of a solid phase. The study analyses and summarizes contemporary scientific research on coal flotation and the dispersion of non-polar reagents. Specifically, it addresses the particle size distribution of coal slime and analyses collector dispersion conditions. Theoretical calculations were made regarding the elementary act of dispersing particle complexes connected by the reagent. The findings indicate that pre-emulsifying non-polar reagents to sizes larger than 3  $\mu\text{m}$  helps achieve a uniform distribution of the collector throughout the pulp. However, it does not provide sufficient treatment of coal particles before flotation. The research shows that, in real-world conditions, the distance between solid phase particles is smaller than their average size. The proposed mechanism for dispersing reagent includes the formation of "particle-reagent" and "particle-reagent-particle" complexes and their breakdown in turbulent pulp flows, allowing the collector particle to adhere to the oleophilic surface of the particle due to strong mutual adhesion. Additionally, a method for calculating the parameters of spherical particle complexes bonded by a non-polar phase under equilibrium conditions has been developed. Theoretical possibilities for dispersing reagents into nanoscale volumes during the formation and breakdown of complexes have been demonstrated. The practical implications of these results suggest ways to improve coal slime processing with collecting reagents without using surfactants or specialized equipment, based on the proposed dispersion mechanism. Using the developed methodology, the study has found that for more oleophilic particles, the forces required to break particle complexes bonded by the reagent will be 1.8 to 2.2 times lower within the investigated range of contact angles of the solid phase with the collector of  $125^\circ$  to  $145^\circ$ . Lastly, it highlights the impact of particle size ratios on dispersion results during the breakdown of complexes, showing that increasing the "contact/break" interactions reduces the volume of the pre-attached reagent in a geometric progression.

**Keywords:** Flotation; Coal slime; Non-polar reagent; Drop size; Dispersion mechanism.

---

## 1. Introduction

Ukrainian coal preparation plants receive raw coal, which is increasingly containing slime sized 0–1 mm, with some cases reaching up to 40% [1]. During the preparation of coal for refining and its processing, secondary slime formation takes place [2], contributing nearly a third more to the volume of this class. While technologies such as spiral separators, hydrosizers and hydroclassifiers are quite effective at processing granular slime, a significant portion of the coal still needs to be refined through flotation. This method is essentially the only way to produce quality concentrate from finer coal. To increase the effectiveness of slime flotation, it is crucial to improve the pulp treatment technologies used before flotation with non-polar collectors.

Non-polar reagents are chemically inert substances, making them nearly insoluble in water and resulting in their presence in the flotation pulp as a separate phase [3]. The volume ratio of reagent, solid phase and water in the feed for flotation equipment during coal slime treatment is about 1 : 400 : 8000. Therefore, it is essential to achieve a uniform distribution of the collecting reagent in the pulp and ensure it contacts as many coal particles as possible before treatment.

A widely accepted method for improving the flotation process is the pre-dispersion of non-polar reagents creating stable and sufficiently concentrated emulsions in water. The determined optimal drop size for the collector during coal flotation ranges from 3 to 20  $\mu\text{m}$  [4]. To disperse flotation reagents before they are fed into the flotation equipment, ultrasonic and mechanical emulsifiers can be used. These devices generate small reagent drops due to high velocity gradients. In ultrasonic devices, dispersion is achieved through acoustic cavitation, which creates and collapses microbubbles, leading to a surge in local turbulence. Under these conditions, the velocity of microstreams in the dispersive phase, with diameters between 1 and 10  $\mu\text{m}$ , can reach up to 300 m/s [5]. In this context, the size of the dispersive phase without surfactants ranges from 1 to 5  $\mu\text{m}$  [6].

In mechanical emulsification, high velocity gradients of the dispersive phase are concentrated around the stirrers, which operate at speeds between 4000 and 20000 rpm<sup>-1</sup> [7-8]. It has been observed that when kerosene is emulsified under intense mixing, droplets form with an average size of approximately 20  $\mu\text{m}$ , while adding surfactants of anionic or cationic type during emulsification decreases the diameter of the droplets to about 1.5 to 2  $\mu\text{m}$  [9].

Creating fine emulsions of non-polar reagents requires stabilizers to prevent coalescence. High concentrations of ionic stabilizers at the "water-reagent" interface not only stop droplets from merging but also hinder their interaction with the solid phase. When droplets are hydrated in the presence of surfactants, they are less likely to stick to the floating solid phase, which limits the use of high-concentration stabilizers for achieving sufficiently fine emulsions. An exception to this is the flotation of oxidized coal, where the emulsion is stabilized by ionic surfactants that adhere to the solid phase through chemisorption [10-11].

In coal preparation plants and laboratory studies, collectors are often added in liquid form along with frothing reagents and promoters, without any prior emulsification [4,7-12]. It is considered that the mechanism for treating the solid phase with non-polar reagents in this case involves stages such as transforming the collector into an emulsion, allowing droplets to adhere to the coal surface, spreading into lenses and coalescing into a film [4,9,10-12]. This ensures effective contact between the particles and bubbles during flotation. However, doubts about this mechanism arose after high-speed photography was used [11]. It was observed that when a non-polar liquid is introduced into the pulp, coal particles immediately adhere to the "reagent-water" interface. In other words, the distribution of the collector involves the solid phase.

At recommended pulp speeds of up to 2 m/s, the turbulence intensity is relatively low, making it difficult to form an emulsion with an average droplet size of a few micrometres without the solid phase. Nevertheless, the variations in technological parameters achieved through different emulsification methods and the addition of collectors in liquid form are quite small. The flotation results from ultrasonic emulsification of diesel fuel with pine oil, compared to adding reagents in liquid form, showed only a 3–3.5% increase in combustible mass recovery [12]. Using high-speed dispersion of the flotation reagent mixture, rather than introducing them into the pulp pipeline without preparation, reduced collector consumption by 20–30% and improved recovery of the valuable component by 3.3% [7]. This indicates that the solid phase likely influences the distribution of collectors among the particles when they are dosed without prior preparation.

Dispersion of water-insoluble collecting reagents is necessary for effective coal flotation; however, prior emulsification requires specialized equipment and stabilizing surfactants, which can have mixed effects on treatment results. Introducing the reagent directly into the pulp is a relatively simple method that can yield fairly high results; however, the widely accepted mechanism for distributing the collector among the floating particles likely does not accurately reflect the actual processes and may limit efforts to find ways to intensify them.

The goal of this research is to establish the characteristics of the system when non-polar reagents are added to the pulp, to refine the mechanism of their dispersion and to identify the key parameters that influence the results of the process. This will help improve the methods used for conditioning flotation pulp.

To achieve this goal, the following objectives have been outlined:

- to explore the mechanism of the dispersion process of non-polar reagents in the presence of coal particles and to develop a method for calculating the parameters of complexes made up of spherical particles bonded by a non-polar phase under equilibrium conditions;
- using the developed methodology, to evaluate how the oleophilicity of coal particles and their size affect the stability of particle complexes bonded by a reagent.

## 2. Methods and materials

The solution to the outlined objectives was approached through theoretical analysis of the results from processing flotation pulp using non-polar collectors with a solid phase mass of  $Q = 1$  tonne in the pulp volume of  $V_p = 14.3 \text{ m}^3$  (solid content of 7%) and a reagent consumption of  $q = 1.5 \text{ kg/t}$  with the density of  $\rho = 850 \text{ kg/m}^3$ .

The slime characteristics were calculated based on the data from granulometric composition of the flotation feed at Preparation Plant "Sviato-Varvarynska" (PP SV) and various countries around the world, as cited in references [9,13-14].

For each size class, the average size of particles  $d_i$  was determined as the arithmetic mean of their size boundaries, the density of the solid phase accounting for ash content  $\rho_i$ , the volume of the particles provided their spherical shape, as well as their total number  $N_i$ .

The number of coal particles in each size class was calculated assuming their proportionality to the combustible mass content  $N_{vi} = N_i (100 - A^{d_i}) / 100$ , where  $A^{d_i}$  is the ash content of the  $i$ -th size class. The volume of reagent per coal particle was determined under the condition of uniform distribution,  $V_a = q / N_v$  and the diameter of a single spherical droplet of this volume  $d_a = (6 V_a / \pi)^{1/3}$ .

## 3. Results and discussion

The calculations indicate that each coal particle is associated with a volume of collector equivalent to a single droplet with a diameter ranging from 3.0 to 6.6  $\mu\text{m}$  (Table 1). Emulsions are generally polydisperse systems, where most of the reagent mass is concentrated in larger droplets, which means the arithmetic mean size is smaller than the volume-weighted mean size. Consequently, the arithmetic mean size of the emulsion required to attach just one droplet of collector to a coal particle will be lower than the minimum value of the optimal size range for emulsions [4]. This contradicts the commonly accepted mechanism for processing particles with non-polar reagents, which assumes contact with multiple droplets.

In practical conditions, it is possible for several droplets to attach to a single particle; however, this makes it unlikely that the reagent will effectively treat all coal particles without additional dispersion. There is also the possibility of two particles interacting with a single droplet, but unless such a complex breaks apart, the reagent cannot influence the interaction between coal and bubbles during flotation.

Table 1. Results of calculating the parameters of interaction conditions between coal particles and a nonpolar reagent.

Options	Source of particle size distribution			
	PP SV	[9]	[13]	[14]
Total ash content of sludge. %	41.4	27.6	39.2	19.4
Arithmetic mean particle diameter $d_{10}$ . $\mu\text{m}$	44	228	132	201
Number of solid phase particles $N \cdot 10^{-13}$ . units/t	30.89	3.79	3.96	1.45
Number of coal particles $N_b \cdot 10^{-13}$ . units/t	12.28	2.53	2.35	1.18
Medium-volume diameter of the reagent droplet $d_a$ . $\mu\text{m}$	3.0	5.1	5.2	6.6
The average distance between particles in the pulp $l$ . $\mu\text{m}$	23	49	47	67

Based on the data obtained, we can conclude that pre-emulsification only facilitates the rapid distribution of the reagent throughout the pulp volume, while the final dispersion occurs as droplets interact with particles in the pulp flow during transport or within flotation equipment. The interaction between phases is driven by the high concentration of solids in the flotation pulp and the small distance between particles, denoted as  $l$ . This parameter is approximately calculated based on the assumption that the particles are spherical and evenly distributed in the pulp, and the average diameter particle  $d_i$  of each of the  $n$  size classes is located within a cube with a side length of  $a_i = d_i + 2b$ , where  $b$  is represents the distance from the particle to the cube's face (Fig. 1). The total volume of all these cubic elements must equal the overall volume of the pulp

$$V_p = \sum_{i=1}^n N_i \cdot (d_i + 2b)^3 \quad (1)$$

Determining the size of  $b$  from equation (1) allows us to calculate the distance between neighbouring particles  $l = 2b$ , which is smaller compared to the average particle size  $d_{10}$  (Table 1).

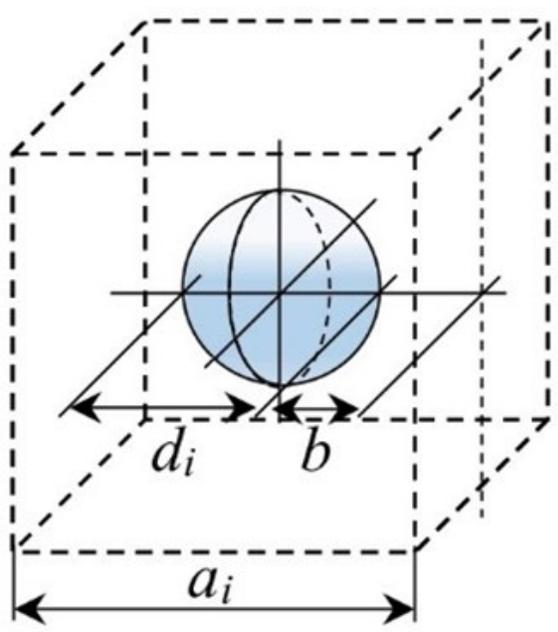


Figure 1. Location of the particle in the elementary volume of the pulp

The processes occurring in concentrated three-phase systems of "liquid-solid-liquid" under high turbulence have not been extensively studied from a hydrodynamic perspective. However, some patterns can be adapted from the theory of two-phase flows, considering the small share of the non-polar phase. It is known that the diffusion coefficients of particles, when their diameter exceeds the Kolmogorov scale of turbulence ( $d_i \gg \lambda$ ), are either equal to it ( $d_i \sim \lambda$ ) or much smaller ( $d_i \ll \lambda$ ), are significantly different and depend on turbulence intensity [15]. This indicates a high likelihood of collisions between particles as well as with the reagent present in large volumes or in the form of an emulsion, potentially leading to the formation of "particle-reagent" and "particle-reagent-particle" complexes, where the solid phase is separated by the collector. These two-phase complexes are much larger than the diameter of the emulsion droplets and

are influenced by large energy-carrying vortices with significant velocity amplitudes. They can even break apart in areas with relatively low energy dissipation rates, where individual emulsion droplets remain stable.

In cases where a complex forms with oleophilic particles, the breakdown occurs within the volume of the reagent, and some of it remains on the solid phase due to the strong adhesion of the collector to the surface. The results of the breakdown process of cylindrical samples with different surface properties from a kerosene layer on water are shown in Fig. 2. On oleophobic surfaces, the reagent does not adhere, as the adhesion to the solid phase is lower than the cohesion. This distribution of the collector among particles is best described as "adhesive dispersion", since the outcome of the process is determined by adhesion forces.

To further explore the results of adhesive dispersion, we have considered a complex of two spherical oleophilic particles with radii  $R_{s1}$  and  $R_{s2}$ , bonded by a reagent in water (Fig. 3).

Under equilibrium conditions, as long as the particles do not touch each other, the interface between the "reagent-water" takes on a minimum value and forms a catenoid, if disregarding the effects of gravitational forces due to the small size of the non-polar phase. A catenoid is created by rotating a catenary curve around the  $X$ -axis, described by the formula  $y = k$

$ch(x/k)$ . where the  $Y$ -axis passes through the curve point at a minimum distance  $k$  from the  $X$ -axis.

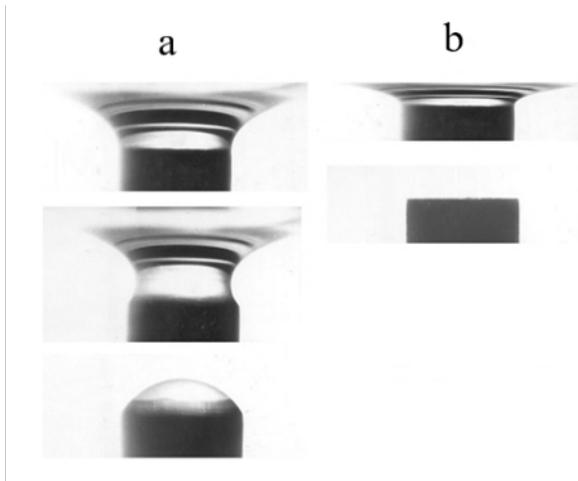


Figure 2. Detachment from the gas layer in water of solid phase samples with different surface properties: a - oleophilic surface, b - oleophobic surfaces.

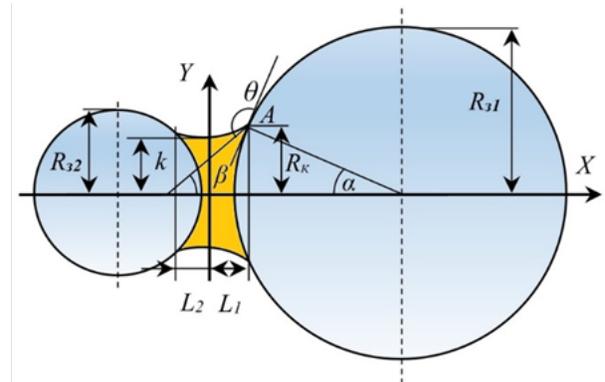


Figure 3. The scheme for calculating the parameters of a complex of coal particles (grains) bound in water by a nonpolar reagent

At the contact angle of the reagent on the solid phase surface  $\theta$ , measured through water, geometrically gives us the angle  $\alpha = \theta - \beta - \pi/2$ . At point  $A$ , with coordinates  $(R_k, L_1)$   $tg \beta = y' = sh(L_1/k)$ , leading to the equation  $R_k = R_{31} \sin(\theta - \arctg(sh(L_1/k)) - \pi/2) = k ch(L_1/k)$ . From this equation,  $L_1$  can be determined for any given values of  $\theta$ ,  $R_{31}$  and  $k$ . The volume of the catenoid  $V_1$  for the parameter  $k$  within  $(0, L_1)$  is equal to

$$V_1 = \pi k^2 \int_0^{L_1} ch^2(x/k) dx = \pi k^2 (L_1 + k sh(L_1/k) \cdot ch(L_1/k))/2 \quad (2)$$

A portion of the catenoid's volume is occupied by a spherical segment with a height of  $h = R_{31} (1 - \cos \alpha)$ , the volume of which  $V_{c1}$  can be found using the formula

$$V_{c1} = \pi h^2 \cdot (R_{31} - h/3) = \pi R_{31}^3 (1 - \cos \alpha)^2 \cdot (2 + \cos \alpha)/3 \quad (3)$$

The volume of the non-polar reagent is determined from equations (2) and (3):  $V_{a1} = V_1 - V_{c1}$  within  $(0, L_1)$ . Similarly, the volume of reagent  $V_{a2}$  is calculated within  $(0, L_2)$ , as well as its total amount  $V_{a12} = V_{a1} + V_{a2}$ .

In practical scenarios for transporting pulp, maintaining an equilibrium state in the system for an extended period is unlikely. However, we can assume that the breakdown of the reagent will occur at the thinnest point of the catenoid. The amount of collector that remains on the particles can be estimated using the methodology described earlier.

Energetically, the probability of complex breakdown depends on the work of cohesion, which is proportional to the cross-sectional area at the potential breakdown site. Calculations for the system parameters, using a collector volume equivalent to a droplet with a diameter of  $5 \mu\text{m}$ , equal particle radii  $R_3$  and contact angles  $\theta$  ranging from  $125^\circ$  to  $145^\circ$ , revealed that for more oleophilic particles, the breakdown area of the complexes and thus the required forces are reduced by 1.8 to 2.2 times within the specified angles (Fig. 4). This enhances the processing rate of highly hydrophobic particles by the reagent and may be one of the reasons for their greater flotation efficiency.

Calculations for the reagent amount equivalent to a droplet of emulsion with a diameter of  $10 \mu\text{m}$ , different particle radii in a complex ranging from  $15$  to  $50 \mu\text{m}$ , and a contact angle of  $\theta = 135^\circ$  showed that as the size ratio of particles decreases, a larger portion of the reagent remains on the larger particles; however, the ratio of the reagent volume to the particle  $V_{a1}/V_3$  increases only slightly (Fig. 5). A small portion of the collector adheres to the smaller particle, and only due to their large quantity does a significant mass of reagent get absorbed by the small particles, which aligns with established flotation principles.

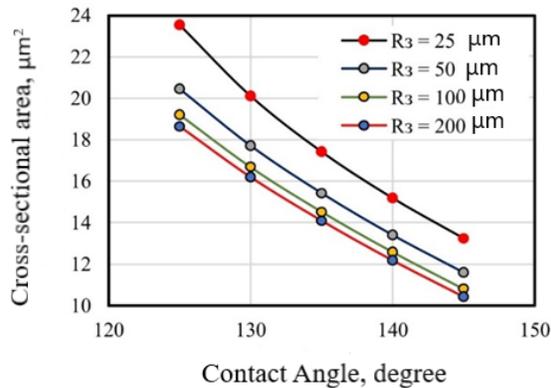


Figure 4. The dependence of the intersection area at the potential rupture site of the complex on different particle sizes from the contact angle.

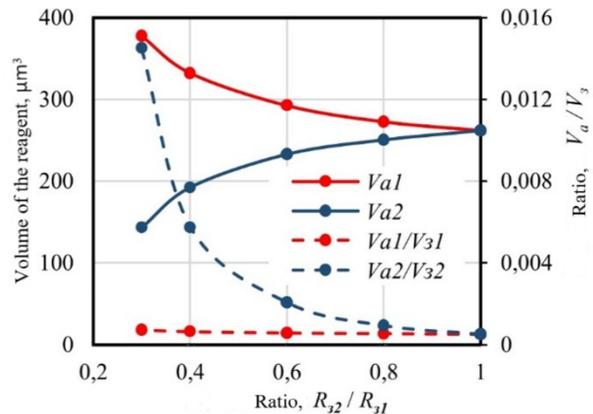


Figure 5. The dependence of the absolute and relative volume of the reagent,  $\mu\text{m}^3$ , which remains on the particles when the complex is destroyed, on the ratio of their sizes.

In the case of complex destruction with particles of the same size, the reagent is distributed evenly. If a particle with a reagent volume  $V_{a1}$  consistently contacts similar-sized particles that take away half of the collector during breakdown, its volume decreases geometrically and after  $n$  "contact/breakdown" events, it will be equal to  $V_{an} = 0.5^{(n-1)} \cdot V_{a1}/2$ . For a droplet of emulsion with a diameter of  $5 \mu\text{m}$  adhering to a separate particle, after 10 effective adhesive dispersion events, the volume diminishes by more than a thousand times. Thus, with enough interaction events, the volume can reach nanoscale dimensions without needing surfactants or specialized equipment to create significant velocity gradients. The described mechanism for processing solid phases with the collector can be effective both in case of its pre-emulsifying and of its addition in liquid form. In the latter scenario, achieving the same level of dispersion will require more time, which could be one of the reasons for the reduced flotation effectiveness when the collector is not pre-emulsified.

The idealized process of dispersing a non-polar reagent discussed above can differ significantly under real conditions. In turbulent flows, particles not only move translationally but also rotate. The shapes of solid phases are often far from spherical and feature many edges and angles with high surface energy compared to faces. These differences enhance the interactions between particles and the reagent, facilitating the formation and breakdown of complexes.

Based on the mechanism of adhesive dispersion of non-polar reagents, the process can be intensified by adjusting the parameters of the turbulent flow. This can be achieved by increasing the velocity of the pulp and changing its flow direction using diaphragms or partitions. A greater increase in the number of dispersion events per unit of time and the effectiveness of the collector in processing coal particles occurs as the surface area of the "water-reagent" interface becomes larger with pre-emulsification.

We developed a technology to convert the non-polar reagent into a vapour state before introducing it into the pulp, which increased the collector's volume by more than 100 times. The low density of the vapour bubbles enhanced the relative velocity of the reagent and particles, while heating reduced interfacial surface tension and the hydration of the collector's surface during heat transfer, which allowed for effective treatment of coal particles with the reagent. Upon entering flotation machines, the physical properties of the collector (density, viscosity and interfacial tension) normalized, ensuring the stability of the "bubble-particle" flotation complexes. Approximation in industrial settings over several months demonstrated the potential to reduce reagent consumption by 40% while increasing the recovery of combustible mass by 1% [16]. Using this technology was limited due to the fire hazard associated with it; however, research is ongoing abroad to address this issue [17]. A promising strategy to enhance the "water-reagent" interface involves introducing the collector into the pulp along with

neutral filler. an air phase. Planned research in this area will take place at the Preparation Plant "Sviato-Varvarynska".

Thus, our calculations of flotation pulp characteristics demonstrated that pre-emulsifying non-polar reagents to sizes of a few microns is not the final stage in processing floating particles. During turbulent mixing in the pulp, particles interact with both the emulsion and the liquid reagent, leading to the formation of "particle-reagent" and "particle-reagent-particle" complexes, where the solid phase is separated by the collector. When these complexes break down, and with enough "contact/breakdown" events, nanoscale droplets of the collector remain on oleophilic particles, ensuring high flotation efficiency. Importantly, the models of behaviour for "particle-reagent" and "particle-reagent-particle" (see Figure 5, for example) relevant not only for flotation processes but also for the oil agglomeration of fine coal in aqueous environments [18- 20].

#### 4. Conclusions

The proposed mechanism for the dispersion process of the reagent includes the formation of "particle-reagent" and "particle-reagent-particle" complexes, as well as their breakdown in turbulent pulp flows, with the collector particle adhering to the oleophilic surfaces of coal granules due to their high mutual adhesion. A methodology has been developed to calculate the parameters of a complex of spherical particles bonded by a non-polar phase under equilibrium conditions. The theoretical potential for dispersing reagents to nanoscale volumes during the formation and destruction of these complexes has been demonstrated.

Using the developed methodology, we have found that for more oleophilic particles, the forces needed to break the complexes of particles bonded by the reagent are 1.8 to 2.2 times lower within the discussed contact angles of the solid phase by the collector ranging from 125° to 145°. The influence of the particle size ratio on dispersion outcomes during complex breakdown has been identified. The increase in the number of "contact/breakdown" events has demonstrated a geometric progression decrease in the volume of the previously adhered reagent.

Future research directions. Future studies should continue to focus on intensifying the process of reagent treatment for pulp by refining the mechanism of adhesive dispersion, which does not require specialized equipment or high concentrations of surfactants to improve the flotation efficiency of coal slime. The base technology for further studies could be the technology for converting the non-polar reagent into a vapour state before introducing it into the pulp.

#### Symbols

PP SV - LLC "Preparation plant "Sviato-Varvarynska"

#### References

- [1] Filippenko YuN, Morozova LA, Fedoseeva SO. Analiz hranulometrycheskoho sostava dobyvaemykh uhlei. Uhol Ukrainy. 2013; 3: 12 – 14.
- [2] Poluliakh AD, Poluliakh DA. Shlamooobrazovanye uhliya. Zbahachennia korysnykh kopalyn: Nauk.-tekhn. zb. 2015; 60(101): 117 – 127.
- [3] Smyrnov VO, Biletskyi VS. Flotatsiini metody zbahachennia korysnykh kopalyn. – Donetsk: Skhidnyi vydavnychiy dim. 2010. 492 p.
- [4] Melik-Haikazian VY, Baichenko AA, Voronchikhina VV. K emulsirovaniu maslianykh flotoreahentov v promyshlennykh uslovyakh i otsenke dyspersnosti poluchaemoi emulsji. Koks i khymii, 1964; 3: 9 – 13.
- [5] Bałdyga J, Makowski Ł, Orciuch W, Sauter C, Schuchmann HP. Agglomerate dispersion in cavitating flows / Chemical engineering research and design. 2009; 87: 474 – 484. <https://sci-hub.se/10.1016/j.cherd.2008.12.015>
- [6] Gaikwad SG, Pandit AB. Ultrasound emulsification: Effect of ultrasonic and physicochemical properties on dispersed phase volume and droplet size. Ultrasonics Sonochemistry; 2008; . 15 (4): 554 – 563. <https://sci-hub.se/10.1016/j.ultsonch.2007.06.011>
- [7] Fedoseeva S.O., Morozov O.A., Morozova L.A. i dr. Razrobotka i ispytanie sposobov emulhyrovanyia reahentov pry flotatsii uhlei. Zbahachennia korysnykh kopalyn: Nauk.-tekhn. zb. 2011. Vyp. 45 (86). p. 119 – 127.

- [8] Oney O. The increase of the performance of ultrafine coal flotation by using emulsified kerosene and the prediction of the flotation parameters by random forest and genetic algorithm. *Archives of Mining Sciences*, 2019; 64 (1): 119 – 130. <https://journals.pan.pl/dlibra/publication/126275/edition/110188/content>.
- [9] Cebeci Y. The investigation of the floatability improvement of Yozgat Ayridam lignite using various collectors. *Fuel*, 2002 ; 81 : 281 – 289. [https://sci-hub.se/10.1016/S0016-2361\(01\) 00165 -X](https://sci-hub.se/10.1016/S0016-2361(01) 00165 -X).
- [10] Wen B, Xia W, Sokolovic JM. Recent advances in effective collectors for enhancing the flotation of low rank/oxidized coals. *Powder Technology*, 2017; 1 – 11 <https://sci-hub.se/10.1016/j.powtec.2017.06.030>.
- [11] Polat M, Polat H, Chander S. Physical and chemical interactions in coal flotation *International Journal Mineral Processing*, 2003; 72: 199 – 213. <https://core.ac.uk/download/pdf/324140906.pdf>.
- [12] Singh R, Singh P. Studies on de-ashing of non-coking coal by froth flotation / *Proceedings of the International Seminar MPT-2002*, 2002; 1: 243 – 249.
- [13] Lu T, Deng Z, Tang Y, Cheng W. Effects of particle size on the flotation behavior of coal slime. *Energy Exploration & Exploitation*, 2023; 41(4): 1344 – 1355.
- [14] Vijaya Kumar TV, Rao SS, Raju GB, Prabhakar S, Shivakumar S, Raman U. Development. testing and plant trails of single reagent system for coal flotation. *Proceedings of the XI International Seminar on Mineral Processing Technology*. 2010; 286 – 294.
- [15] Kryvoshchekov VY. Opredelenye koeffitsienta diffuzii tverdykh chastyts v turbulentnom potoke pulpy. *Zbahachennia korysnykh kopalyn: Nauk.-tekhn. zb.*, 1999; (45): 77 – 84.
- [16] Ohloblin ND, Samoïlov AI, Samoïlyk VH, Dubrov YuS. Podacha reahenta-sobiratelia v paroobraznom sostoianii na TsOF «Nikitovskaia». *Obohashchenie i briketirovanie uhlia: Nauch.-tekhn. ref. sb.*, 1982; 3: 5 – 7.
- [17] Liao Y, Cao Y, Liu C, Zhao Y, Zhu G. Comparison of the effect of particle size on the flotation kinetics of a low-rank coal using air bubbles and oily bubbles. *Journal of the Southern African Institute of Mining and Metallurgy*, 2017; 117(6): 561 – 566. [https://scielo.org.za/scielo.php?script=sci\\_arttext&pid=S2225-62532017000600009](https://scielo.org.za/scielo.php?script=sci_arttext&pid=S2225-62532017000600009).
- [18] Biletskyi VS, Molchanov P, Orlovskyy V, Shpylovyi L. Research into the mechanism of aggregate-forming objects contact with oil aggregation of finely-dispersed coal. *Mining of mineral deposits*, 2017; 11(4): 19 – 28. <https://doi.org/10.15407/mining11.04.019>.
- [19] Biletskyi VS, Molchanov P, Sokur M, Gayko G, Savyk V, Orlovskyy V, Liakh M, Yatsyshyn T, Fursa R. Research into the process of preparation of Ukrainian coal by the oil aggregation method. *Eastern-European Journal of Enterprise Technologies*, 2017; 3-5 (87): 45–53. <https://doi.org/10.15587/1729-4061.2017.104123>
- [20] Biletskyi V, Desna N, Orlovskyy V, Biletskyi V. Studying the Physical Properties of Coal-Oil Concentrate. *Petroleum and Coal*, 2024; 66(4): 1349-1357.

*To whom correspondence should be addressed: Dr. Natalia Desna. State University of Economics and Technology. 50005. Kryvyi Rih. 16 Medychna Str.. Ukraine. E-mail: [desnana@ukr.net](mailto:desnana@ukr.net)*