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The Relationship between the Floatability of Low-Rank Coal and Its Adhesion to Air Bubbles in Aqueous Diacetone Alcohol Solutions

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Abstract

Aggregative flotation tests of coal rank 31.1 for particle sizes −0.15, −0.25, −0.385, and −0.5 mm at a constant collector dosage (100 kg/t) and at frother reagent dosages varying from 20 to 50 kg/t were carried out. Calculations of the adhesion of aqueous diacetone alcohol (frother reagent) solutions to a coal surface precoated with *n*-alkanes were also made on the basis of contact angle values asured earlier. The coal flotation results obtained were correlated with the contact angle, work of adhesion, and detachment force of an air bubble from the coal surface. On the basis of the results it was determined that an increase of diacetone alcohol concentration causes an increase of coal recovery and concentrate yield, especially for fine-grained flotation feeds, and the quality of the concentrates decreased simultaneously. It was also found that there is a relationship between the yield of concentrates and the contact angle, the detachment force, and the work of adhesion. The maximal detachment force corresponded to the maximal concentrate yield and the minimal work of adhesion.

INTRODUCTION

Benefication of increasing coal production is necessary because it leads to sensible utilization as well as decreasing environmental pollution (*1*–*5*). One of the methods often used to clean fine coal is froth flotation (*1*–*6*), for which theoretical studies lag behind industrial development.

A fundamental problem of the froth flotation process is mineralization of air bubbles (*1, 7, 8*), which depends, among other things, on the stability of the air bubble–particle aggregates formed and the circumstances of their formation (*1, 7–10*). A measure of the stability of the aggregates is the force needed to remove an air bubble from the particle surface (*8–11*). This force is related to the surface free energy of a solid and liquid (water or water solution) (*8–11*), i.e., to the adhesion of the liquid to the solid surface (*12*).

The detachment force and the work of adhesion are important parameters from which the efficiency of the froth floatation process may be predicted.

Hence, the aim of this paper was the determination of (a) the influence of frother reagent on the aggregative flotation results of low-rank coal and their correlation with the detachment force of air bubbles from the surface of coal, (b) the contact angle of water on coal in the presence of the frother reagent and *n*-alkanes, and (c) the work of adhesion of aqueous frother solutions to the surface of coal. For this purpose, aggregative flotation tests of different size fractions of coal of rank 31.1 were carried out by using a constant dosage of the collector and variable dosages of the frother reagent. On the basis of the contact angle, the work of adhesion of aqueous frother reagent solutions to the surface of coal of rank 31.1 was also calculated.

EXPERIMENTAL

The aggregative floatation tests were carried out for coal of rank 31.1 (*14*) from the Siezsra colliery. The original coal flotation feed was fractionated by the wet method into four size fractions: −0.15, −0.25, −0.385, and −0.5 mm, and then made into four flotation feeds.

The ash grades in these flotation feeds were 50.39% (−0.15), 45.71% (−0.25), 41.58% (−0.385), and 42.26% (−0.5).

The given flotation feed of coal of rank 31.1 was enriched by the aggregative flotation method (*15, 16*) by using kerosene as a collector and diacetone alcohol as a frother reagent.

On the basis of the first series of flotation tests, it was found that good flotation of coal of rank 31.1 starts at dosages of the collector and the frother reagent amounting to 100 and 20 kg/t, respectively.

Therefore, all further flotation tests were carried at a constant collector dosage of 100 kg/t and a variable frother reagent dosage ranging from 20 to 50 kg/t. The aggregative flotation method (*15, 16*) consists of the selective aggregation of coal particles which occurs during intensive mixing of the flotation pulp with the addition of kerosene (collector). The microaggregates formed were then separated from the gangue in a subaeration flotation laboratory machine.

The aggregation of coal particles was done in a special cylindrical container of 2 dm^3 volume by using 60 g coal samples at 16.7 wt% pulp density and adding the dosage of kerosene. This slurry was mixed for 5 min at 4000 rpm. Then the slurry was transferred to a 0.55-dm^3 flotation cell. The frother, diacetone alcohol, was added in the required amount. Then flotation of the coal microaggregates was carried out for 5 min. The effectiveness of aggregative flotation was determined by evaluating the percentage recovery of coal, the percentage yield of the concentrates, the ash grade in the concentrates and wastes, as well as the percentage reduction in ash grade.

RESULTS AND DISCUSSION

The results of the aggregative flotation of coal of rank 31.1 are shown in Figs. 1-5. In these figures, Curves 1, 2, 3, and 4 show the changes of the flotation parameters for the flotation feeds of size fractions −0.15, −0.25, −0.385, and −0.5 mm, respectively.

The changes of the concentrate yield and coal recovery are depicted as a function of diacetone alcohol concentration in Figs. 1 and 2, respectively.

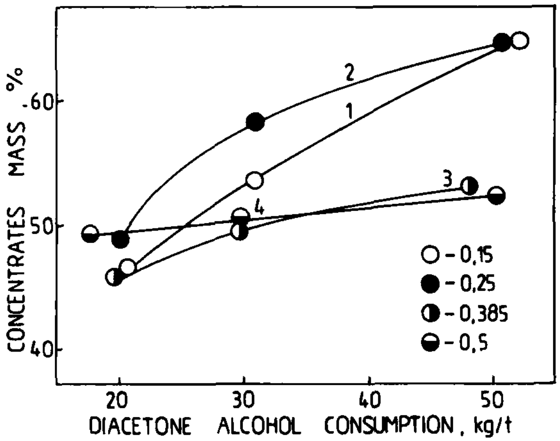

FIG. 1. Concentrate yield as a function of diacetone alcohol dosage for flotation feeds of size fractions −0.15 (Curve 1), −0.25 (Curve 2), −0.385 (Curve 3), and −0.5 mm (Curve 4).

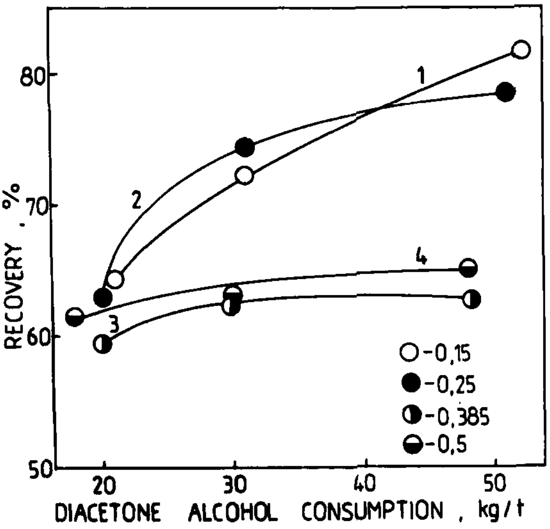

FIG. 2. Recovery of coal as a function of diacetone alcohol dosage for flotation feeds of size fractions −0.15 (Curve 1), −0.25 (Curve 2), −0.385 (Curve 3), and −0.5 mm (Curve 4).

The recovery of coal was calculated from

$$\text{Coal recovery} = \frac{M_c(100 - A_c)}{M_f(100 - A_f)} \times 100 \qquad (1)$$

where M_c and M_f are the weight of the concentrate and feed, respectively, and A_c and A_f are the ash grades in the concentrate and feed, respectively.

For the fine-grained flotation feeds (−0.15 and −0.25 mm), the increase of frother consumption from 20 to 50 kg/t caused an increase of the flotation yield (Fig. 1) and the recovery of coal (Fig. 2) by about 18 and 15%, respectively.

For the flotation feed of size fraction −0.385 mm, the increases of the same flotation parameters were 3 and 7% (Curve 3). The smallest increases of these parameters were obtained for the flotation feed of particle size −0.5 mm. Both parameters increased only about 3% in the above-mentioned range of frother consumption (Curves 4).

Thus, the flotation response of the fine-grained particles (−0.15 and −0.25 mm) of coal of rank 31.1 is larger than that for the coarse-grained ones (−0.385 and −0.5 mm).

The difference in the flotation behavior of these two kinds of size fraction (fine and coarse) is also observed in changes of the ash grade in the concentrates and wastes. For fine grained feeds (−0.15 and −0.25 mm) the ash grade in the concentrates increases with an increase in the consumption of diacetone alcohol (Fig. 3, Curves 1 and 2).

In this case, good recovery of coal and the flotation yield of the concentrates are obtained as a result of the decreased quality of the concentrates. The ash grade in the concentrates of fine-grained feeds −0.15 and −0.25 mm increases from 31 to 37% and from 30 to 34%, respectively, but in the case of coarse-grained feeds −0.385 and −0.5 mm the ash grade in the concentrates does not change much in the same range of frother consumption (Fig. 3, Curves 3 and 4).

Changes of the ash grade in wastes are illustrated in Fig. 4. The largest coal losses were obtained for coarse-grained flotation feeds (−0.385 and −0.5 mm) (Curves 3). The ash grade in these wastes is about 57.5% and decreases slightly (about 2%) with increasing consumption of diacetone alcohol. The smallest losses of coal were obtained for fine-grained flotation feeds (−0.15 and −0.25 mm) (Fig. 4, Curves 1 and 2). For both flotation feeds the ash grade in wastes increased by about 5%, and the highest ash grade in wastes was obtained for the flotation feed of −0.15 mm with a diacetone alcohol consumption of 50 kg/t.

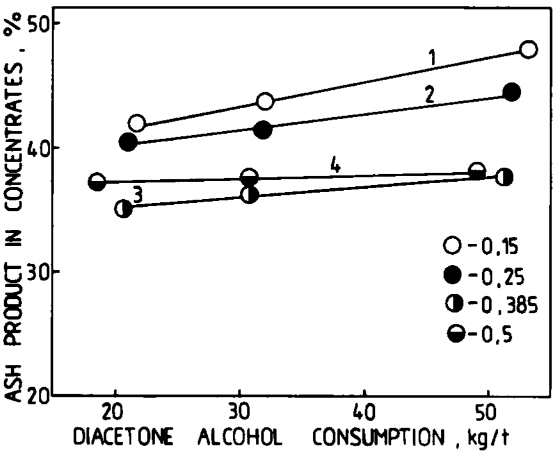

FIG. 3. Ash grade in concentrates as a function of diacetone alcohol dosage for flotation feeds of size fractions −0.15 (Curve 1), −0.25 (Curve 2), −0.385 (Curve 3), and −0.5 mm (Curve 4).

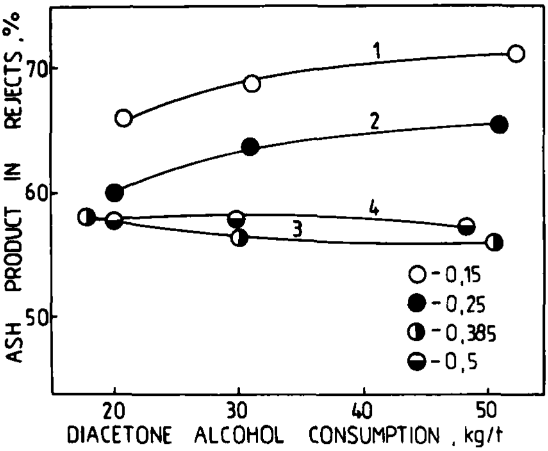

FIG. 4. Ash grade in wastes as a function of diacetone alcohol dosage for flotation feeds of size fractions −0.15 (Curve 1), −0.25 (Curve 2), −0.385 (Curve 3), and −0.5 mm (Curve 4).

From these data it appears that the best recovery of coal is achieved for fine-grained flotation feeds (−0.15 and −0.25 mm) and that coal recovery increases with increased diacetone alcohol consumption.

However, the selectivity of the aggregative flotation process was lowest for these flotation feeds and decreased with increasing consumption of the frother reagent (Figs. 3 and 4, Curves 3 and 4). This is seen more clearly from the data presented in Fig. 4, where ash reduction in the concentrates is plotted as a function of diacetone alcohol consumption. Ash reduction was calculated from

$$\text{Ash reduction} = \frac{A_c(100 - A_f)}{A_f} \times 100 \qquad (2)$$

From Eq. (2) it is seen that ash reduction for the fine-grained feeds (−0.15 and −0.25 mm) decreased from 38% (−0.15) and 35% (−0.25) to 25% as the consumption of diacetone alcohol increased from 20 to 50 kg/t (Fig. 5, Curves 1 and 2). In the same range of frother consumption for the −0.385 mm flotation feed, ash reduction decreased from 42 to 34%. Only for the −0.5 flotation feed did ash reduction not change in the range of frother consumption studied.

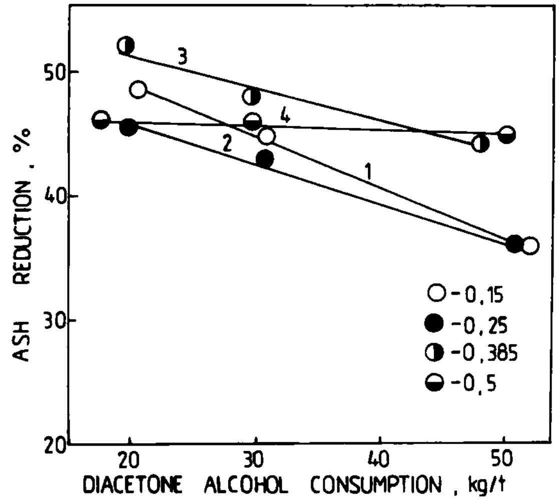

FIG. 5. Ash reduction in concentrates as a function of diacetone alcohol dosage for flotation feeds of size fractions −0.15 (Curve 1), −0.25 (Curve 2), −0.385 (Curve 3), and −0.5 mm (Curve 4).

On the basis of the results presented above, we can state that increased frother reagent consumption in the aggregative flotation of coal of rank 31.1 caused an increase of flotation concentrate yield and coal recovery, and at the same time the quality of concentrates decreased, especially for fine-grained flotation feeds.

To explain such a behavior of coal of rank 31.1 in flotation in the presence of diacetone alcohol, we assumed that its molecules are adsorbed on the coal surface as well as on the gangue surface. Activation of the coal surface under the influence of diacetone alcohol is confirmed by our studies of the wettability of coal (*17*) and the stability of coal grain–air bubble aggregates (*18*).

The detachment force of air bubbles from the coal surface is a measure of the stability of the aggregates (*18*), and this force should determine the flotability of coal. Another important parameter directly connected to the detachment force is the work of adhesion of a liquid to the solid surface (*12*).

For the system studied, this is the work of adhesion of aqueous diacetone alcohol solutions to the surface of coal precoated with a film of an apolar collector. For this system the work of adhesion is given by the equation (*19*)

$$W_A = \gamma_{Sf} + \gamma_L - \gamma_{Sf/L} \tag{3}$$

where W_A is the work of adhesion, γ_{Sf} is the surface free energy of coal precoated with a film of apolar liquid, γ_L is the surface tension of aqueous diacetone alcohol solutions, and $\gamma_{Sf/L}$ is the interfacial free energy of coal/apolar liquid film–aqueous diacetone alcohol solutions.

The equilibrium of a coal/apolar liquid film–air bubble–aqueous diacetone alcohol solutions system is described by

$$\gamma_{Sf} - \gamma_{Sf/L} - \pi e = \gamma_L \cos \theta \tag{4}$$

where θ is the contact angle measured through the aqueous phase and πe is the difference between the surface free energy of the coal/apolar liquid film at the interfacial region of coal/apolar liquid film–air and at the interfacial region of the coal/apolar liquid film–aqueous diacetone alcohol solutions.

By introducing Eq. (3) into Eq. (4) we obtain

$$W_A - \pi e = \gamma_L (\cos \theta + 1) \tag{5}$$

The work of adhesion may be calculated by using the measured values of the contact angle if $\pi e = 0$ (*20*).

In a previous paper (*13*) we found that contacting with and then removing air bubbles in aqueous diacetone alcohol solutions from the surface of coal precoated with *n*-alkane film led to constant values of the contact angle characteristic of the given system. By introducing those constant values of the contact angle (*13*) and the measured γ_L values (*10*) into Eq. (5), we calculated the work of adhesion of aqueous diacetone alcohol solutions to the surface of coal of rank 31.1 precoated with *n*-alkanes, assuming $\pi e = 0$.

The calculated W_A values are shown in Fig. 6 as a function of diacetone alcohol concentrations. Curves 1, 2, and 3 refer to W_A values for aqueous diacetone alcohol solution adhesion to the surface of coal of rank 31.1 precoated with *n*-hexane, *n*-undecane, and *n*-hexadecane, respectively.

In Fig. 6, constant values of the detachment forces of air bubbles from the coal surface of rank 31.1 precoated with *n*-hexane (Curve 1′), *n*-undecane (Curve 2′), and *n*-hexadecane (Curve 3′) are plotted as a function of diacetone alcohol concentrations in water. The values of the detachment forces used are the force for the hundredth air bubbles measured earlier (*18*).

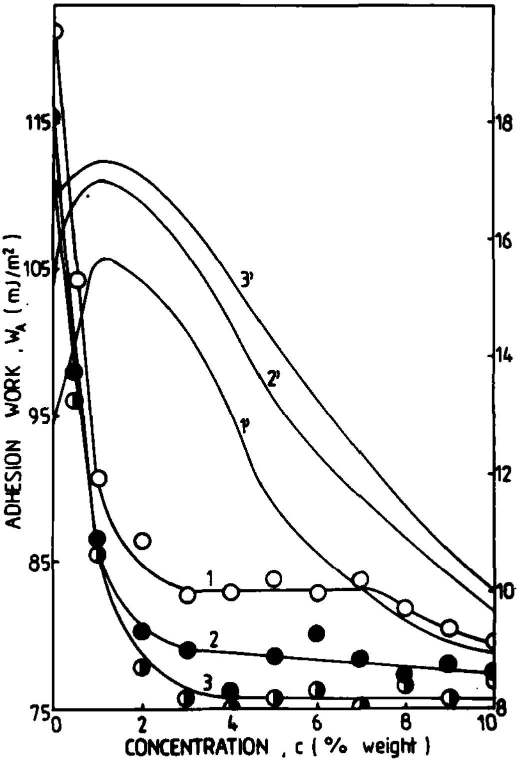

FIG. 6. Values of adhesion work of aqueous diacetone alcohol solutions calculated from Eq. (5) to the surface of coal precoated with *n*-hexane (Curve 1), *n*-undecane (Curve 2), and *n*-hexadecane (Curve 3) as a functions of diacetone alcohol concentration, and the detachment force of air bubbles from the surface of coal precoated with *n*-hexane (Curve 1′), *n*-undecane (Curve 2′), and *n*-hexadecane (Curve 3′) as a functions of diacetone alcohol concentration.

From Fig. 6 it is seen that an increase of diacetone alcohol concentration in water from 0 to 2% caused an instant decrease of W_A values. Above a 3% concentration of diacetone alcohol, W_A values for coal precoated with *n*-undecane (Curve 2) and *n*-hexadecane (Curve 3) are practically constant.

In the case of coal precoated with *n*-hexane, W_A values (Curve 1) are constant in the range of the concentrations from 3 to 7%, but above this concentration the W_A values slightly decrease. The initial decrease of W_A

values with increasing concentrations corresponds with an increase of the detachment forces (F_0). F_0 values reach their maximum at 1% diacetone alcohol concentration (c), and any further increase in alcohol concentration causes a sharp decrease of the forces for all the systems studied. Taking into account the fact that higher efficiency of the flotation process is obtained at smaller W_A values and larger F_0 values, the most beneficial conditions to create persistent coal grain–air bubble aggregates exist at a 1% diacetone alcohol concentration.

This conclusion is confirmed by the data presented in Fig. 7. In this figure, for coal of rank 31.1 precoated with *n*-undecane, we show θ (Curve 1′), F_0 (Curve 2′), and W_A (Curve 3′) as functions of diacetone alcohol concentration from 0 to 10%. These data overlap changes of the concentrate yield for feeds of size fractions −0.15 (Curve 1) and −0.25 mm (Curve 2) as functions of diacetone alcohol consumption. The curves in Fig. 7 were plotted by assuming that the properties of a *n*-undecane film on a coal surface are similar to the properties of a kerosene film on the same surface, and that the maximal dosage of diacetone alcohol (50 kg/t) is attributed to the formation of diacetone alcohol solution in water at a concentration of about 1%. θ and F_0 values were taken from Refs. *13* and *18*, and W_A values were calculated from Eq. (5).

From the data in Fig. 7 it is seen that changes in flotation concentrate yields (Curves 1 and 2) are nearly parallel to those of θ and F_0 values

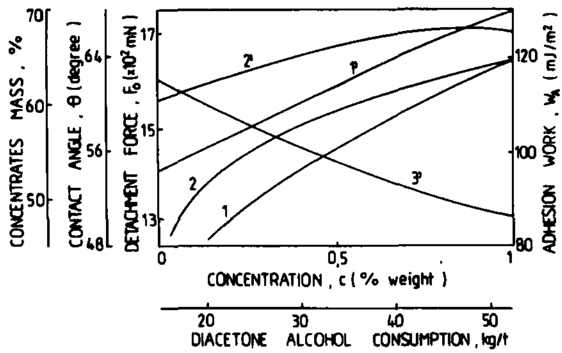

FIG. 7. Concentrate yield of coal for the flotation feeds size fractions − 0.15 (Curve 1) and −0.25 mm (Curve 2) as a function of diacetone alcohol dosage and the contact angle (Curve 1′), detachment force (Curve 2′), and adhesion work (Curve 3′) as a function of diacetone alcohol concentration for coal of rank 31.1 precoated with *n*-undecane.

(Curves 1′ and 2′). For fine-grained flotation feeds (−0.15 and −0.25 mm), an increase in concentrates yield with varying dosages of the frother (diacetone alcohol) corresponds to an increase of θ and F_0 values as a function of diacetone alcohol concentration, and the W_A values also decrease linearly. Thus, the largest values of the concentrate yields correspond to the smallest W_A and the largest F_0 and θ values.

In our opinion, however, studies involving gangue should be continued to obtain better knowledge of the influence of diacetone alcohol on the flotation of coal.

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