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# COMPOSITION OF BITUMEN-AIR AGGREGATES FLOATING TO FROTH LAYER DURING PROCESSING OF TWO DIFFERENT OIL SANDS

Results of determination and analysis of the composition of bitumen-air aggregates floating to froth layer during processing two types of the oil sands: an average grade (11.1% bitumen Estuarine ore) and a low grade (7.2% bitumen Marine ore) are presented. Flux of the bitumen-air aggregates floating to the froth layer inside the Syncrude Research EXP Primary Separation Vessel was monitored and recorded on videotapes using the Luba Tube sampling technique. Sequences of the frames grabbed from these video recordings were analysed to determine the aggregate dimensions, shapes and rise velocities. On a basis of the aggregates' dimensions and rise velocities the composition of the aggregates was evaluated. Three reference state models were presented. In addition to the two models described in an earlier study, a new theoretical approximation (called model C) describing velocity of contaminated bubbles within a range of Reynolds numbers $0.2 < Re < 20000$ was developed. The model C was found to be the most suitable choice as a "reference state" necessary for the aggregate composition calculation. It was found that the average aggregate size and the amount of the bitumen carried to the froth layer depended on the grade of the oil sand processed. In the case the average grade oil sand the average value of the Feret diameter was of an order of 1 mm and the average aggregate contained ca. $8.6*10^{-4}$ g of bitumen. In the case of a low grade oil sand the average value of the Feret diameter was lower (0.6 mm) and the average aggregate contained less bitumen (ca. $1.3*10^{-4}$ g).

*Key words* – bitumen-bubble aggregate; aggregate composition, dimension and velocity.

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## INTRODUCTION

In every flotation process grains of valuable mineral are transported to a froth layer in a form of bubble-grain aggregates. According to Leja (1982) the selective attachment of a hydrophobic particle to an air bubble in a flotation cell constitutes the most important act of the flotation process. As a result of this elementary act of flotation the stable bubble-grain aggregates are formed where the air bubbles act as carriers. Flotation kinetics and recovery depend on number, velocity and composition of the aggregates floating to the froth layer inside a flotation machine. High number of heavy loaded aggregates, i.e. having a lot of solids attached, will indicate high flotation kinetics and recovery. When there is no flow of the "loaded" aggregates then there is no flotation benefication. Thus, monitoring of the aggregate flow inside flotation cell can supply, besides information about mechanism of processes occurring beneath the froth layer, also a lot of useful practical information's about progress and possible outcome of the flotation process. Moreover, it can be used for comparison of performance of various flotation cells and for evaluation the optimum process conditions. It can be also used for obtaining information about the design of a separation vessel by comparison the aggregate's fluxes in various areas of the vessel. A method described in details recently (Małysa et al., 1998, 1999a) was used to monitor the flow of bitumen-air aggregates inside a flotation cell.

The paper presents results of analysis of the bitumen-air aggregates fluxes inside a separation vessel. Size, shape, rise velocities and composition of the aggregates floating to froth layer inside the primary separation vessel during processing of two different types of the oilsand were determined and compared. Relationship describing rise velocity of unloaded air bubbles of identical dimensions as the aggregates are needed as a "reference state" for calculation the mass of bitumen contained in the bitumen-bubble aggregates floating to the froth layer. A new (more general) model describing bubbles' velocity is introduced and a new method of calculation the mass of bitumen in the aggregates is presented in the paper.

## THEORETICAL

To calculate the mass of bitumen contained in the bitumen-air aggregates a relationship describing rise velocity of unloaded air bubbles of identical dimensions as the aggregates is used as the "reference state". In the presence of surface active components in the system the bubble contamination is inevitable. In our previous study (Małysa et al., 1999b) two models of bubble motion were used. The first, called model A, describes the motion of unloaded contaminated bubbles and is based on the empirical relationship developed by Clift et al. (1978). The terminal velocity of a rising contaminated bubble can be given as:

$$U = \frac{\mu}{\rho\, d}\left(\frac{g\,\mu^4 \Delta\rho}{\rho^2 \sigma^3}\right)^{-0.149}\left(0.94 H^{0757} - 0.857\right) \tag{1}$$

where

$$H = \frac{4}{3}\frac{g\,\Delta\rho\, d^2}{\sigma}\left(\frac{g\,\mu^4 \Delta\rho}{\rho^2 \sigma^3}\right)^{-0.149} \tag{2}$$

$d$ is diameter of a bubble, $\rho$ and $\mu$ are density and viscosity of a medium, $\Delta\rho$ is a density difference between the continuous medium and a bubble, $\sigma$ is the surface tension and $g = 981$ cm/s$^2$ is the gravity acceleration. The relationship (1) is valid only for:

$$2 < H < 59.3 \tag{3}$$

Assuming that in aqueous medium $\mu = 0.01$ g/cm s, $\rho = 1$ g/cm$^3$ and $\sigma =$ 60 mN/m the bubble velocity can be expressed as a function of its diameter and the density difference:

$$U = 49.29\,\Delta\rho^{0.495} d^{0.514} - \frac{0.298}{\Delta\rho^{0.149} d} \tag{4}$$

where the bubble diameter $d$ is expressed in cm, $\Delta\rho$ in g/cm$^3$ and $U$ in cm/s. For the unloaded bubble ($\Delta\rho \approx 1$ g/cm$^3$) the restricting condition (3) can be written as:

$$0.052 \le d \le 0.28\,\text{cm} \tag{5}$$

As it can be concluded from Eqs.2 and 3 for the partially loaded bubbles the range of applicability of the relationship (4) will be shifted towards bigger bubble sizes. For example for $\Delta\rho \approx 0.5$ g/cm$^3$ the condition (5) will be given as: $0.06 \le d \le 0.4$ cm.

The second model, referred to as Model B, was introduced after Masliyah et al. (1994). It describes the motion of non-contaminated bubble which surface is fully mobile. The rising velocity is obtained from the implicit relationship:

$$U = \left( \frac{g\,\Delta\rho\,d}{12\rho} \frac{Re}{1 + 0.077\,Re^{0.65}} \right)^{0.5} \tag{6}$$

where the Reynolds number $Re$ is defined as:

$$Re = \frac{U\,d\,\rho}{\mu} \tag{7}$$

In the aqueous medium Eq.6 assumes the form:

$$U = 9.04\,\Delta\rho^{0.5} d^{0.5} \left( \frac{Re}{1 + 0.077\,Re^{0.65}} \right)^{0.5} \tag{8}$$

Since the Eq.6 is valid for $Re < 130$ its applicability is limited to relatively slowly rising small bubbles.

Taking into account rather serious limitations of these two models we propose here a new approach, referred to as the model C, which is based on the solution of the Oseen equation for the motion of objects in the viscous fluids (Landau and Lifszyc, 1992). The solution of this equation can be expressed in terms of the series expansion in Reynolds number. The drag coefficient defined as the ratio of the viscous drag force (in the steady state equal to the buoyancy force) acting on the moving object to the inertia force:

$$C_D = \frac{4\,F_D}{\pi\,\rho\,U^2 d^2} \tag{9}$$

can be approximated (Goldstein, 1929) by:

$$C_D = \frac{12}{\mathrm{Re}}\left(1 + \frac{3}{16}\mathrm{Re} - \frac{19}{1280}\mathrm{Re}^2 + \Lambda\right) \tag{10}$$

where the zero term of the expansion corresponds to the Stokes drag coefficient:

$$C_D = \frac{12}{\mathrm{Re}} \tag{11}$$

It was found that already the linear correction term gives a fair approximation up to Re = 2. For higher Reynolds numbers the numerical solution of the Oseen equation has to be used. The interpolation formula (Goldstein, 1929) which provides a correct match with the exact solution of the Oseen equation and can be applied for a very broad range of the Reynolds numbers: $0.2 < \mathrm{Re} < 20000$ can be written as follows:

$$C_D = \frac{12}{\mathrm{Re}}\left(\frac{7}{6}\mathrm{Re}^{0.15} + 0.02\,\mathrm{Re}\right) \tag{12}$$

Applying this interpolation formula we obtain for velocity of the contaminated bubbles:

$$U = \frac{\Delta\rho\, g\, d^2}{18\,\mu}\left(\frac{7}{6}\mathrm{Re}^{0.15} + 0.02\,\mathrm{Re}\right)^{-1} = 5450\,\Delta\rho\, d^2\left(\frac{7}{6}\mathrm{Re}^{0.15} + 0.02\,\mathrm{Re}\right)^{-1} \tag{13}$$

Model C can be applied for the whole range of bubble diameters, rising velocities and degree of loading. Thus, it is not subjected to limitations as models A and B used previously. Therefore, model C being a theoretical approximation formula describing motion of contaminated bubbles seems to be the most suitable relationship to be used as the "reference state" for evaluation of the bitumen contents in the aggregates.

Fig.1. Velocity as a function of diameter for contaminated (models A and C) and non-contaminated (model B) bubbles.
Rys.1. Prędkość baniek w obecności surfaktantów (modele A i C) i w czystej wodzie (model B) w funkcji średnicy bańki.

Figure 1 presents the comparison of the dependence of the rising velocity of unloaded bubble on its Feret diameter, as calculated according to models A, B and C. It can be seen that for bubbles bigger than 0.6 mm models A and C predict almost identical rising velocity. However, the model A cannot be applied if the diameter of unloaded bubble is smaller than ca. 0.55 mm. Model B, describing motion of bubbles in absence of any surface active contaminants, predicts much faster motion than both A and C models for contaminated bubbles. Since in flotation some surface active contamination is always present model B can be used only for the smallest bubbles and should be treated as a upper limit of the feasible bubble velocity. Model C is not only in agreement with predictions of the model A for bubbles bigger than 0.6 but moreover, at the smallest bubble diameters the velocity values predicted by the Model C tend to reach values calculated from the Model B. This is also consistent with data presented by Clift et al. (1978) that velocities of bubbles in contaminated and pure water start to be similar at small diameters.

In the flotation an air bubble is a carrier transporting the attached material which generally has higher density than a continuous phase. Thus, the aggregate apparent density $\rho_{aggr.}$ is larger than air density $\rho_{air}$ and smaller than density of the continuous medium. The total mass of any aggregate is a sum of the mass of air and the mass of bitumen $M_{bit.}$ contained in the aggregate and can be expressed (Malysa et al., 1999b) as:

$$M_{bit.} = \frac{\pi}{6}\rho_{bit.}d^3_{aggr.}\left(1 - \frac{\rho_{bit.} - \rho_{aggr.}}{\rho_{bit.} - \rho_{air}}\right) \tag{14}$$

where $d_{aggr.}$ is the aggregate equivalent spherical diameter and $\rho_{bit.}$ is the bitumen density. The aggregate apparent density $\rho_{aggr.}$ was calculated from values of the apparent density difference $\Delta\rho$ between the continuous phase and the aggregate. The apparent density difference $\Delta\rho$, which caused lowering velocity of unloaded air bubble to the measured velocity of the bitumen-air aggregate, was found by solving the Eqs. 4, 8 and 13 of the Models A, B and C, respectively.

## EXPERIMENTAL

The experiments were carried out in a 0.51 m diameter Primary Separation Vessel (PSV) used in the 2 tonnes per hour Syncrude Research Exploratory Extraction Pilot, EXP, located in Edmonton, Canada. A schematic of the EXP bitumen extraction system is shown in Fig. 2.

Fig.2. A schematic of the Syncrude Research Exploratory Unit.
Rys.2. Schemat Syncrude Research Exploratory Unit (pilotowej instalacji badawczej).

Oil sand slurry containing oil sand, hot water and caustic was prepared using the delumper/mixing box. The 50 °C slurry was conditioned and transported by a 5.08 cm diameter pipeline. Flood water was added to the pipeline slurry before feeding to the separation circuit. The separation circuit configuration consisted of a circular PSV and a Tailing Oil Recovery (TOR) unit. During the experiments reported, the PSV was operating at a three stream output mode where PSV froth was the only product stream; PSV middlings and tailings were sent to TOR for further bitumen recovery. TOR was also operating in a three stream output mode where TOR froth was recycled and added to the PSV feed; TOR middlings and tailings were the two output streams containing majority of solids.

Flux of bitumen-air aggregates inside the Primary Separation Vessel was recorded and analysed during processing of two different oil sands: an average grade oil sand, which was an 11.1% bitumen Estuarine ore, and a low grade oil sand, which was a 7.2% bitumen Marine ore. Both oil sands were processed at their corresponding optimum operating conditions. In terms of chemicals addition no caustic was used for the average grade oilsand while 0.5 wt% of caustic was added for the low grade ore processing.

The Luba Tube used to record the aggregates flow was described in details previously (Malysa et al., 1999a). It consisted of an aluminium circular tube of inner diameter 5 cm having on the top a rectangular aluminium box 10x 11x 14.5 cm with three glass windows for the video camera recordings. The locked Luba Tube was immersed on a depth of 43 cm into the PSV, i.e. its bottom opening was located 43 cm from the lip of the PSV launder. The whole Tube was filled with a clean water before the bottom entrance of the Tube was opened to allow the species in the slurry to enter inside. The flux of the aggregates was recorded using Sony Video Camera at shutter speed 1/4000 s. The video recordings obtained on the Hi8 tape were re-recorded on the VHS High Grade Video Tape and analysed.

The obtained video recordings were digitised and analysed as described previously (Małysa et al., 1999a) using the SigmaScan Pro Automated Image Analysis and SigmaPlot Software's. Area, Feret diameter and shape factor were determined for the aggregates analysed. Feret diameter ($d_F$), or the equivalent circular diameter (Russ, 1995)

$$d_F = \left( \frac{4\ \text{Area}}{\pi} \right)^{1/2} \tag{15}$$

is the diameter of a fictious circular object that has the same area as the irregular object being measured. Shape factor (SF):

$$SF = \frac{4\ \pi\ \text{Area}}{\text{Perimeter}^2} \tag{16}$$

is a quantitative description of a particle non-sphericity - a perfect circle has a shape factor of unity, and a line has a shape factor approaching zero. The velocity $U_{aggr.}$ of an aggregate was calculated as:

$$U_{aggr.} = \frac{\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}}{\Delta t} \tag{17}$$

where $(x_2, y_2)$ and $(x_1, y_1)$ are co-ordinates of an aggregate on frame “i+1” and “i”, respectively, and $\Delta t$ is the time interval between the frames.

## RESULTS AND DISCUSSION

Figure 3 presents examples of the frames grabbed from the video recordings of the aggregate fluxes during processing average (Fig. 3A) and low (Fig. 3B) grade oilsand. An image of a rod of diameter 1.58 mm is also inserted into the frames to show the absolute dimensions of the bitumen-air aggregates.

Fig.3. Example of frames showing the aggregates floating during processing of an average (part A) and a low (part B) grade oilsand.

Rys.3. Przykładowe obrazy agregatów wypływających do warstwy piany podczas przeróbki piasków roponośnych o średniej (część A) i niskiej (część B) zawartości bituminu.

A few important features can be observed immediately from Fig. 3: i) there was a wide range of the aggregates' sizes, ii) majority of aggregates had irregular shapes, iii) larger aggregates were flowing during processing average grade oilsand.

As illustrated in Fig. 3 a wide spectrum of the bitumen-air aggregates was observed on the recordings and these aggregates had various rising velocities. Therefore, to obtain information about the dependence of the aggregate rise velocity on the observation time and about velocity at the steady state flow, an average value of the aggregates rise velocity was calculated for every frame analysed at various observation times (Małysa et al., 1999a). Figures 4A and 4B present the aggregate average velocity as a function of the time of observation.

Fig.4. Aggregate average velocity as a function of the observation time for average (part A) and low (part B) grade oilsand.

Rys.4. Średnia prędkość agregatów w funkcji czasu obserwacji dla piasków o średniej (część A) i niskiej (część B) zawartości bituminu.

The average aggregate rise velocity initially decreases rapidly with observation time. Then, it reaches a plateau value characteristic for a steady state flow in the Luba Tube and at longer observation times it decreases further. This course of variation of the average aggregate rise velocity with the time of observation is related to the Luba Tube operation conditions as was described elsewhere (Małysa et al., 1998, 1999a). Empty and full points represent the data obtained in analysis carried out independently in Cracow and Edmonton labs. It is seen in Fig. 4 that the agreement is really good, especially taking into account that not the same sequences of frames were analysed in both labs. This good agreement is certainly related to a fact that the number of aggregates analysed was very high (over 1000) and it shows that the obtained values of the average aggregate velocity are really representative and reliable. The aggregate average velocity at the steady state flow was 4.9±1.4 and 4.5±1.3 cm/s for the average (Fig. 4A) and low (Fig. 4B) grade oilsands, respectively. It is also worth to point out that the planned periods of the Luba Tube to be opened were 60s and 30s for the average and low grade oilsands, respectively. A similar time periods for the plateau values on the velocity vs. time dependencies were also found (c.f. Figs 4A and 4B). Taking into account that the Luba Tube opening mechanism was operated manually the agreement is remarkably good.

Figures 5A and 5B present values of the shape factor as a function of their Feret diameter for individual aggregates at the steady state flow. As described above a value of the shape factor quantifies degree of irregularities associated with the observed bitumen-air aggregate.

Fig.5. Shape factor of individual aggregates as a function of their Feret diameter; part A - average, part B - low grade ore.

Rys.5. Parametr kształtu pojedynczych agregatów w funkcji ich średnicy Fereta: część A – ruda o średniej, część B – ruda o niskiej zawartość bituminu.

It is seen in Fig. 5 that a whole spectrum of aggregate shapes was observed in the Separation Vessel. Shape factor values fluctuated, especially in the case of smaller aggregates, from 1 (spherical shape) to 0 (linear shape). Average values of the shape factor were: 0.53±0.24 and 0.54±0.21 for average (Fig. 5A) and low (Fig. 5B) grade oilsands, respectively.

Figures 6-7 present histograms of the aggregates rise velocities and their Feret diameters.

Fig.6. Histograms of the aggregates rise velocities during processing of average (part A) and low (part B) grade oilsand.

Rys.6. Histogramy prędkości wypływania agregatów w trakcie flotacji piasków o średniej (część A) i niskiej (część B) zawartości bituminu.

It is seen in Figs 6A and 6B that majority of the aggregates had velocity within the range 2-7 cm/s. This is consistent with the fact reported above that the aggregate average velocity at the steady state flow was very similar during processing the both oilsands. Distribution of the aggregate sizes was, however, quite different. In the case of the average grade ore there was a lot of aggregates having dimensions up to 2 mm with an average of 1.0±0.6 mm. In the case of the low grade ore the majority of the aggregates had Feret diameter not larger than 1 mm with an average of 0.61±0.36 mm. Quantitative data showed in Fig. 7 confirm the qualitative observations from the grabbed frames (Fig. 3) that bigger aggregates floated during processing the average grade than during processing the low grade oilsand.

Fig.7. Histograms of the aggregates Feret diameters during processing of average (part A) and low (part B) grade oilsand.

Rys.7. Histogramy średnic Fereta agregatów w czasie flotacji piasków o średniej (część A) i niskiej (część B) zawartości bituminu.

Previously (Małysa et al., 1999b), a correlation between the average Feret diameter and rise velocity of the aggregates was used for determination of a mass of bitumen contained in the aggregate. Value of the average Feret diameter was determined as a mean value of the aggregate sizes measured on a given frame of the recording. However, a wide variety of the aggregate sizes and velocities was observed on practically every frame of the recordings. Moreover, number of aggregates was very different on various frames. Thus, values of the average Feret diameters were calculated from very different numbers of aggregates (on some of the frames there was only a few aggregates) and they showed rather high standard deviations. Moreover, if on a given frame there were only 1 or 2 big aggregates amongst overwhelming majority of the small ones then these large aggregates were not seen in the analysis. Therefore, it was found more advantageous to group aggregates into size classes independent of observation time, i.e. from various frames (different observation times). The individual aggregates with dimensions differing by less than 0.4 mm were put into one class. Next, their mean value, which will be called thereafter as *class* *average Feret diameter*, was calculated. Then, a correlation between values of the class average Feret diameter and rise velocities of the aggregates was sought.

Figure 8 show the dependencies of the aggregate velocity on the class average Feret diameter for the aggregates of average (Fig. 8A) and low (Fig. 8B) grade oilsands.

Fig.8. Average velocity as a function of the class average Feret diameter. Points with bars present the experimental data for the aggregates of average (part A) and low (part B) grade oilsands. Lines show velocity of unloaded bubbles as calculated from the models A, B and C.

Rys.8. Średnia prędkość agregatów w funkcji ich średniej w klasie średnicy Fereta. Punkty z zaznaczoną wielkością błędu przedstawiają dane doświadczalne dla agregatów powstających przy przeróbce piasków o średniej (część A) i niskiej (część B) zawartości bituminu. Linie pokazują prędkość baniek bez bituminu (nieobciążonych) obliczonych z modeli A, B i C.

Points with bars (showing standard deviations of velocity distribution within a class of the aggregate sizes) present the experimental data, while the lines are the fitted dependencies given, respectively, for average and low grade ores as:

$$U_{aggr.} = 4.9\,x^{0.233} \qquad (18)$$

and

$$U_{aggr.} = 5.1\,x^{0.466} \qquad (19)$$

where x is the class average Feret diameter. The dependencies of velocity of unloaded air bubbles on their dimensions are also shown in Fig. 8. Individual lines refer to the three models described above and are marked as: Model A (contaminated bubbles), Model B (clean bubbles), Model C (theoretical approximation for contaminated bubbles). The velocity of bitumen-air aggregate was lower than the velocity of an unloaded air bubble of identical diameter because bitumen entity attached to air bubble had density higher than the air and water densities.

The apparent density of a bubble-bitumen aggregate was found by the calculations of the density difference that caused lowering velocity of unloaded air bubble to the measured velocity of a bitumen-air aggregate of identical dimension. Velocity of unloaded air bubble is, as was described above, the "reference state" needed to determine the mass of bitumen contained in a bitumen-air aggregate. Thus, the mass of bitumen will depend on the choice of "reference state".

Figure 9 presents dependencies of the aggregate apparent density on its Feret diameter obtained from the three models and illustrates how a choice of the "reference state" affects the apparent density. The aggregate apparent density was calculated from values of the apparent density difference $\Delta\rho$ between the aggregate and the continuous phase. The apparent density difference $\Delta\rho$, which caused lowering velocity of unloaded air bubble to the measured velocity of the bitumen-air aggregate, was found by solving numerically (in respect to $\Delta\rho$) the appropriate equations of the Models A, B, and C. Points in Fig. 9 show the values of the aggregate apparent density calculated from the measured velocity values for average grade oilsand, while the lines show the aggregate apparent density calculated on the basis of the regression line fitted to the measured velocity values (c.f. Fig. 8A).

Fig.9. The aggregate apparent density calculated from the models A, B and C as a function of the class average Feret diameter.

Rys.9. Efektywna gęstość agregatów obliczona na podstawie modeli A, B i C w funkcji ich średniej w klasie średnicy Fereta.

It is seen in Fig. 9 that at diameters larger than 1.0 mm the calculated apparent density obtained from the Models A and C are identical. As expected, application of the Model B leads always to higher values of the aggregate apparent density.

Figure 10 presents the mass of bitumen contained in the bubble-bitumen aggregate as a function of the aggregate Feret diameter. The mass of bitumen was calculated (Eq.14) using values of the apparent density obtained from the Model C. As seen in Fig. 10 the mass of bitumen contained in the aggregate increased with the aggregate diameter and values from practically zero up to almost 0.005 g were found. It is seen also in Fig. 10 that the mass of bitumen contained in the aggregates floating during processing average and low grade oilsands were quite similar. This implies that bubbles of similar dimensions were introduced into the flotation cell and the increase in the aggregate dimensions was due to an increase in the amount of bitumen attached to the air bubbles.

Fig.10. Mass of bitumen contained in the aggregate as a function of the class average Feret diameter. Full and empty points refer to low and average grade oilsands, respectively.

Rys.10. Masa bituminu w agregacie w funkcji średniej w klasie średnicy Fereta. Punkty pełne i puste odnoszą się odpowiednio do piasków o średniej i niskiej zawartości bituminu.

Fact that the mass of bitumen contained in an aggregate increases with the increasing aggregate diameter (Fig. 10) does not mean that majority of bitumen was transported to the froth layer by the largest aggregates because their population was relatively small (see Fig. 7). Therefore, these results need to be considered in a reference to the relative population of the aggregates of various size classes. Figures 11A and 11B present the histograms of the mass of bitumen transported to the froth layer by various classes of the aggregate sizes during processing average (Fig. 11A) and low (Fig. 11B) grade oilsands. Fraction of the bitumen $F_{bit.}$ transported by a given class of aggregates was calculated as:

$$F_{bit.} = \frac{M_i N_i}{\sum_k M_i N_i} \qquad (20)$$

where $N_i$ is the number of aggregates in a given *i*-class size, $M_i$ is the mass of bitumen carried by aggregates of the *i*-class size, and $k$ is number of the class sizes.

Fig.11. Histograms of the mass of bitumen transported to the froth layer by various classes of the aggregate sizes. Part A - average, part B - low grade ore.

Rys.11. Histogramy masy bituminu przenoszonego do warstwy piany przez agregaty o różnych klasach wielkości. Część A – ruda o średniej, część B – ruda o niskiej zawartość bituminu.

It is seen in Fig. 11A that during processing of the average grade ore the majority of the bitumen was transported to the froth layer by the aggregates of dimensions ca. 1.5 mm, and over 95% by aggregates of dimensions within the range 1.0 - 2.8 mm. In the case of the low grade ore (Fig. 11B) the majority of the bitumen was transported by smaller aggregates of dimensions below 1.5 mm.

Every aggregate consists of bitumen and air, where the air bubble acts as a carrier. On the basis of the aggregate diameter and mass of bitumen the equivalent diameters of air bubble and bitumen contained in the aggregate can be calculated as described elsewhere (Małysa et al., 1999b). Figure 12 presents comparison of the equivalent diameters of bitumen particle and air bubble making-up the bitumen-air aggregate.

Fig.12. The equivalent diameter of bitumen entity as a function of the equivalent diameter of air bubble associated with the bitumen-air aggregate.

Rys.12. Równoważna średnica cząstki bituminu w funkcji równoważnej średnicy bańki tworzącej agregat.

It is seen in Fig. 12 that the equivalent diameter of bitumen contained in an aggregate is of a similar order of magnitude as the bubble diameter. This is a most striking difference in comparison to metal ores flotation where grain dimensions (Trahar, 1981) are normally many times smaller than the bubble size (Yoon and Luttrell, 1989). However, it should be remembered that bitumen density (1018 kg/m$^3$) is only slightly higher than water, while density of metal ores is always much higher. Flotation limit for coarse particles (Ralston, 1992) is inversely proportional to the density difference between the particle and water. Due to low bitumen density, air bubbles can carry larger bitumen particles up. It is worthy to note that, as can be seen in Fig. 12, the air bubbles smaller than 0.4 mm didn't carry any bitumen

Figure 13 presents the equivalent air bubble diameters as a function of the aggregate Feret diameter.

Fig.13. The equivalent diameter of air bubble as a function of the aggregate Feret diameter. Full line with the slope equal to 1 represents the unloaded air bubbles.
Rys.13. Równoważna średnica bańki w funkcji średnicy Fereta agregatu. Pełna linia o nachyleniu równym 1 przedstawia nieobciążoną bańkę.

Solid line in Fig. 13 is the line 1:1, i.e. it shows variations of the equivalent bubble diameter with the aggregate Feret diameter for the hypothetical case of the "aggregates" consisting of air only. Thus, deviations from the line 1:1 indicate how much the aggregates were loaded with bitumen (solids). Larger deviations implied that more bitumen was contained in these aggregates. As can be seen in Fig. 13 the deviations increase with increasing diameter of the aggregate and the deviations are of similar magnitude for the both grades of the oilsand. Thus, the aggregates of identical dimensions were loaded in a similar degree with bitumen, but in the case of low grade ore the population of big aggregates was much smaller. In terms of bitumen recovery the low grade oilsand had recovery significantly lower than the average grade oilsand. Average mass of bitumen transported by an average single aggregate in the case of average grade oilsand was $8.6*10^{-4}$ g. This is a mean value from a population of 1020 aggregates analysed. In the case of the low ore the average (from the population of 1336 aggregates analysed) mass of bitumen transported by a single aggregate was $1.3*10^{-4}$ g.

## CONCLUSIONS

Monitoring of the aggregate fluxes inside a flotation cell can supply important information about progress of the separation process, performance of the cell, and the type of the ore processed.

A new, more general, model (Model C) describing rise velocity of unloaded bubbles in contaminated water was presented. This model was used as a "reference state" for calculation of mass of bitumen contained in the aggregates on the basis of the known sizes and rise velocities of the bitumen-air aggregates floating to froth layer.

It was found in analysis of the aggregates floating inside a flotation cell during processing 2 different ores that the amount of the bitumen in ore was straightforward reflected by the size of the aggregates floating to the froth layer and the average mass of the bitumen contained in the aggregates.

In the case of the average grade oilsand the average mass of bitumen, $Mb_{av.}$, contained in an average aggregate was $8.6*10^{-4}$ g - and the average aggregate size was 1.0±0.6 mm. In the case of low grade oilsand the average size of the aggregates was smaller (0.61±0.36 mm) and the average mass of bitumen contained in the average aggregate was smaller ($Mb_{av.}=1.3*10^{-4}$ g). Simultaneously, the aggregate average shape factors were very similar (0.53 and 0.54) for both oilsands indicating that the aggregate shapes were rather far away from the spherical shape. Thus, dimensions of the aggregates and their shape factors can be considered as a quick tentative information about mass of the bitumen carried in the aggregate inside the Separation Vessel.

Analysis of the aggregate sizes and their shape factors in different experiments can be used for evaluation of a progress of the separation process under different conditions. If the conditions of aeration were identical in the analysed experiments then larger aggregate sizes would indicate that more bitumen was transported to the froth layer.

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## REFERENCES

CLIFT R., GRACE J.R., WEBER M.E., 1978, *Bubbles, Drops and Particles*, New York San Francisco London, Academic Press, 221.

GOLDSTEIN S., 1929, *The Steady Flow of Viscous Fluid past a Fixed Spherical Obstacle at Small Reynolds Number*, Proc. Roy. Soc. A, **123**, 225.

LANDAU L., LIFSZYC E., 1992, *Hydrodynamika,* Warszawa, PWN (polish edition).

LEJA J., 1982, *Surface Chemistry of Froth Flotation*, New York and London, Plenum Press.

MAŁYSA K., NG S., CZARNECKI J., MASLIYAH J., 1998, *The Method of Determination of Sizes, Rise Velocities and Composition of Aggregates Floating to Froth Layer*, Physicochem. Problems Min. Processing, No.32, 91.

MAŁYSA K., NG S., CYMBALISTY L., CZARNECKI J., MASLIYAH J., 1999 a, *A Method of Visualization and Characterization of Aggregates Flow Inside a Separation Vessel. I. Size, Shape and Rise Velocity of the Aggregates*, Intern. J. Mineral Process., **55**, 171.

MAŁYSA K., NG S., CZARNECKI J., MASLIYAH J., 1999b, *A Method of Visualization and Characterization of Aggregates Flow Inside a Separation Vessel. II. Composition of the Air-Bitumen Aggregates,* Intern. J. Mineral Process., **55**, 189.

MASLIYAH J.H., JAUHARI R., GRAY M.R., 1994, *Drag Coefficient for Air bubbles Rising Along an Inclined Surface,* Chem. Enging. Sci., **49,** 1905.

RALSTON J., 1992, *The Influence of Particle Size and Contact Angle in Flotation* [in:] J.S.Laskowski and J.Ralston (Eds) *Colloid Chemistry in Mineral Processing,* Elsevier, 203.

RUSS J.C., 1995, *The Image Processing Handbook* - 2nd Edition, CRC Press, Inc., 511.

TRAHAR W.J., 1981, *A Rational Interpretation of the Role of Particle Size in Flotation*, Int. J. Miner. Process., **8**, 289.

YOON R.-H., LUTTREL G.H., 1989, *The Effect of Bubble Size on Fine Particle Flotation*, Mineral Process.and Extractive Metall. Review, **5**, 101.

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SKŁAD AGREGATÓW BITUMIN-BAŃKA WYPŁYWAJĄCYCH DO WARSTWY

PIANY W PROCESIE PRZERÓBKI DWÓCH RÓŻNYCH PIASKÓW ROPONOŚNYCH

W pracy przedstawiono wyniki badań rozmiarów, kształtu, szybkości oraz składu fazowego agregatów wypływających do warstwy piany w trakcie przeróbki piasków roponośnych o średniej (11.1% - ruda Estuarine) oraz niskiej (7.2% - ruda Marine) zawartości bituminu. Strumień agregatów bitumin-bańka płynących wewnątrz komory flotacyjnej był monitorowany przy zastosowaniu metody próbkowania w aparacie Luba Tube [Małysa et.al., 1999a] i rejestrowany na taśmach video. Pomiary wykonano w trakcie przeróbki piasków bitumicznych w instalacji pilotowej Syncrude Research Separation Vessel. Komora flotacyjna (Primary Separation Vessel) miała średnicę 0.51 m i przerabiano w niej 2 tony rudy na godzinę. Sekwencje zarejestrowanych na taśmach video obrazów wypływających agregatów zamieniono na obraz cyfrowy i analizowano przy pomocy odpowiedniego komputerowego programu analizy obrazu [Małysa et.al., 1999b]. W pomiarach tych wyznaczono rozmiar, kształt i szybkość wypływania agregatów do warstwy piany. Na podstawie wyznaczonych rozmiarów agregatów oraz ich szybkości wypływania obliczono skład fazowy agregatów bitumin-bańka, tj. zawartości gazu i fazy stałej. Dla wyznaczenia masy bituminu zawartej w agregatach bitumin-bańka niezbędna jest znajomość prędkości wypływania pustych baniek o identycznych rozmiarach. Przedstawiono trzy modele charakteryzujące ruch nieobciążonej bańki. Do opisanych wcześniej dwu modeli zachowania bańki w środowisku zanieczyszczonym substancjami powierzchniowo-aktywnymi i w czystej wodzie zaproponowano trzeci (tzw. model C), który prezentuje ruch bańki w szerokim zakresie liczb Reynoldsa $0.2<Re<20000$ w obecności zanieczyszczeń substancjami powierzchniowo aktywnymi. Wykazano, że model C stanowi najodpowiedniejszy "stan odniesienia" konieczny do wyznaczenia składu agregatów. Wykazano, że średnia wielkość agregatów i ilość bituminu wynoszonego do warstwy piany zależały od jakości przerabianego piasku roponośnego. W 0przypadku piasku o średniej zawartości bituminu średnia wartość średnicy Fereta agregatów była rzędu 1 mm, a średni agregat zawierał około $8.6*10^{-4}$ g bituminu. W przypadku piasku uboższego w bitumin średnia wartość średnicy Fereta była mniejsza (0.6 mm) i średni agregat zawierał mniej bituminu (około $1.3*10^{-4}$ g).
*Slowa kluczowe* – agregat bitumen-bańka, skład, wielkość i prędkość agregatów.