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POLYMER WASTES' FLOTATION SEPARATION RESEARCH RESULTS

Abstract. For separation of plastic wastes (polyamide (PA), acrylonitrile butadiene styrene (ABS) and polystyrene (PS), a flotation method is proposed. Using this method, the effect of concentration of surface-active substances (surfactants), which were used as polidocanol, sulphanole and a mixture of surfactants containing sodium laureth sulfate and diethanolamide, was studied.

The research results analysis of the flotation separation of a mixture of crushed plastic wastes was carried out according to the calculated values of the extraction of a floated component ε and the purity of a concentrate β. It was noted that the maximum extraction of the floated component depends on the polymer and surfactant type. A mixture of surfactants at lower concentrations allows to achieve greater extraction of the floated component with less foaming ability.

The research results on the extraction of polystyrene from the air flow rate at various concentrations of surfactants' mixture show that the extraction has a maximum at a certain air flow rate. At low air flow rates, the working volume of liquid is not saturated enough with gas bubbles. If the optimal value of air flow rates is exceeded, many gas bubbles are formed that are not involved in the flotation process.

The research results on the extraction of polystyrene from the aerated liquid layer height at various concentrations of surfactants' mixture show that, at a low height of the aerated liquid layer, the probability of collision of a plastic particle with an air bubble is low and some potentially floated particles seek the bottom of an apparatus without having time to collide with an air bubble.

When assessing the influence of liquid temperature on the flotation process, it was found that increasing the liquid temperature above 20°C leads to a sharp decrease in ABS and PS extraction. This is explained by the fact that the dependence of the surfactants' foaming ability on the temperature is characterized by solubility curves and for most surfactants they have an extremum.

Key words: flotation, plastic wastes, surface-active substances, concentration, air flow rate, liquid layer height, temperature.

Introduction. In the world there is a constant increase in the consumption of polymer materials (PM) [1,2], which occupy a leading position in terms of production of raw materials.

The accelerated growth in the production of polymer materials and the expansion of their applications in various industries is explained by their manufacturability, ease, convenience, cost-effectiveness, safety, a set of valuable operational properties and high aesthetics. Plastics are serious competitors to glass, ceramics and metal [3].

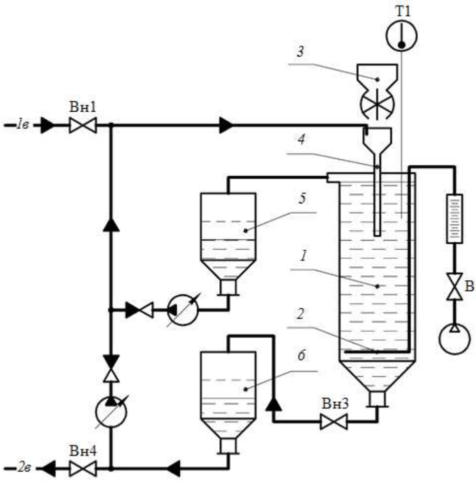
At the same time, the use of products from polymer materials certainly causes waste formation. The increase in PM production and consumption inevitably entails an increase in the amount of their wastes.

In recent years, the problem of processing plastic wastes has taken an important place in the world, since the bulk of wastes is destroyed by inefficient methods [4-8].

Promising processes for the separation of PM are flotation based on various wettability, since they are quite simple in hardware and reliable. This requires the presence of surface-active substances and gas bubbles in the working volume of an apparatus [9,10].

Experimental plant and research methodology. A diagram of the laboratory-scale plant of a column flotation apparatus with pneumatic aeration of liquid to study the effect of the main process parameters on the flotation separation of a mixture of crushed plastics is shown in figure 1.

The plant includes the reservoir *1* for carrying out the flotation process, which is filled with water from the line *1в* using the valve Вн1. Inside the reservoir *1*, at its bottom, the aerator *2* is fixed for introducing air into the working volume of the apparatus in the form of bubbles. The working volume of the apparatus is the volume of liquid between the aerator and the foam layer (liquid surface). The aerator is installed in the lower part of the apparatus with the ability to adjust the plant's depth to determine the optimal aerated liquid height. The air flow rate supplied from the compressor to the reservoir *1* is regulated by the valve Вн2 and is controlled by a rotameter.



1 – reservoir; *2* – aerator; *3* – bladed batcher; *4* – feeder; *5*, *6* – separators; Вн1–Вн4 – valves;
T1 – thermometer. Flows: *1в* – water to fill the reservoir; *2в* – water drain
Figure 1 – A diagram of the laboratory-scale plant of a column flotation apparatus with pneumatic aeration of liquid

The feeding of crushed plastics is regulated by the bladed batcher *3*, in the body of which a rotor with radial blades made of elastic material is installed, which prevents its jamming. The feeding is organized through the feeder *4* in the middle part of the column with the ability to control the depth of feeding to study its effect on the flotation process. For a better independent outflow of the resulting foam product (concentrate) from the liquid surface and its overflow from the column for further processing, the laboratory plant provides for a constant circulation of circulating liquid. The circulating liquid is fed to the column through the feeder *4*, which prevents particles of crushed plastics from getting stuck in it. To separate solid and liquid phases of the foam product, the separator *5* is used, and for tails, the separator *6* is used when opening the valve Вн3. The separators *5* and *6* also serve to accumulate a buffer volume of the circulating liquid, necessary for its constant circulation using pumps. The liquid, if necessary, is drained from the plant through the line *2в* with the help of the valve Вн4 valve. The liquid temperature in the reservoir *1* is measured by the thermometer T1.

The experimental research technique consists in the following sequence of actions.

1. Prepare in advance a sample of the studied crushed plastics with the mass $m_{исх}$. Due to the complexity of further manual sorting of the concentrate in a multilateral study of the flotation process, it is recommended to apply a sample of a mixture of crushed plastics weighing about 10 g. In the laboratory plant, it is possible to study the dependences of the extraction of certain types of plastics on physical and operational factors, while the flotation is fed with the sample $m_{исх}$ containing one type of crushed plastic. It is also possible to study the separation of a mixture of several types of crushed plastics. In the second case, the sample $m_{исх}$ should contain particles of crushed hydrophobic plastic with the mass $m_{исх}^{фл}$ and particles of crushed hydrophilic plastic with the mass $m_{исх}^{ос}$. When studying the separation of plastics, it is recommended to feed for the flotation a mixture of plastics in a ratio of 1:1, since the literature cites the fact that the most complex mass ratio for separating the components of a mixture is generally 1:1.

2. At the beginning of work with the laboratory plant, shown in figure 3.1, it is necessary to open the valve Вн1 and fill it with water from the line *1в*, while separators *5* and *6* are also filled with the buffer volume of the circulating liquid.

3. When filling the plant with water, introduce the required amount of surfactants, which are mixed in the liquid flow during its feeding and subsequent circulation.

4. Using adjustable pumps, install the required circulation of the circulating liquid.

5. Turn on the compressor and, opening the valve Вн2, feed air to the working volume of the apparatus through the perforated aerator *2*, which is installed to the required depth. Due to the aerator, the air will be evenly distributed over the cross section of the apparatus in the form of small bubbles.

6. Using the valve Вн2, establish the air flow rate necessary for the experimental study, controlling its value with the rotameter.

7. In the mechanical bladed batcher *3*, pour the pre-prepared sample of crushed plastics with the mass $m_{\text{исх}}$.

8. Turn on the mechanical bladed batcher *3* and feed the material. In this case, the particles enter the feeder, washed by the circulating liquid, and then into the working volume of the apparatus. As a result of the flotation, a part of the crushed particles falls into the foam product, and the other part – in the sediment. The three-phase foam product due to the constant circulation of the circulating liquid by gravity pours over the upper edge of the column and enters the separator *5* to separate the solid phase – the concentrate.

9. After the flotation process is over (when there will be no material particles in the working volume of the apparatus), close the valve Вн2 and stop the circulation of the circulating liquid by the adjustable pumps, turning them off.

10. Select the concentrate from the separator *5* and dry it.

11. After drying the concentrate, determine its mass $m_{\text{конц}}$. When studying the separation of the mixture of several types of crushed plastics from the dried concentrate with the mass $m_{\text{конц}}$, it is necessary to select the floated component (particles of hydrophobic plastic) and also determine its mass $m_{\text{конц}}^{\text{фл}}$.

12. The accumulated sediment, as necessary, is discharged from the bottom of the column to the separator *6* using the valve Вн3, and it is manually removed from the separator *6*.

Thus, to study the influence of a certain parameter on the flotation process, a series of experiments is carried out in which only the studied parameter changes, and the remaining conditions are maintained constant. After the series of experiments with one parameter, the next series is carried out, in which the influence of another parameter on the flotation process is studied.

Since the geometric characteristics of the experimental plant are not universal, it is customary to reduce the air flow rate fed to the apparatus and measured by the rotameter to a unit of cross-sectional area of the apparatus.

Research results. To analyze the research results of the flotation separation of the mixture of crushed polymer materials, the extraction of the floated component ε and the concentrate purity β were calculated using the formulas presented below in [11]:

$$\varepsilon = \frac{m_{\text{конц}}^{\text{фл}}}{m_{\text{исх}}^{\text{фл}}} \cdot 100\%, \tag{1}$$

$$\beta = \frac{m_{\text{конц}}^{\text{фл}}}{m_{\text{конц}}} \cdot 100\%, \tag{2}$$

where $m_{\text{конц}}^{\text{фл}}$ – the mass of the floated component (particles of crushed hydrophobic plastic) in the concentrate, kg; $m_{\text{исх}}^{\text{фл}}$ – the mass of the floated component (particles of crushed hydrophobic plastic) in the initial sample, kg; $m_{\text{конц}}$ – the mass of the concentrate, kg.

The experimental research results were processed in the form of graphical dependences of the flotation indices on the concentration of various types of surfactants, shown in figures 2-5.

As can be seen from Figures 2-5, the extraction has a maximum at a certain concentration of surfactants, namely: about 10^{-2} kg/m^3 for ABS using sulphanole and polidocanol; less than $3 \cdot 10^{-3}$ kg/m^3 for ABS using the surfactants' mixture; $5.41 \cdot 10^{-3}$ kg/m^3 for PS using the surfactants' mixture.

The presence of the maximum extraction of the floated component ε in figures 2-5 suggests the regularity of the effect of the surfactants' concentration on the extraction of the floated component. This can be explained by the same nature of the dependence of foaming ability on the surfactants' concentration. At a concentration higher than the maximum, the foam formation decreases due to the difficulty of the surfactants' diffusion into the surface layer [12]. However, the foaming ability of the surfactants is not determinative in this case, since, as can be seen from Figures, the value of the surfactants' concentration at which the maximum extraction of the floated component is achieved depends on the polymer and surfactant type.

A positive feature is that the maximum polymer extraction is achieved with a rather low concentration of the surfactants [13,14]. Moreover, the surfactants' mixture at lower concentrations allows to achieve greater extraction of the floated component which in the same way affects the foaming ability [15].

According to the results of calculations of the extraction of the floated component ε and the concentrate purity β from the air flow rate during the flotation separation of the mixture of crushed polyamide and acrylonitrile butadiene styrene using various surfactants, the dependences shown in Figures 6-8 were obtained.

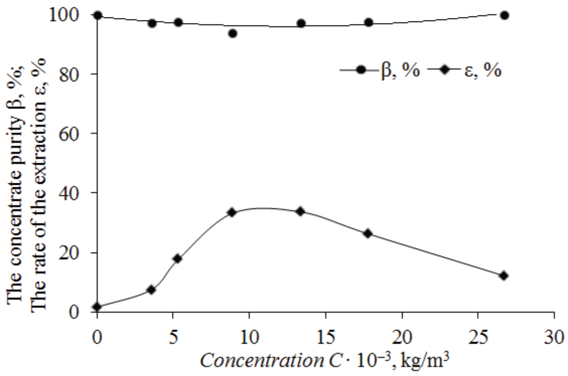


Figure 2 – Dependences of the concentrate purity and the ABS extraction on the sulphanole concentration at the air flow rate of 0.062 $m^3/(min \cdot m^2)$

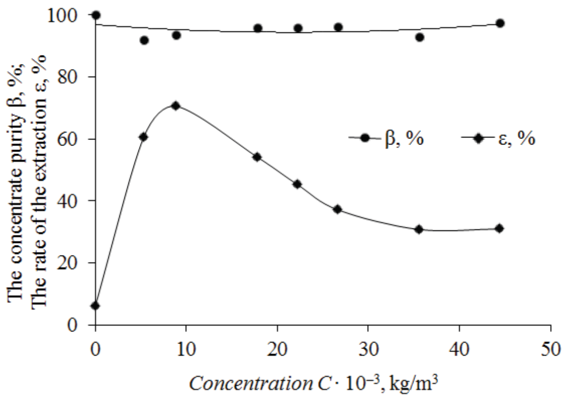


Figure 3 – Dependences of the concentrate purity and the ABS extraction on the polidocanol concentration at the air flow rate of 0.062 $m^3/(min \cdot m^2)$

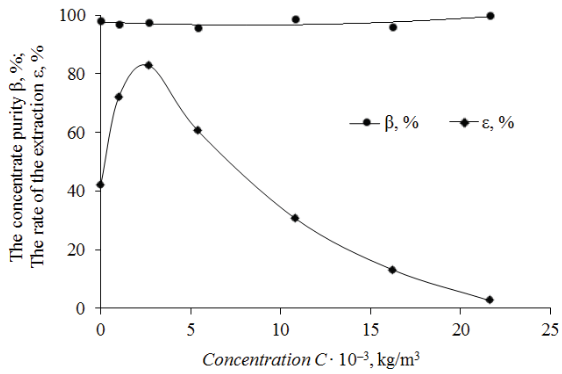


Figure 4 – Dependences of the concentrate purity and the ABS extraction on the surfactants' concentration at the air flow rate of 0.104 $m^3/(min \cdot m^2)$

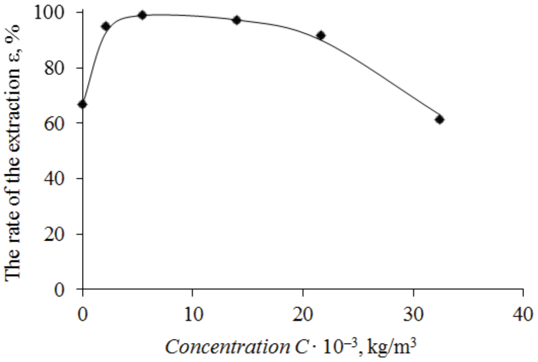


Figure 5 – Dependences of the PS extraction on the surfactants' concentration at the air flow rate of 0.072 $m^3/(min \cdot m^2)$

Further, according to the research results presented in [16], the dependences of PS extraction on the air flow rate are presented, obtained at the surfactants' mixture concentration of $5.41 \cdot 10^{-3}$ and $16.22 \cdot 10^{-3}$ kg/m^3 (figure 9).

As can be seen from figures 6-9, the extraction has a maximum at a certain air flow rate. The presence of the maximum extraction of the floated component in these Figures suggests a characteristic effect of the air flow rate on the polymer flotation process. At low air flow rates, the process is inefficient, since the working volume of the liquid is not saturated enough with gas bubbles. If the optimal value of air flow rate is exceeded, many gas bubbles are formed that are not involved in the flotation process. Such bubbles moving through the liquid can create turbulent flows that impede the flotation of particles. When moving in the turbulent liquid flow, the "bubble – particle" complex is prone to destruction, as particles and bubbles have different inertia (mass) [17].

Also, from the above dependences, it may be concluded that the value of the air flow rate at which the maximum extraction of the floated component is achieved depends on the polymer and surfactant type. The nature of the air flow rate effect at different concentrations of surfactants does not change – only the extraction of the floated component changes.

When using polidocanol, the maximum ABS extraction is 17% higher than when using sulphanole, and reaches 70.5%. However, the concentrate purity in this case is reduced by 2.5%, namely, to 93.5% [18]. When using the mixture of surfactants containing sodium laureth sulfate and diethanolamide, the ABS extraction reaches 95%, and the concentrate purity – 98.7%. And when using the same surfactants' mixture during the PS flotation, its extraction reaches 99%.

To determine the optimal aerated layer height of the working liquid from the experimental data presented in [16], the dependences of the PS extraction on the surfactants' concentration were determined for different heights of the aerated liquid layer, which are shown in figure 10.

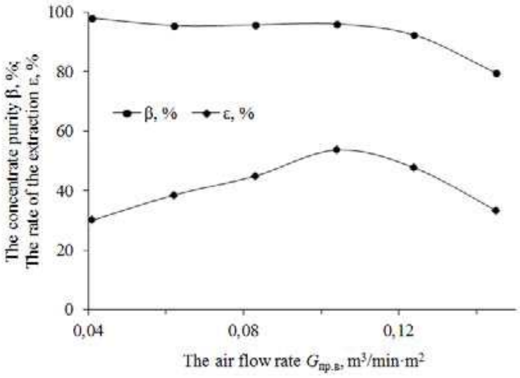


Figure 6 – Dependences of the concentrate purity and the ABS extraction on the air flow rate at the sulphanole concentration of $11.56 \cdot 10^{-3}$ kg/m^3

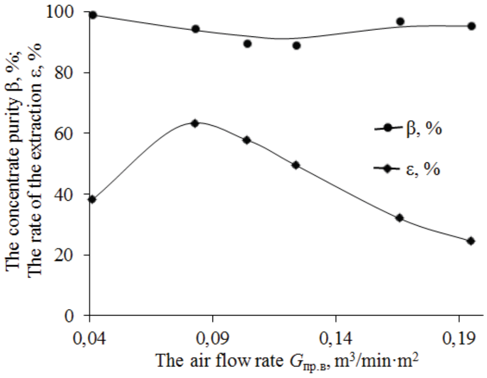


Figure 7 – Dependences of the concentrate purity and the ABS extraction on the air flow rate at the polidocanol concentration of $8.89 \cdot 10^{-3}$ kg/m^3

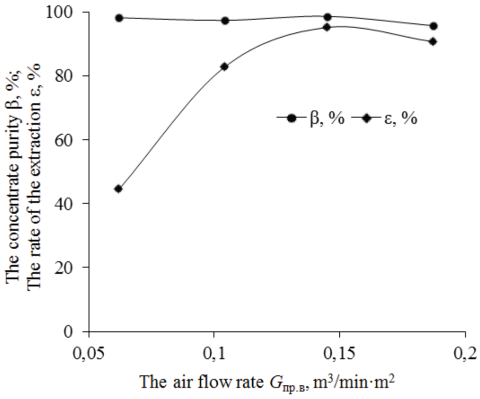


Figure 8 – Dependences of the concentrate purity and the ABS extraction on the air flow rate at the surfactants' mixture concentration of $2.7 \cdot 10^{-3}$ kg/m^3

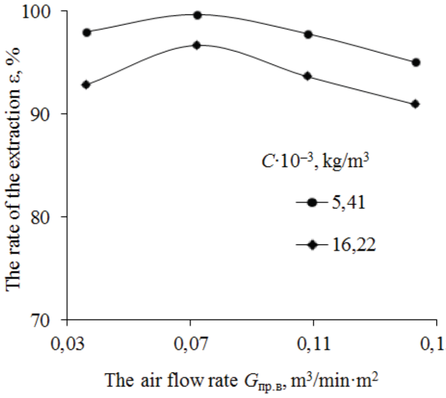


Figure 9 – Dependences of the PS extraction on the air flow rate at various surfactants' mixture concentration

As can be seen from Figure 10, the PS extraction has a maximum at a low surfactants' concentration, namely, $5.41 \cdot 10^{-3}$ kg/m^3, and reaches 99% with a sufficient height of the aerated liquid layer.

At a low height of the aerated liquid layer, the probability of collision of a plastic particle with an air bubble is low and some potentially floated particles seek the bottom of the apparatus without having time to collide with an air bubble. The optimal height of the processed liquid layer $H_о$ corresponds to a certain air flow rate. And when the height of the liquid layer is less than the optimal ($H_ж < H_о$), the achievement of the required extraction rate of the dispersed phase is possible, for example, with an increase in the air flow rate [19].

In order to more clearly display the effect of the aerated liquid layer height on the PS extraction, the corresponding dependences were obtained at the surfactants' concentration of $2.16 \cdot 10^{-3}$ and $5.41 \cdot 10^{-3}$ kg/m^3, shown in figure 11.

As can be seen from figure 11, a sufficient height of the aerated liquid layer is 0.5-0.6 m; its further increase does not have a strong effect on the PS extraction. Exceeding the optimal aerated liquid layer height leads to an increase in the material consumption of the apparatus and an increased consumption of the working liquid and surfactants, as well as to an extension of the path of movement of the "bubble – particle" complexes, which can increase the probability of their destruction [19].

The graphical dependences given above were obtained without additional heating of the working liquid (about 10-15°C). In assessing the effect of the liquid temperature on the flotation process, the experimental research was carried out, the results of which are reflected in [16]. After processing the results of these experimental research, the dependences of the ABS and PS flotation indices on the liquid temperature *t* were plotted, shown in figures 12, 13.

As can be seen from figures 12 and 13, increasing the liquid temperature above 20°C leads to a sharp decrease in the ABS and PS extraction. It should be noted that in figures 12 and 13 there is a pattern of the influence of the liquid temperature on the floated components' extraction. This is, probably, explained by the fact that the dependence of the surfactants' foaming ability on the temperature is characterized by the solubility curves and for most surfactants they have an extremum [20,21]. It is likely that an increase in the temperature of the solution leads to the dehydration of the dissolved surfactant molecules. Moreover, they separate as an individual macrophase, which leads to a decrease in the number of surfactant molecules involved in the flotation process.

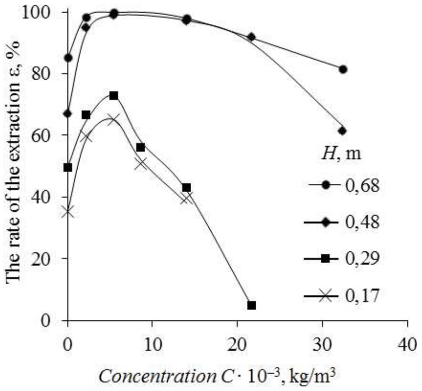


Figure 10 – Dependences of the PS extraction
on the surfactants' mixture concentration
at different heights of the aerated liquid layer

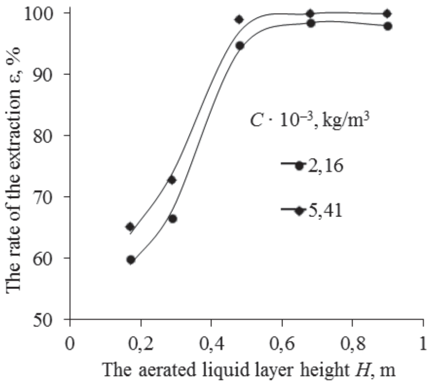


Figure 11 – Dependences of the PS extraction
on the aerated liquid layer height at different
surfactants' mixture concentration

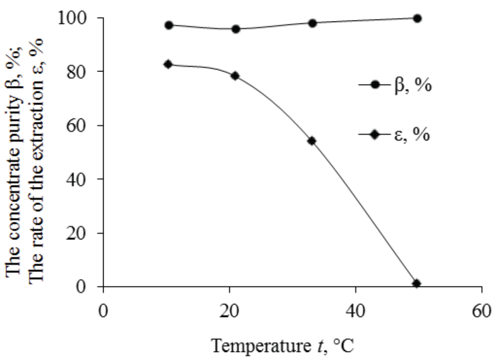


Figure 12 – Dependences of the concentrate purity
and the ABS extraction on the liquid temperature
at the surfactants' mixture concentration containing sodium
laureth sulfate and diethanolamide, $2.7 \cdot 10^{-3}$ kg/m^3
and at the air flow rate of 0.104 m^3/min·m^2

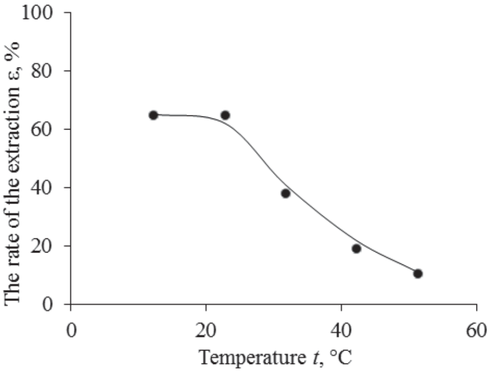


Figure 13 – Dependence of the PS extraction on the liquid
temperature when the aerated liquid layer height is 0.17 m,
the surfactants' mixture concentration is $5.41 \cdot 10^{-3}$ kg/m^3
and the air flow rate is 0.072 m^3/h·m^2

Conclusions. For separation of plastic wastes (polyamide, acrylonitrile butadiene styrene and polystyrene, the flotation method is proposed. Using this method, the effect of the surface-active substances' concentration, which were used as polidocanol, sulphanole and the mixture of surfactants containing sodium laureth sulfate and diethanolamide, was studied.

According to the research results, it was noted that the maximum extraction of the floated component depends on the polymer and surfactant type. A positive feature is that the maximum polymer extraction is achieved with a rather low concentration of surfactants. The mixture of surfactants at lower concentrations allows to achieve greater extraction of the floated component with less foaming ability.

The research results on the extraction of the floated component from the air flow show that its maximum extraction depends on the polymer and surfactant type. The nature of the air flow rate effect at different concentrations of surfactants does not change – only the extraction of the floated component changes.

The research results on the extraction of the floated component from the aerated liquid layer height show that the certain air flow rate corresponds to the optimal height of the processed liquid layer, and when the liquid layer height is less than the optimal, the required degree of the dispersed phase extraction is possible, for example, with increasing the air flow rate.

When assessing the influence of the liquid temperature on the flotation process, it was found that increasing the liquid temperature leads to a sharp decrease in the floated component extraction. This is explained by the fact that the dependence of the surfactants' foaming ability on the temperature is characterized by the solubility curves and for most surfactants they have an extremum.

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ПОЛИМЕРЛІК ҚАЛДЫҚТЫҢ ФЛОТАЦИЯЛЫҚ БӨЛІНУІН ЗЕРТТЕУ НӘТИЖЕЛЕРІ

Аннотация. Пластмасса қалдықтарын бөлу үшін (полиамид (ПА), акрилонитрилбутадиенстирол (АБС) және полистирол (ПС) флотациялық әдіс ұсынылды. Көрсетілген тәсілді пайдалана отырып, құрамында натрий лаууретсульфаты және диэтаноламид бар синтанол, сульфанол және ПБЗ қоспасы қолданылған беттік белсенді заттардың (ПАЗ) шоғырлану әсері зерттелді.

Пластмассаның ұсақталған қалдық қоспасының флотациялық бөлінуінің зерттеу нәтижелерін талдау флотацияланатын компонент шығарудың есептелген мәні және таза β концентраты бойынша жүргізілді. Флотацияланатын компонент алу полимер мен ПБЗ түріне байланысты екендігі атап өтілді. Оң ерекшелігі, ПБЗ-ның аса төмен концентрациясы барысында полимерлер шығарылады. ПБЗ қоспасы аз концентрацияда флотацияланатын компонентті көбік шығаруда көбірек алуға мүмкіндік береді.

ПБЗ қоспасының түрлі концентрациясында полистиролды ауа шығынынан бөліп алуды зерттеу нәтижелері ауаның көп шығым шығаратынын көрсетеді. Ауаның аз шығымында сұйықтық мөлшері газ көпіршіктерімен жеткіліксіз түрде қаныған. Ауа шығымының оңтайлы мәнінен асқанда флотация процесіне қатыспайтын газ көпіршіктері пайда болады. Көпіршіктер сұйықтық арқылы бөлшек флотациясына кедергі келтіретін турбулентті ағын жасай алады. Сұйықтықтың турбуленттік ағынында қозғалғанда «көпіршік – бөлшектер» кешені қирауға бейім келеді, себебі бөлшектер мен көпіршіктер түрлі инерционды (масса) болады. ПБЗ түрлі шоғырлануы барысында ауа шығынының әсер ету сипаты өзгермейді, яғни флотацияланатын компонентті алу жағдайы ғана өзгереді.

ПБЗ қоспасының түрлі концентрациясы барысында сұйықтықтың аэрирленетін қабатының биіктігінен полистиролды алуды зерттеу нәтижелері сұйықтықтың аэрирленетін қабат биіктігінде пластмассаның бөлшектің ауа көпіршігімен араласу ықтималдығы аз және кейбір әлеуетті флотацияланатын бөлшектер ауа көпіршігімен араласпай-ақ аппараттың түбіне түсіріледі. Өңделетін сұйықтық қабатының оңтайлы биіктігіне ауаның белгілі бір шығымы сәйкес келеді.

Флотация процесіне сұйықтық температурасының әсерін бағалау кезінде сұйықтық температурасының 20°С-тан жоғары көтерілуі АБС және КС шығымын күрт төмендетеді. Бұл ПБЗ көбіктеу қабілетінің температураға тәуелділігі ерігіш қисығымен сипатталады және ПБЗ көпшілігі үшін олар экстремумға ие. Ерітінді температурасының жоғарылауы ПБЗ ерітілген молекулалар дегидратациясына әкеп соқтыруы мүмкін.

Бұл ретте олар жеке макрофаз түрінде бөлінеді, бұл флотация процесіне қатысатын ПБЗ молекулалар санын төмендетеді.

Түйін сөздер: флотация, пластмасса қалдықтары, беттік белсенді заттар, концентрация, ауа шығыны, сұйықтық қабатының биіктігі, температура.

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РЕЗУЛЬТАТЫ ИССЛЕДОВАНИЙ ФЛОТАЦИОННОГО РАЗДЕЛЕНИЯ ПОЛИМЕРНЫХ ОТХОДОВ

Аннотация. Для разделения отходов пластмасс (полиамида (ПА), акрилонитрилбутадиенстирола (АБС) и полистирола (ПС)) предложен флотационный способ. С использованием указанного способа изучено влияние концентрации поверхностно-активных веществ (ПАВ), в качестве которых использовались синтанол, сульфанол и смесь ПАВ, содержащая лауретсульфат натрия и диэтаноламид.

Анализ результатов исследований флотационного разделения смеси измельченных отходов пластмасс проводился по рассчитанным значениям извлечения флотируемого компонента ε и чистоты концентрата β. Отмечено, что максимальное извлечение флотируемого компонента, зависит от типа полимера и ПАВ. Положительной особенностью является то, что максимальное извлечение полимеров достигается при довольно низкой концентрации ПАВ. Смесь ПАВ при меньших концентрациях позволяет достичь большего извлечения флотируемого компонента при меньшей пенообразующей способности.

Результаты исследований извлечения полистирола от расхода воздуха при различной концентрации смеси ПАВ показывают, что извлечение имеет максимум при некотором расходе воздуха. При малых расходах воздуха рабочий объем жидкости недостаточно насыщается пузырьками газа. При превышении оптимального значения расхода воздуха образуется много газовых пузырьков, не участвующих в процессе флотации. Пузырьки, двигаясь через жидкость, могут создавать турбулентные потоки, препятствующие флотации частиц. При движении в турбулентном потоке жидкости комплекс «пузырек – частица» склонен к разрушению, поскольку частицы и пузырьки имеют различную инерционность (массу). Характер влияния расхода воздуха при различной концентрации ПАВ не изменяется – изменяется лишь извлечение флотируемого компонента.

Результаты исследований извлечения полистирола от высоты аэрируемого слоя жидкости при различной концентрации смеси ПАВ показывают, что при малой высоте аэрируемого слоя жидкости вероятность столкновения пластмассовой частицы с пузырьком воздуха низкая и некоторые потенциально флотируемые частицы опускаются на дно аппарата, так и не успев столкнуться с пузырьком воздуха. Оптимальной высоте слоя обрабатываемой жидкости соответствует определенный расход воздуха.

При оценке влияния температуры жидкости на процесс флотации установлено, что повышение температуры жидкости выше 20°C приводит к резкому снижению извлечения АБС и ПС. Это объясняется тем, что зависимость пенообразующей способности ПАВ от температуры характеризуется кривыми растворимости и для большинства ПАВ они имеют экстремум. Вероятно, повышение температуры раствора приводит к дегидратации растворенных молекул ПАВ. При этом они выделяются в виде отдельной макрофазы, что приводит к снижению количества молекул ПАВ, участвующих в процессе флотации.

Ключевые слова: флотация, отходы пластмасс, поверхностно-активные вещества, концентрация, расход воздуха, высота слоя жидкости, температура.

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