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REMEDIATION OF ANIONIC DYE (BROMPHENOL BLUE) FROM AQUEOUS SOLUTIONS BY SOLVENT SUBLATION

Background. The accumulation of toxic effluent components is a considerable hazard to water resources potential of the country. It particularly relates to waste water pollutants belonging to II–IV hazard classes such as organic dyes and diluents.

Objective. The goal of this research was to investigate the main principles of Bromphenol Blue remediation from water by solvent sublation technique and to determine optimum process conditions.

Methods. Bromophenol blue (BB), an anionic dye, was removed from aqueous solution by solvent sublation of a BB – hexadecylpyridium complex (sublate) into isopentanol. The pH of the solution was determined by potentiometric method. Dye concentrations of the sample solutions were measured with the use of absorption spectroscopy.

Results. The effects of the following parameters on the solvent sublation were experimentally studied: the molar ratio of hexadecylpyridium chloride (HPC) to BB, pH of the aqueous phase, the removal process duration, type of organic solvent, the size of bubbles generated in the sparger and the addition of electrolytes (like KCl) and nonhydrophobic organic compounds (like ethanol). By making central composite orthogonal design and deriving second order mathematical model with the aid of MS Excel 2003 it was found that the maximum efficiency of depicted process can be attained in a case of carrying it out under the following optimum conditions: temperature 10 °C, surfactant/dye molar ratio 1.94:1; process duration – 15.3 min.

Conclusions. Within this research the main principles of Bromophenol Blue removal from water by solvent sublation were investigated. The second order experiment statistical model was derived with the use of central composite orthogonal design. The maximum relative standard deviation was equal to 4,7 %. Optimum conditions were determined: According to obtained results the highest level of BB elimination reached within the experiment was equal to 97.5 % and the residual dye content didn’t exceed the maximum allowable concentration (the M.A.C.) of acidic dyes 0.25 mg/dm^3.

Keywords: dye; Bromphenol Blue; optimum conditions; mathematical model; sublate spectrophotometry.

Introduction

It’s well-known that water is a unique substance which extinction will cause the death of every living organism. Despite the key role of water in the human life every year the worsening of nature water quality is increasing rapidly. Annually around 450 m^3 of effluent, containing wide range of pollutants, is discharged directly into the rivers and other surface water basins. More than a half of this amount doesn’t undergo any effective pretreatment

Unfortunately, Ukraine doesn’t remain beyond this ecological problem, moreover, it endures its exacerbation phase. According to international standards, mainly all of our big rivers and their tributaries belong to the category of polluted or highly polluted waters. There are numerous rivers where the content of one or several impurities exceeds the maximum allowable concentration (the M.A.C.) in dozens of times, for example, the Dnipro, the Desna, the Stryj River, the Siverskyj Donets and others.

The accumulation of toxic effluent components is a considerable hazard to water resources potential of the country. It particularly relates to waste water pollutants belonging to II–IV hazard classes such as organic dyes and diluents.

The main sources of water pollution by dyes are the following: textile industry, chemical plants, cellulose and paper industry and pharmaceutical industry. It is assumed that during dye production the loss of target product is nearly 1–2 % and in the case of dye usage 1–10 % loss occurs. For reactive dyes, this figure can be about 4 % [1]. Perhaps, this is caused by dye dilution in the water used for its synthesis, and the amount of such water is enormous: it takes approximately 100–225 tons of water to produce 1 ton of dye [2].

Textile industry also stands out, as it yields a large amount of effluents. It is estimated that about 10–15 % of dyes are released into processing water during different procedures [3].

So it’s obvious that the discharge of such raw effluent into the surface water entails high-level pollution thus in natural water dyes concentrations highly exceed affordable limits (0.05–0.25 мg/dm^3).

Due to complicated chemical structure of synthetic dyes they can't be biochemically decomposed in aqueous systems therefore local treating plants are not able to cope with this problem. Synthetic dyes are also extremely hazardous pollutants of natural environment due to the effect of potentiation. As a consequence, the result of such interactions is often unexpected.

Entering the environment dyes easily colour the water and the surrounings thus causing unfavorable estetic impression, worsening water organoleptic properties. In addition, dyes can significantly effect the photosynthesis ability of water inhabitants by decreasing water transparency. Dyestuff can be toxic for some flora and fauna species because of aromatic rings and chlorine substituents in their structure [3]. This can lead to total extinction of water living organisms, self-treatment processes disruption and human intoxication.

Thus synthetic dyes can cause significant environmental pollution and bring a serious risk factor for human diseases too.

There are different methods of wastewater treatment that provide either elimination or destruction of dyes such as: chemical processes (the use of Fentons reagent, ozonation, photocatalytic decolourization, electrochemical destruction), physical treatments (adsorption, membrane filtration, ion exchange, electrokinetic coagulation, etc.) and microbiological decomposition (decolourisation by white-rot fungi, anaerobic textile-dye bioremediation systems and adsorption by living/dead microbial biomass) [4, 5]. However all these techniques are often too expensive for applying, ineffective or produce much sludge. Therefore the search for more effective, inexpensive and low-waste method for dyes remediation from water still remains actual.

In this case solvent sublation is a good alternative. In this special adsorptive bubble separation non-foaming technique some organic solvent placed on the top of aqueous phase is used to collect the sublate adsorbed on the bubble surfaces of an ascending gas stream. This method, with its advantages of simultaneous separation and concentration, has recently attracted much attention in many fields. Based on the former reports and researches the following advantages of solvent sublation can be outlined:

1) high separation efficiency;
2) high concentration coefficient;
3) low dosage of organic solvent;
4) soft separation process;
5) simple operation and equipment [6, 7].

Moreover, this technique provides the possibility of the further dye recovery after its elimination. However the main disadvantage of solvent sublation is lower capacity in comparison with flotation but it can be overcome by the bubble size decreasing.

Solvent sublation consists of two underlying individual processes: bubble mass transfer and the mass transfer of thin film of water (water droplets). Sublate formation occurs after the injection of the surfactant into dye solution. Then this complex adsorbs on the bubble surface. After that the sublate adsorbed on water-gas interface is levitated to the top of the column. Sublate can't dissolve into the organic phase immediately, it keeps on staying on the water-organic interface of the water droplets.

Then the sublate enters into the organic phase by diffusive transport between the organic layer and water-organic boundary layer, which is driven by a concentration gradient. The sublate concentration on the bubble surface is higher than on the water-organic interface. In addition, after bubble rupturing the bubble surface transforms into the water-organic interface between water droplets and the organic phase, and the total area of the interface is rapidly reduced. However the amount of the sublate on the interface remains the same (is not reduced). Therefore the sublate concentration on the water-organic interface is highly increased, so the separation balance greatly turns to the organic phase [6].

Problem statement

The objective of this research was to investigate the main principles of Bromphenol Blue remediation from water by solvent sublation technique and to determine optimum process conditions.

To rich this goal the next tasks had to be completed:

1) to study experimentally the effect of the major influencing factors on the solvent sublation process;
2) to generate the central composite design;
3) to build a mathematical model that could adequately describe the process.

Materials and methods

The scheme depictured below was used to carry out solvent sublation process (Fig. 1). ∂

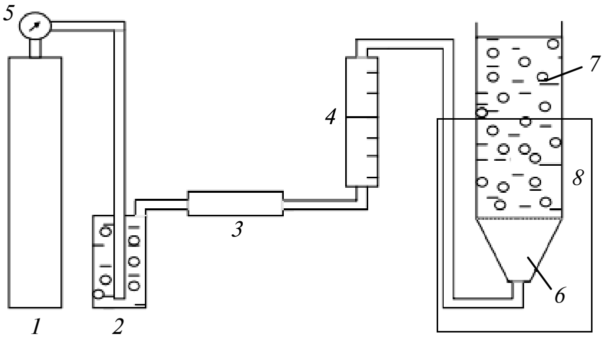

Fig. 1. Flowsheet of the experimental unit: *1* — gas cylinder; *2* — humidifier; *3* — filter; *4* — gas flow rate; *5* — pressure meter; *6* — Schott filter; *7* — solvent sublation column; *8* — thermostat

Solvent sublation process took place in glass column 7. It was 42 cm in length with an initial diameter of 3.3 cm and had 2 access ports. Gas bubbles were generated in a Schott filter of 16 μm porosity. By changing the porosity of the gas sparger (16, 40,100 and 160 μm), different bubble sizes were also created, thus altering the surface area of gas bubbles. Compressed nitrogen was supplied by the gas cylinder 1 and moved through the humidifier and the filter to the bottom of the solvent sublation column. Gas rate was measured by flow rate meter 4. Thermostat was used to maintain system temperature near the desired setpoint.

To determine dye concentration in the aqueous phase, the sample solution was withdrawn from the top access port for analysis.

Reagent-grade HPC was used as a collector without further purification. Reagent grade BB and the other reagents were all analytical grade.

For the solvent sublation running, HPC was added to the sample solution (250 sm^3) to form the dye-surfactant complex; the solution containing 1.5 10^{-5} mol/dm^3 (10 mg/dm^3) BB was poured into the sublation column; and 5 mL of isopentanol was added immediately; then the timer was started and samples of aqueous solution were taken for analysis at specified times.

The pH of the solution was measured with the pH-meter Portlab 102. UV-visible spectra of the sample solutions were measured with the scanning spectrophotometer Portlab 501 at the maximum peak of 588 nm.

Results and discussion

Parameters influencing the solvent sublation process can be classified as those, that effect the aqueous and organic solutions and those, which are operational factors. Parameters of the first group are classified as those that relate to aqueous phase composition (pH, ionic strength, presence of various species) and those that are connected with organic phase composition (organic solvent: type and volume, presence of different additives). The operational parameters are: gas flow rate and temperature.

pH of the aqueous solution is a very important factor because it determines the presence of ionic species, which are involved in solvent sublation process. Such processes as hydrolysis, complex formation and precipitation of insoluble substances are governed by pH values of aqueous solutions.

The presence of surfactant is also very important factor for solvent sublation because usually it makes extracted ion-pairs more hydrophobic. In addition, surfactants tend to reduce the surface tension of aqueous solution and decrease the size of bubbles generated in the sparger [8].

Hexadecylpyridium chloride (HPC) was used as the surfactant in all cases because it showed high efficiency in the process of BB removal by solvent sublation during previous researches.

It's known, that higher sublate solubility in organic layer enhances dye removal efficiency. In this research different organic compounds were investigated to find out the proper one.

Mean bubble radius that is formed by Schott filter is one of the crucial process parameters.

Gas flow rate is also an important factor for solvent sublation run. According to the former publication [9], the increase of gas flow rate enhanced the removal efficiency due to mass transfer intensification. Therefore in this study the experiment was conducted under the maximum permitted gas flow rate condition (50 sm^3/h). At higher gas flow rates, the oil-water interface can be drastically disrupted and some drops of the top organic layer can return back to solution.

The effect of the molar ratio of HPC to BB on solvent sublation

HPC together with BB formed hydrophobic complex that interacted with gas bubbles. Then hydrophobic compound was levitated on a bubble surface to the top of an aqueous column where it encountered a solvent layer (isopentanol) to which the material was transferred as the bubbles moved through the solvent layer.

Results of this experiment are shown below (Fig. 2).

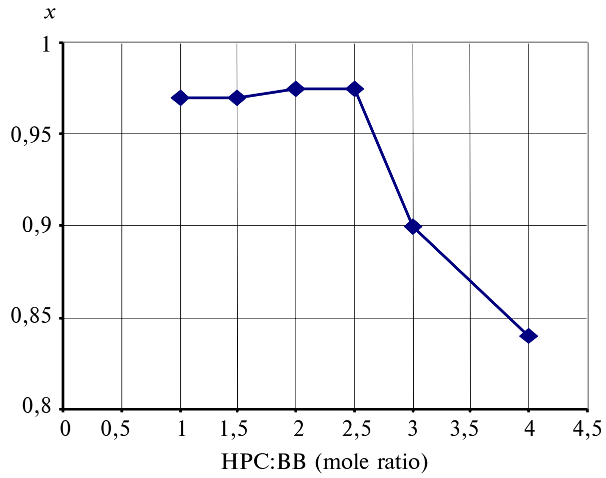

Fig. 2. The dependence of BB removal efficiency on the molar ratio of HPC to BB. pH 1,1

The graph shows that molar ratios HPC:BB 2:1 and 2,5:1 caused the highest dye remediation equal to 97.5 % providing the lowest residual dye concentration in the water. The range of molar ratios HPC:BB from 1:1 to 1,5:1 didn't represent affordable results, perhaps due to incomplete formation of a dye-surfactant complex. When the ratio was higher than 2,5:1, solvent sublation efficiency was lower, presumably due to the competition of excess surfactant ion with the dye-surfactant complex for the bubble surface.

Large excess of surfactant can also lead to emulsification of isopentanol thus the dye-surfactant complex in the isopentanol may constantly be dispersed back into the solution and the separation efficiency can decrease greatly [9].

The effect of process duration on solvent sublation

Dye concentration in the aqueous phase was measured every 5 minute for 30 minutes. As graph shows (Fig. 3), the optimum process duration was equal to 15 minutes with 97.5 % BB removal accordingly.

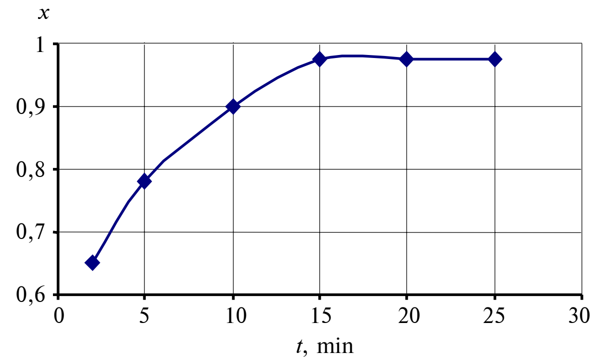

Fig. 3. The variation of BB removal efficiency in dependence on the elapsed time. ??HPC:BB (mole ratio) 2:1, pH 1,1, pore diameter 16 μm

The effect of organic solvent nature on the process effectiveness

Within this research the influence of such organic frame particularities as carbon chain length and the degree of branching in the carbon chain was investigated. The next compounds were used as the organic solvent: n-pentanol, isopentanol, 1-hexanol, 1-octanol and 2-octanol (Fig. 4).

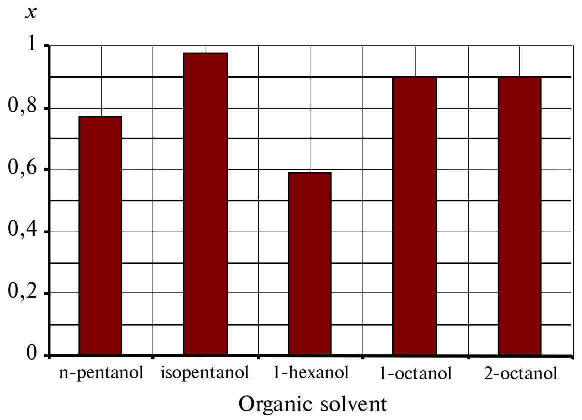

Fig. 4. The variation of BB removal efficiency in dependence on the organic solvent type. HPC:BB (mole ratio) 2:1, pH 1,1, pore diameter 16 μm

The diagram shows that the highest BB removal equal to 97.5 % was achieved by the use of isopentanol as an organic solvent. So, according to attained results, the branching of the carbon chain influenced the treatment process in the positive way, in sharp contrast to the effect of normal structure of the carbon chain. For example, in the case of n-pentanol BB removal is much lower and is equal to 77 %. The first possible reason lies in the fact that probably there is much better solubility of dye-surfactant complex in organic solvent with higher degree of branching in the carbon chain. And the other one may lie in the fact that it is easier to hold big-sized sublate by branched carbon skeleton solvent. In the case of using n-hexanol the lowest dye elimination was obtained.

However depicted tendency can't adequately describe the behaviour of solvents which have longer carbon chains, for example, 8 or more carbon atoms. In such case both 1-octanol and 2-octanol retained almost equal amounts of dye. Therefore the degree of carbon chain branching didn't play any essential role there. Both of these two isomers attained 90 % of BB removal, but this efficiency is lower than in the case of isopentanol. This can be explained by difficulties of the sublate solubility or retaining within the solvent layer characterised by more complicated skeleton.

The effect of the mean bubble diameter on the solvent sublation

As it was previously mentioned, the size of bubbles generated in the sparger is one of the key factors in solvent sublation. Attained results are shown in Fig. 5.

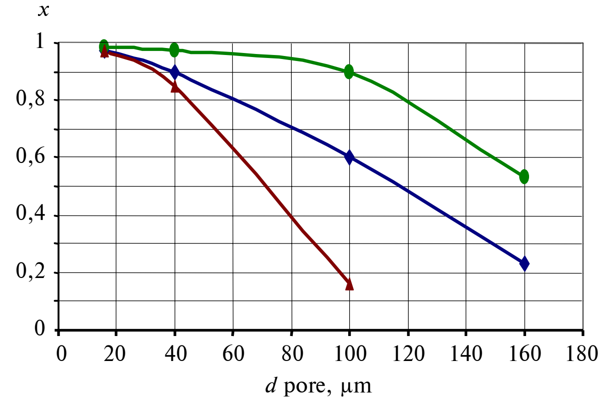

Fig. 5. The variation of removal efficiency in dependence on the bubble size. HPC:BB (mole ratio) 2:1, pH 1,1: ◆ – $x = f(d$ pore) (d in. = 33 mm); ● – $x = f(d$ pore) (d in. = 21 mm); ▲ – $x = f(d$ pore) (d in. = 40 mm)

Graphs show that the removal efficiency increased with the decrease of generated bubble diameter. The highest recoveries were obtained for all three columns with initial diameters 21, 33 and 44 mm in the case of applying Schott filter of 16 µm porosity $x = 98.5$, 97.5 and 97.5 % respectively. Attained data proved that the bigger pore size was, the lower remediation efficiency it caused, and the worst results were obtained in the case of the largest gas bubbles: $x = 53$, 23, 16 %.

Bubble size reduction caused the increase of the interfacial area per unit volume of air ($3/r$), thus the bubble residence time was also extended because smaller bubbles had lower rise velocities. Smaller bubbles also enhanced mass transfer from the liquid phase to the bubbles due to very large surface area per unit volume of air.

According to represented graphs (see Fig. 5) the decrease of the column initial diameter intensified the removal process. This can be explained by higher retention time of the bubble in the system.

The effect of pH on solvent sublation

In contrast to results of the former reports [8, 9], this research revealed that in the case of BB removal pH of the aqueous phase slightly influenced the process run.

Results of the experiment are represented below (Fig. 6).

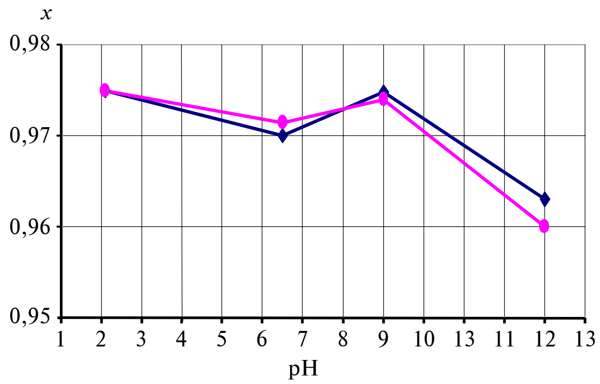

Fig. 6. The dependence of the BB removal efficiency on the pH value. HPC:BB (mole ratio) 2:1, $\tau = 15$ min: ◆ – $x =$ $= f(\text{pH})$; ● – $x = = f(\text{pH})$ simultaneous

Graphs show that the increase of pH reduced treatment efficiency. At pH 12 the lowest BB removal was detected: $x = 96$ % that corresponds to the residual dye concentration in water equal to 0.4 mg/dm^3 which exceeds the M.A.C.

Such behaviour can be explained by the next equilibrium established in aqueous solution:

$$B + A^- \underset{\text{OH}^-}{\overset{\text{H}^+}{\rightleftarrows}} HA + BH^+ \rightleftarrows [HA - BH^+]\,, \quad (1)$$

where B represents the HPC; HA is the dye (Bromphenol Blue); A^- is the deprotonated anion of BB and BH^+ is the protonated HPC cation.

According to the equation (1) the increase of the acidic pH drives the equilibrium toward a larger concentration of BH^+, which easily binds with HA to form the complex $[HA - BH^+]$. By contrast, the increase of the basic pH drives the equilibrium toward a larger concentration of B and the complex quantity decreases [9].

In spite of slight effect of pH on the BB removal observed throughout the experiment, the most proper pH value for efficient treatment was pH 1.1 because it assured the lowest value of residual dye concentration 0.25 mg/dm^3 equal to the M.A.C.

Effects of co-solutes

The influence of the inorganic salt, KCl, used as a co-solute, on the sublation of the BB-HPC complex is shown in Fig. 7.

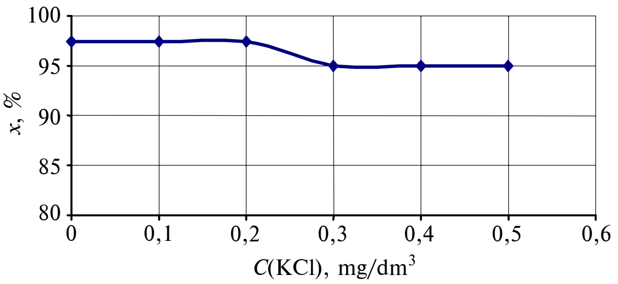

Fig. 7. The dependence of the BB removal efficiency on the KCl concentration. HPC:BB (mole ratio) 2:1, τ =15 min

The increase of the KCl concentration is correlated with the decrease in the percent removal and the elimination efficiency. This finding was attributed to an ion-pair equilibrium that existed in the aqueous solution between the dye and surfactant molecules. In aqueous solution, the following equation is applicable:

$$HP^+B^- + K^+Cl^- \rightleftharpoons HP^+Cl^- + K^+B^-, \quad (2)$$

where HP^+B^- is Bromphenol Blue-hexadecylpyridium complex.

So according to Le Chatelier's principle, the increase of the salt concentration (KCl) drove the equilibrium toward a smaller concentration of BB-HPC complex. Thus, the effectiveness of removal declined.

The effect of 0,006–0,086 mole fractions of ethanol added to the bulk solution was also studied. Results are represented below (Fig. 8).

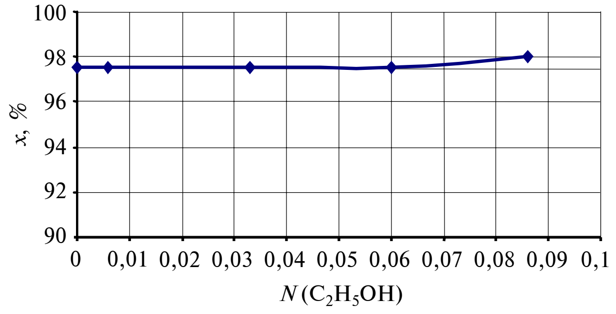

Fig. 8. The effect of ethanol molar fraction on BB removal efficiency. HPC:BB (mole ratio) 2:1, τ =15 min

The graph shows that lower molar fractions of ethanol had no significant influence on dye removal and only the highest quantity of this cosolute equal to 0,086 molar fraction entailed slight increase in treatment efficiency equal to 98 %.

Dye remediation enhancements might occur due to the next factor. The addition of ethanol changed bubble properties considerably; more very small bubbles were evident upon addition of ethanol than when ethanol was absent. This is a well-known effect that arises from the lowering of water surface tension, which prevents the bubbles from growing larger. Such smaller bubbles provide a very large surface area per unit volume of air, which enhances mass transfer of the contaminant from the liquid phase to the bubbles [9].

Mathematical model deriving and the determination of optimum conditions

Central composite orthogonal design was selected to derive mathematical model (second order) with the aid of MS Excel 2003 [10, 11]. The following model was obtained:

$$Y = 66{,}22 + 0{,}43\cdot Z_1 + 6{,}79\cdot Z_2 + 2{,}59\cdot Z_3 - 0{,}06\cdot Z_3\cdot Z_2 + 0{,}01\cdot Z_1\cdot Z_3 + 0{,}13\cdot Z_2\cdot Z_3 - 0{,}02\cdot Z_1^2 - 0{,}07\cdot Z_3^2,$$

according to the next definition: Z_1 – temperature factor; Z_2 – surfactant excess factor; Z_3 — process duration factor.

By deriving mathematical model, represented above, it was found that the maximum efficiency of depicted process can be attained in a case of carrying it out under the following optimum conditions: temperature 10 °C, surfactant/dye ratio 1.94:1; process duration — 15.3 min.

The test of the significance of regression coefficients showed that four of them are insignificant however they can't be excluded from the model since it will entail dramatic accuracy decrease.

The check of the model adequacy proved that it can accurately describe the process and can be used for further simulations. The maximum relative standard deviation was equal to 4.7 %.

Conclusions

To sum up, within this report contemporary state of water pollution problem caused by synthetic dyes was analysed, covering the main methods, typically used for dyes decomposition and remediation. Solvent sublation was proposed as an effective alternative.

The main principles of Bromophenol Blue removal from water by solvent sublation were investigated. The following major factors and their influence on treatment process were studied in detail: pH, type of organic solvent, the mean bubble diameter, gas flow rate, molar ratio of surfactant to dye and the presence of such additives as KCl and ethanol.

Acidic pH, fine bubble radius had a positive effect on the removal efficiency. The increase of gas flow rate up to 50 sm^3/min also enhanced the treatment. The highest dye removal was obtained in the case of isopentanol used as the solvent. Smaller fractions of ethanol (0.006–0,06) had no significant effect on the efficiency of the solvent sublation, only the quantity of this co-solute equal to 0,086 molar fractions slightly improved the treatment effectiveness. The increase of KCl concentrations gradually decreased the dye removal efficiency due to the equilibrium driving toward the smaller concentration of BB-HPC complex.The initial dye concentration was 10 mg/dm^3.

The second order experiment statistical model was derived with the use of central composite orthogonal design. The check of model adequacy proved that it can accurately describe the process and can be used for further simulations. The maximum relative standard deviation was equal to 4,7%.

To assure attaining the maximum treatment efficiency the next optimum conditions were determined: temperature 10 °C, surfactant/dye ratio 1,94:1; process duration – 15.3 min. It was found that the process should be conducted under such conditions: pH 1.1, solvent – isopentanol, Schott filter nominal pore size – 16 μm, molar ratio surfactant:dye – 2:1.

The recovery efficiency was 97.5 % and the corresponding residual Bromphenol Blue content in the aqueous phase was equal to 0.25 mg/dm^3 which didn't exceed the maximum allowable concentration. Attained results can be used in further studies.

Further researches of this team will deal with the determination of the complete sublate formation mechanism, confirmed by thermodynamic calculations. Possible ways of organic phase utilization after the treatment process will also be covered.

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ВИДАЛЕННЯ АНІОННОГО БАРВНИКА (БРОМФЕНОЛОВОГО СИНЬОГО) З ВОДНИХ РОЗЧИНІВ МЕТОДОМ ФЛОТОЕКСТРАКЦІЇ

Проблематика. Накопичення токсичних компонентів стічних вод є суттєвою небезпекою для водного потенціалу держави. Це особливо стосується забруднювачів стічних вод, що належать до II–IV класів небезпеки, таких як барвники та розчинники.

Мета дослідження. Вивчити основні закономірності вилучення з води бромфенолового синього технологією флотоекстракції та визначити оптимальні умови процесу.

Методика реалізації. Бромфеноловий синій, аніонний барвник, видалявся з водних розчинів флотоекстракцією комплексу бромфеноловий синій–гексадецилпіридиній (сублат) в ізопентанол. pH розчинів визначався за допомогою потенціометричного методу. Концентрації барвника зразків розчинів вимірювались методом абсорбційної спектрофотометрії.

Результати дослідження. Було експериментально досліджено характер впливу на флотоекстракцію таких параметрів: pH середовища, молярне співвідношення ПАР:барвник, тривалість процесу, природа органічного розчинника, розмір пухирців, згенерованих у розприскувачі, додавання електролітів (як KCl) та негідрофобних органічних сполук (як етанол). З допомогою MS Excel 2003 через побудову центрального композиційного ортогонального плану та виведення математичної моделі другого порядку було виявлено, що максимальна ефективність описаного процесу може бути досягнута за таких оптимальних умов: T = = 10 °C, мольне співвідношення ПАР:барвник = 1,95:1, тривалість процесу – 15,3 хв.

Висновки. У ході дослідження було вивчено основні закономірності вилучення з води бромфенолового синього. Експериментально-статистична модель другого порядку була виведена з використанням центрального композиційного ортогонального плану. Максимальне відносне відхилення дорівнювало 4,7 %. Було визначено оптимальні умови. Відповідно до отриманих результатів, найвищий ступінь вилучення бромфенолового синього, досягнутий у ході експерименту, дорівнював 97,5 % і залишковий вміст барвника не перевищував гранично допустимої концентрації кислотних барвників 0,25 мг/дм^3.

Ключові слова: барвник; бромфеноловий синій; оптимальні умови; математична модель; сублат; спектрофотометрія.

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УДАЛЕНИЕ АНИОННОГО КРАСИТЕЛЯ (БРОМФЕНОЛОВОГО СИНЕГО) ИЗ ВОДНОГО РАСТВОРА МЕТОДОМ ФЛОТОЭКСТРАКЦИИ

Проблематика. Накопление токсичных компонентов сточных вод представляет существенную опасность для водного потенциала государства. Это особенно касается загрязнителей сточных вод, относящихся к II–IV классам опасности, таких как красители и растворители.

Цель исследования. Изучить основные закономерности извлечения из воды бромфенолового синего технологией флотоэкстракции и определить оптимальные условия процесса.

Методика реализации. Бромфеноловый синий, анионный краситель, удалялся из водных растворов флотоекстракцией комплекса бромфеноловый синий – гексадецилпиридиний (сублат) в изопентанол. pH растворов определялся с помощью потенциометрического метода. Концентрации красителя образцов растворов измерялись методом абсорбционной спектрофотометрии.

Результаты исследования. Был экспериментально исследован характер воздействий на флотоэкстракцию следующих параметров: pH среды, молярное соотношение ПАВ:краситель, продолжительность процесса, природа органического растворителя, размер пузырьков, сгенерированных разбрызгивателем, добавки электролитов (как KCl) и негидрофобных органических соединений (как этанол). С помощью MS Excel 2003 путем построения центрального композиционного ортогонального плана и вывода математической модели второго порядка было установлено, что максимальная эффективность описанного процесса может быть достигнута при следующих оптимальных условиях: T = 10 °С, мольное соотношение ПАВ:краситель = = 1,95:1, продолжительность процесса – 15,3 мин.

Выводы. В ходе исследования были изучены основные закономерности извлечения из воды бромфенолового синего. Экспериментально-статистическая модель второго порядка была выведена с использованием центрального композиционного ортогонального плана. Максимальное относительное отклонение равно 4,7 %. Были определены оптимальные условия. Согласно полученным результатам, высшая степень извлечения бромфенолового синего, достигнутая в ходе эксперимента, равна 97,5 % и остаточное содержание красителя не превышало предельно допустимой концентрации кислотных красителей 0,25 мг/дм^3.

Ключевые слова: краситель; бромфеноловый синий; оптимальные условия; математическая модель; сублат; спектрофотометрия.

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