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Optimizing Dye Wastewater Purification: Ultrasonic and Flotation With Ozonation Synergy

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ABSTRACT

The article presents the results of experimental studies of the efficiency of purification of model and real wastewater from dyeing and finishing industries using pneumatic flotation using an ozone-air mixture instead of air and a combination of ultrasonic treatment and ozonation. The influence of gas mixture consumption, dye concentration, and ozone concentration in the gas mixture on the cleaning efficiency was studied. The purification efficiency was assessed by optical density and COD. By using an ozone-air mixture instead of air in the flotation process, an efficiency increase of up to 12 times was achieved. It has also been shown that wastewater treatment efficiency increases by up to 12% when combining ozone-air flotation with ultrasonic treatment at 630 W and operating frequency 22% ± 10% kHz. This effect may be associated, first of all, with the dispersion of bubbles of the ozone-air mixture, which leads to an increase in their total surface and, accordingly, to the rise in the kinetics of mass transfer—ozone dissolution.

1 | Introduction

Effective wastewater treatment remains a critical global challenge due to the increasing release of complex industrial pollutants, which pose significant environmental and health risks, necessitating the development of more efficient and sustainable purification technologies [1–3]. The difficulty of treating colored wastewater is because organic contaminants (dyes, surfactants, and others) are biochemically stable and are found in wastewater mainly in a dissolved state [4, 5]. To decolorize dyes and mineralize other organic contaminants, fairly deep destruction of their molecules is required since they have a fairly high molecular weight [6, 7]. The problem of treating wastewater from dyeing industries is a very urgent task, primarily to prevent the entry of highly toxic organic compounds into water bodies [8]. After preliminary treatment at local treatment facilities, wastewater from dyeing and finishing industries rarely reaches the Chemical Oxygen Demand (COD) discharge standards, for which purpose wastewater is often diluted with clean water [9, 10]. Methods for treating wastewater from dyeing and finishing industries can be divided into three groups. The first group of methods includes coagulation [11, 12], reagent pressure flotation [13, 14], and electrocoagulation [15, 16]. The second group includes methods such as sorption on active carbons and macroporous ion exchangers [17, 18], reverse osmosis [19, 20], ultrafiltration [21, 22], and foam separation [23, 24]. The third group combines destructive redox

methods that cause deep transformations of organic compounds. During destructive cleaning, organic dyes are broken down into simpler, easily oxidized organic products or mineral compounds, and surfactants are destroyed with loss of surface-active properties. Of the destructive methods, the most widely used are the treatment of wastewater with oxidizers [25, 26], electrochemical [27], or photo-catalytic effects [28–30]. Regarding photocatalysts, the most effective purification is achieved using micro- and nano-sized particles of photocatalysts [31, 32]. Currently, these studies are carried out mainly in laboratory conditions, due to the difficulty of separating photocatalyst particles after purification. One of the modern trends in wastewater treatment is the combination of treatment methods to achieve a synergistic effect. For example, the use of pressure flotation—membrane bioreactor—ozone oxidation [33]. For example, ozonation followed by coagulation [34], or coagulation followed by flotation [35]. Many articles note the positive effect of ozone on the coagulation process [36]. At the same time, an interesting direction is the combination of flotation with ozonation. This approach was proposed earlier, for example, for pressure flotation [37]. The achieved level of reduction in COD was 88%, suspended solids 92%, and total nitrogen 67.7%. An effective phosphorus removal of 94.6% was achieved only after subsequent coagulation. A similar experiment was conducted by the authors [38] on wastewater from cosmetics production plants. However, pressure flotation using ozone was complemented by pre-coagulation of wastewater. The cleaning efficiency in terms of COD was 81.3% and in terms of suspended solids 96.3%. The known results in this direction are summarized in [39]. The effectiveness of a combination of two processes: micro- and nanoflotation with ozonation was studied, technical and operational factors influencing the process (bubble size, pH conditions, addition of coagulant and flocculant) were studied, the effectiveness of flotation with ozone and air on model and industrial wastewater was studied, the potential reduction in operating costs and treatment efficiency, and the effect of ozone on the potential increase in wastewater biodegradability was investigated. A comparison of such combined methods as coagulation-flocculation and ozone flotation was studied in [40]. This work also studied the effect of the flow rate of the ozone-air mixture in the range of 0.2–1 L/min. Gravity membrane filtration and ozone flotation were studied in [41]. The authors of [42] studied complex purification using a combination of coagulation and ozone flotation. Several processes such as ozonation, flotation, coagulation, and decolorization can be performed in one integrated reactor [43]. The results showed that the reduction efficiency of COD, color, turbidity, and suspended solids in the ozone flotation process could reach 25.4%, 49.9%, 95%, and 96%, respectively. Meanwhile, the processing cost was reduced by 47% compared with the electrocatalytic process. It was noted in [44] that the effective dose of ozone for treating municipal wastewater was 0.8–1.6 mg O_3/L. It should be noted that these studies are still relevant today [45, 46]. The use of ozone has additional benefits, such as the disinfection of wastewater and the internal surface of wastewater treatment facilities and pipelines [47], as well as their corrosion [48, 49]. Despite the presence of a few publications on this topic, they present point studies, without a broad assessment of ozonation parameters (ozone concentration in the ozone-air mixture, a wide range of ozone-air mixture consumption, the influence of dye concentration, etc.).

An analysis of literature sources shows that combined systems for treating wastewater from dyeing and finishing industries, as well as the use of methods that allow intensifying existing treatment methods, are considered promising today. Some of these methods can be considered ozonation [33], the use of ultrasonic treatment [50, 51], and hydrodynamic cavitation [52]. Modern literary sources note positive effects when using ultrasound to purify wastewater from dyes and surfactants, which initiates additional flotation and coagulation effects and activates heat and mass transfer processes.

Ultrasonic treatment itself is not highly effective, while it can intensify other methods. For example, in combination with electrocoagulation, it helps prevent the deposition of contaminants on the surface of electrodes [53]. The combined use of ultrasonic treatment and ozone was studied in [54–56]. The influence of emitter power and treatment time on the destruction of surfactants was studied [54]. It has been shown that when the power increases from 20 to 40 W, the effective destruction time decreases from 15 to 5 min. In turn, the use of ozone is also promising in water purification systems. The combination of ozonation with H_2O_2, ultraviolet radiation, catalysts, and ultrasonic treatment leads to increased formation of hydroxyl radicals and increased efficiency of the purification process [57].

This paper presents research on the combined treatment of wastewater from dyeing and finishing industries using ultrasonic treatment and ozone flotation.

The main objectives of this study were: (i) to study the influence of parameters when using ozone instead of air in the flotation process on the efficiency of wastewater treatment from dyes; (ii) to study the influence of ozone flotation parameters using ultrasonic dispersion.

2 | Materials and Methods

2.1 | Materials and Reagents

To evaluate the effect of different degradation methods, methylene blue (basic) dye was chosen. For the experiment, model dye solutions with concentrations of 2.5, 5, and 10 mg/L and 0.02% surfactant content (sodium dodecyl sulfate) were used. The treatment efficiency was also assessed using real wastewater from the enterprise. Composition of wastewater: pH 7.26, suspended solids 487.5 mg/L, chlorides 1681.25 mg/L, sulfates 245.8 mg/L, oil products 0.39 mg/L, surfactants 2.11 mg/L, COD 327.5 mg O_2/L, dry residue 906.5 mg/L, and iron 3.46 mg/L. The temperature of the treated wastewater was 21°C ± 2°C.

2.2 | Wastewater Treatment Approaches

For pneumatic flotation with ozone, two ozonizers were used: VGO-15 (2.7 gO_3/m^3) and Pinuslongaeva F1 (8.3 gO_3/m^3). The volume of water being treated was 1 L, and the height of the liquid layer was 20 cm. The flow rate of the ozone-air mixture at the outlet of the ozone generator was 2.5, 3.75, and 6.25 L/min. Thus, the specific consumption of the ozone-air mixture is 2.5, 3.75, and 6.25 L/(L·min). Wastewater from the enterprise was

purified at a constant flow rate of the gas mixture of 6.25 L/min (correspondingly, the specific flow rate was 6.25 L/(L·min)). The ozone concentration in the gas mixture during the treatment of wastewater from the enterprise was 8.3 g/m^3. Ceramic aerators were used to disperse the gas mixture. For ultrasonic treatment (cavitation), an ultrasonic installation with a piezoelectric emitter manufactured by INLAB (Russia) IL 100–6/1 was used. Installation power—630 W, operating frequency—22 ± 10% kHz, oscillation amplitude—no less than 40 μm. The intensity of sound vibrations under the experimental conditions was 79 W/cm^2. The flotation process was carried out periodically for each selected processing condition. During the treatment process, flotation sludge accumulates on the surface of the treated wastewater. The resulting flotation sludge was removed after completion of the flotation process.

2.3 | Wastewater Characterization Techniques

The purification efficiency of the model and real wastewater was determined by optical density with conversion to actual concentration using the Equation (1):

$$\varphi = (S_0 - S_n/S_0) \times 100\% \quad (1)$$

where C_0 is the concentration of the initial dye solution or COD, mg/L; C_n is the concentration of the dye solution or COD after treatment, mg/L.

To determine the optical density, a PE-5300vi spectrophotometer was used. The maximum absorption for the dye methylene blue is observed at 660 nm. The maximum absorption for wastewater is observed at a wavelength of 300 nm. Also, the treatment efficiency of real wastewater was measured using the COD indicator. The results were processed using MatLab software.

3 | Results and Discussion

3.1 | Flotation of Dyeing Industry Wastewater Using Ozone

The results obtained for the purification of model wastewater with an air mixture with an ozone content of 0 g/m^3 (Figure 1), 2.7 g/m^3 (Figure 2), and 8.3 g/m^3 (Figure 3) show a natural increase in cleaning efficiency with increasing flow rate gas mixture and ozone concentration, as well as with a decrease in the initial concentration of methylene blue dye. The results of the flotation of model wastewater using air showed a maximum treatment efficiency of around 20% (Figure 1). From the results obtained, it is clear that the air mixture flow rate should be more than 3 L/min and the processing time should be at least 20 min. When using ozone, the gas mixture flow rate must also be at least 3 L/(L·min) and the cleaning time must be at least 15 min. Previously, in [58], we showed that the optimal time for water saturation with ozone is about 10 min. This is confirmed by the data obtained, presented in Figures 2 and 3. The data obtained correlates with the data of the article [59] where the authors used model wastewater with acid red dye 18. With a cleaning time of 25 min, 100% purification was achieved. In the article [60], a purification efficiency of 99% was achieved in 15 min of purifying water from synthetic dye.

A model was obtained that describes the effectiveness of the dependence of ozone concentration in the ozone-air mixture (0,

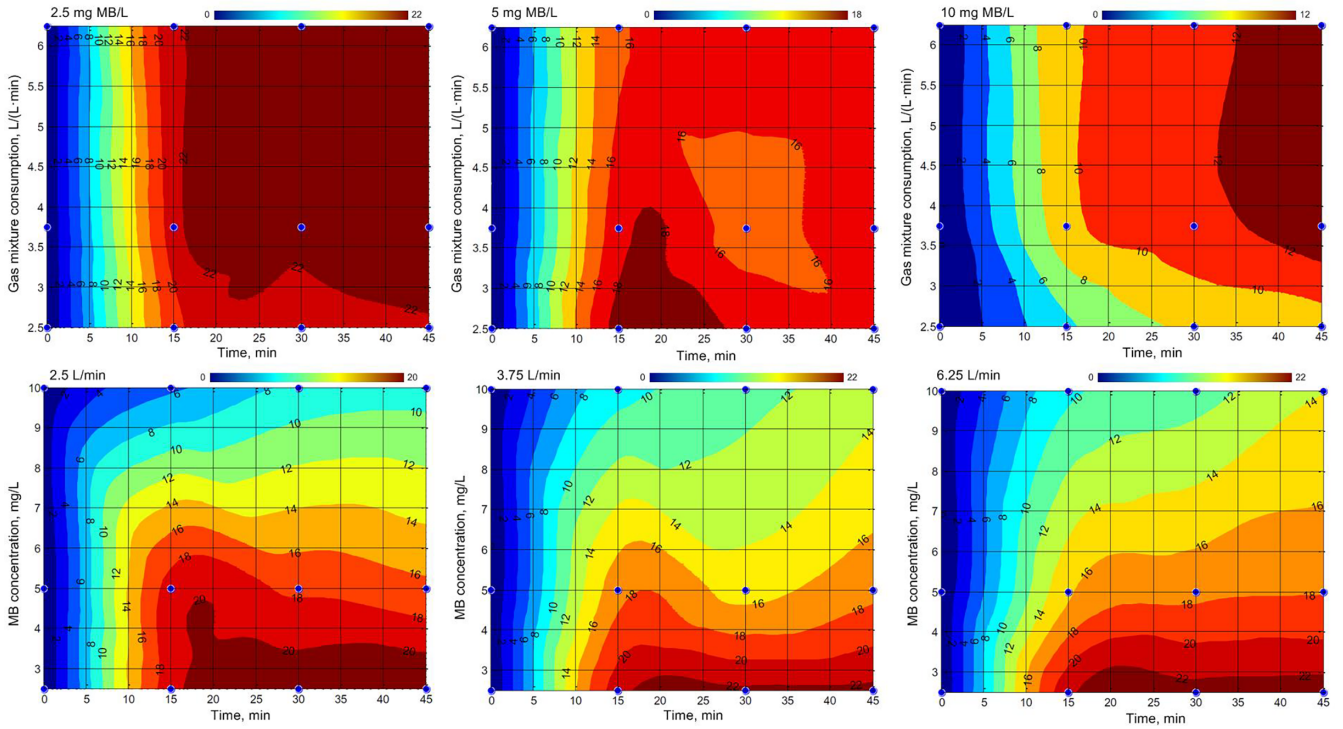

FIGURE 1 | Cleaning efficiency depends on the flow rate of the ozone-air mixture, the concentration of methylene blue and the treatment time at an ozone concentration in the ozone-air mixture of 0 g/m^3 (air aeration).

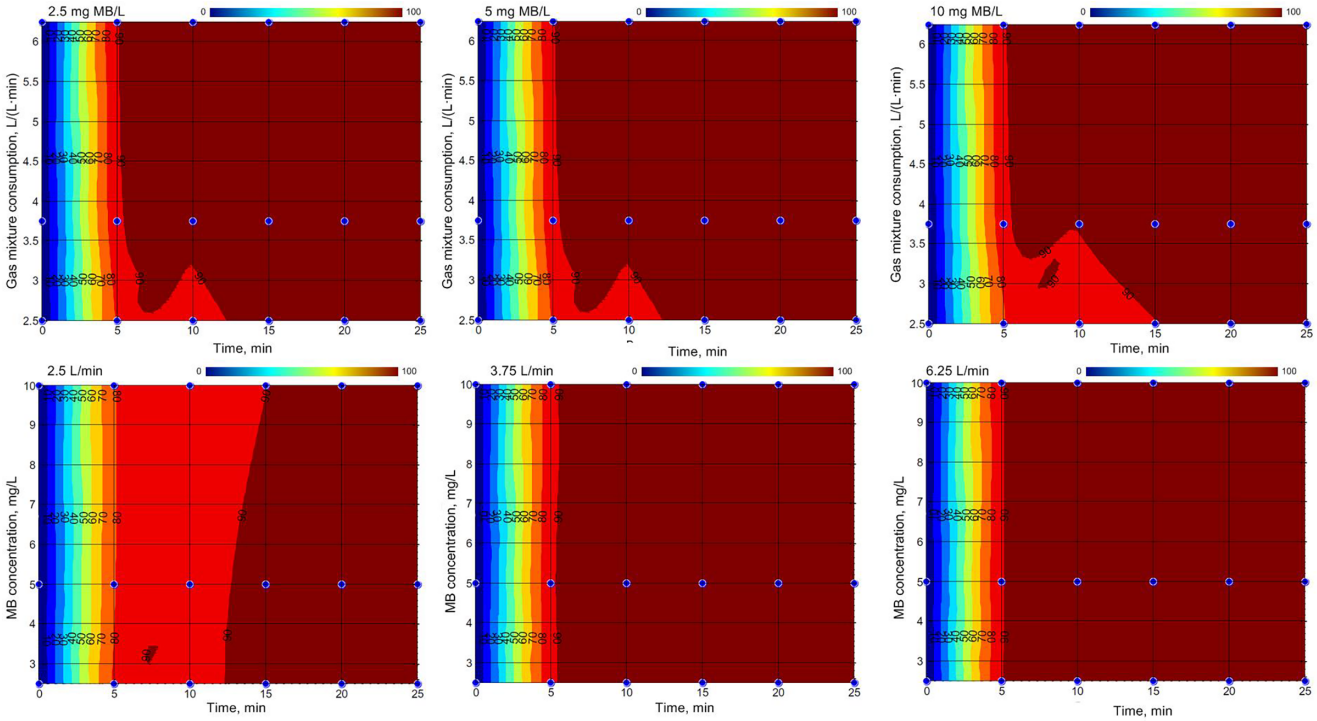

FIGURE 2 | Cleaning efficiency depends on the flow rate of the ozone-air mixture, the concentration of methylene blue and the treatment time at an ozone concentration in the ozone-air mixture of 2.7 g/m^3.

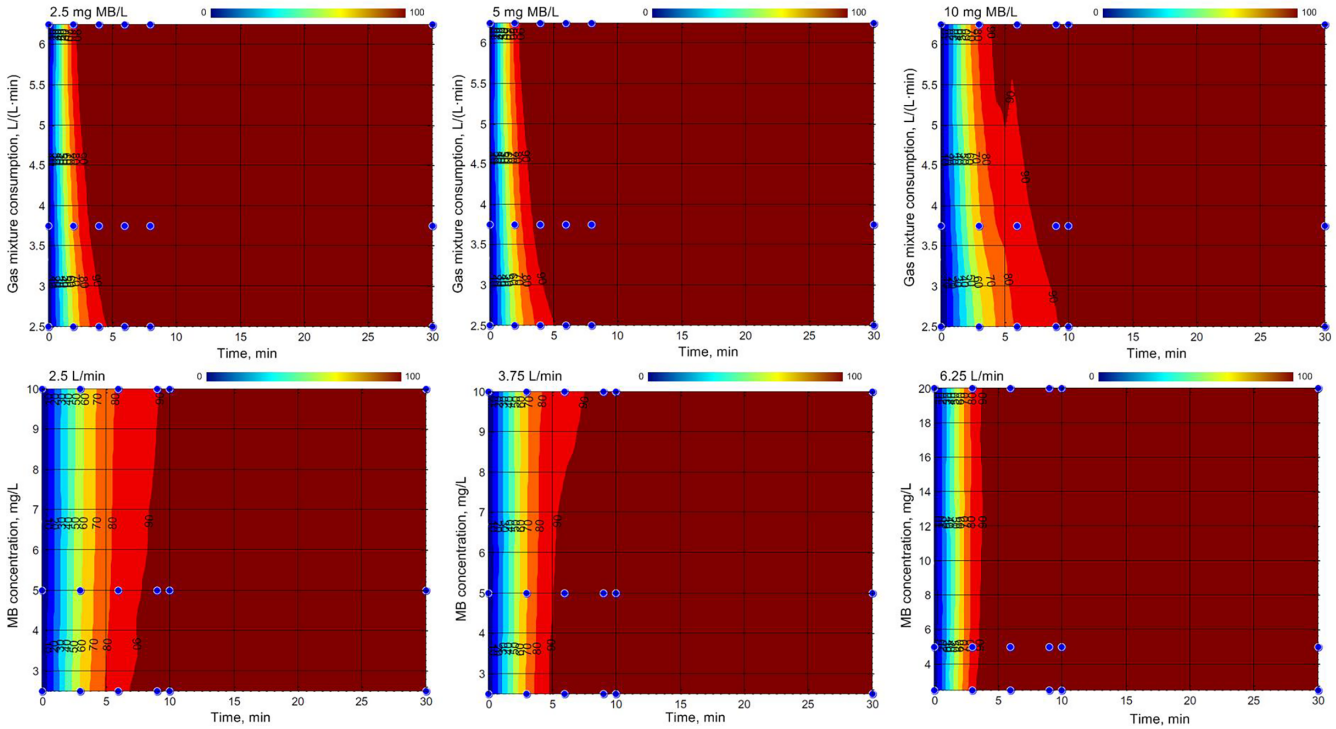

FIGURE 3 | Cleaning efficiency depends on the consumption of the ozone-air mixture, the concentration of methylene blue and the treatment time at an ozone concentration in the ozone-air mixture of 8.3 g/m^3.

2.7, and 8.3 g/m^3), the flow rate of the ozone-air mixture (2.5, 3.75, and 6.25 L/(L·min)), dye solution concentration (2.5–10 mg/L), treatment time (0–30 min) on cleaning efficiency. The coefficient of determination of the resulting model (2) is 0.67.

$$\begin{aligned} Ef_D = {} & 23.9462 + 2.8240 \cdot C_{O3} + 4.5315 \cdot V + 0.3184 \cdot C_{MB} \\ & + 0.2911 \cdot T + 0.2680 \cdot C_{O3} \cdot V - 0.1627 \cdot C_{O3} \cdot C_{MB} \\ & + 0.2768 \cdot C_{O3} \cdot T + 0.0348 \cdot V \cdot C_{MB} - 0.0046 \cdot V \cdot T \end{aligned}$$

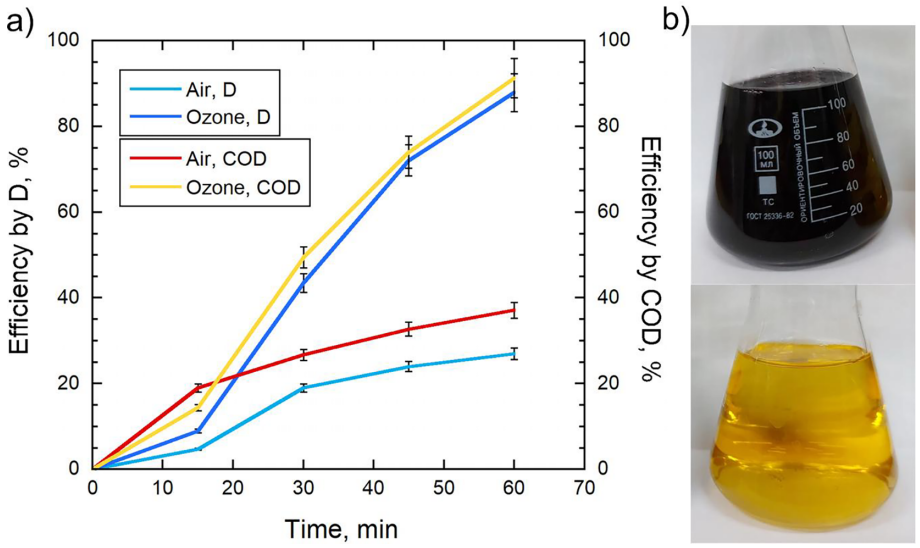

FIGURE 4 | Efficiency of wastewater treatment of the enterprise (average data of two parallel experiments): (a) separate ozone and air as control and (b) samples before and after treatment by ozone for 60 min.

$$- 0.0462 \cdot C_{MB} \cdot T + 0.0021 \cdot C_{O3} \cdot V \cdot C_{MB} - 0.0084 \cdot C_{O3} \cdot V \cdot T + 0.0100 \cdot C_{O3} \cdot C_{MB}\, T + 0.0021 \cdot V \cdot C_{MB}\, T + 0.0001 \cdot C_{O3} \cdot V \cdot C_{MB}\, T - 0.4882 \cdot V^2 - 0.0323 \cdot C_{MB}^2 \quad (2)$$

The results of wastewater treatment (with a set air flow rate of 6.25 L/(L min)) of the enterprise showed a treatment efficiency of 37.1% in terms of COD when using an ozone-air mixture of 91.3%, which is 2.45 times higher than when using air (Figure 4). The resulting graphs show that when air is used, there is a predominant decrease in COD. The optical density of the initial wastewater is beyond the detection limit of the device ($D = 3.0$). Taking this optical density value ($D = 3.0$) as the initial value, the cleaning efficiency when using air is 27.0%, when using an ozone-air mixture 87.9%, which is 3.25 times higher than when using air. Figure 4 shows that a noticeable effectiveness of sedum using an ozone-air mixture is observed after 15 min of treatment. This correlates well with data on the kinetics of water saturation with ozone. These results were confirmed in previously published data [23, 27].

Thus, the use of ozone involves two cleaning mechanisms. The first is pneumatic flotation. The second is the chemical destruction of organic compounds. Wastewater from dyeing and finishing industries contains high concentrations of not only organic (dyes, surfactants, etc.) but also inorganic substances (NaCl). It is known that the solubility of ozone in water depends on pH. In a slightly alkaline environment, ozone dissociates very quickly, and in an acidic environment, it exhibits greater resistance. The high efficiency of using ozone to reduce the coloration of wastewater with synthetic dyes lies in the fact that ozone interacts most vigorously with unsaturated bonds. As is known, almost all organic dyes are derivatives of aromatic compounds, that is, their molecules are built based on benzenoid, naphthalene, anthracene, heterocyclic, and so on structures, that is, contain unsaturated bonds. In addition, most of the currently produced organic dyes are azo dyes in chemical structure, that is, contain azo bonds. Both azo bonds and double bonds of aromatic rings are destroyed first when interacting with ozone, and decomposition products are formed that contain parts of the molecules of the original dyes. Since when all unsaturated bonds are destroyed by ozone, the reaction products are aliphatic hydroxy compounds, their further destruction under the influence of ozone occurs slowly.

To increase the efficiency of wastewater purification from organic pollutants using ozone by the second mechanism, as in conventional flotation, using air, one must strive to increase the surface area of the bubbles by reducing their size. This will also lead to a decrease in the rate of bubble rise and an increase in mass transfer (ozone dissolution), an increase in internal pressure, an increase in free radicals, and bubble stability [61].

3.2 | Combination of Ultrasonic Treatment and Ozonation

Figures 5 and 6 show models obtained based on experimental results of wastewater treatment based on optical density (Figure 5) and COD (Figure 6).

Regression equations were obtained to describe the cleaning efficiency in terms of optical density (Ef_D) and COD (Ef_{COD}) on the ozone concentration in the ozone-air mixture (0–8.3 g/m^3) and treatment time (0–30 min). The coefficient of determination of model (3) is 0.9862 and model (4) is 0.9904, respectively.

$$Ef_D = -5.499 + 25.85 \cdot t + 1.113 \cdot C_{O3} - 15.04 \cdot t^2 + 2.713 \cdot t \cdot C_{O3} - 0.03245 \cdot C_{O3}^2 + 2.757 \cdot t^3 - 0.3304 \cdot t^2 \cdot C_{O3} - 0.04265 \cdot t \cdot C_{O3}^2 + 0.0003 \cdot C_{O3}^3 - 0.1579 \cdot t^4 + 0.0152 \cdot t^3 \cdot C_{O3} + 0.00156 \cdot t^2 \cdot C_{O3}^2 + 0.0002625 \cdot t \cdot C_{O3}^3 \quad (3)$$

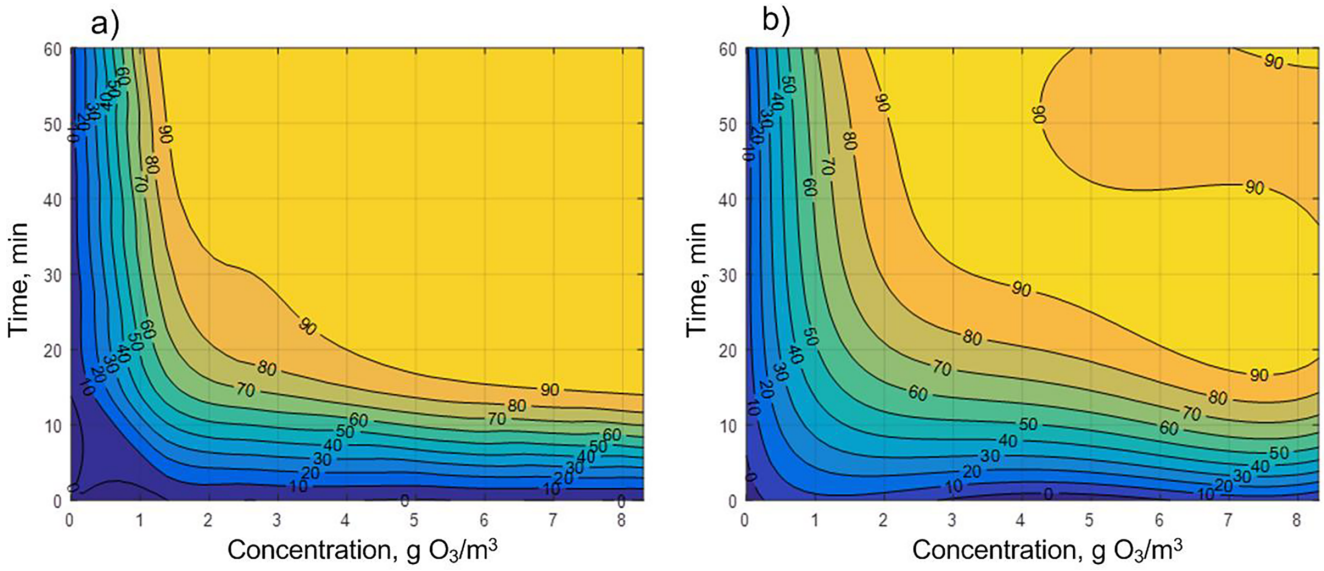

FIGURE 5 | Treatment efficiency by optical density depending on the ozone concentration in the ozone-air mixture and processing time: (a) experimental data and (b) modeling results.

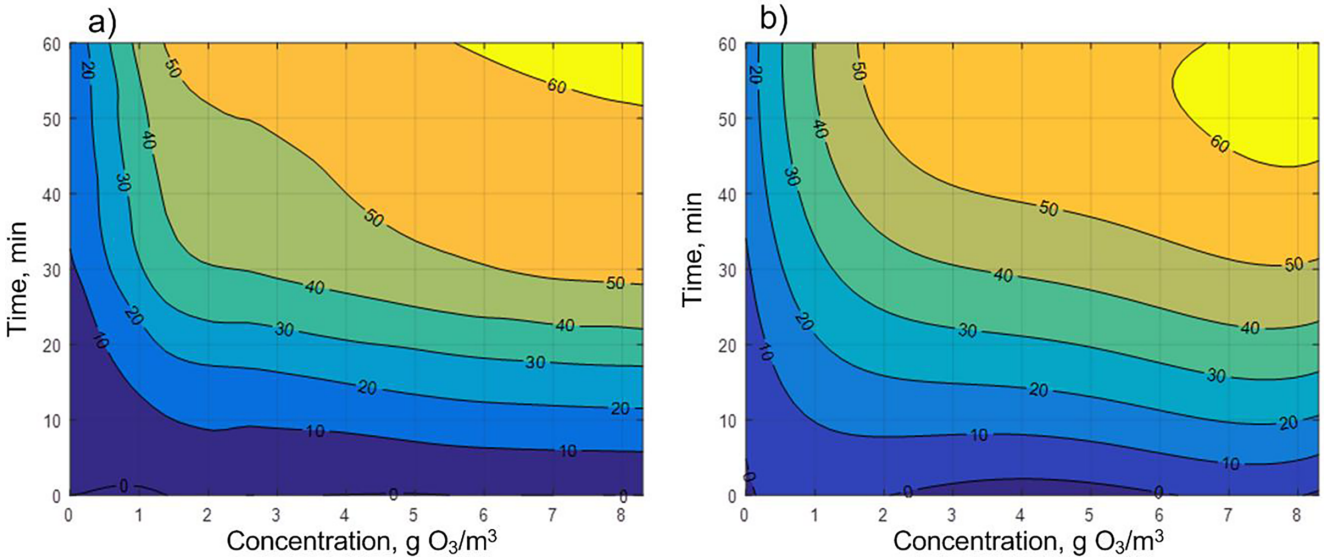

FIGURE 6 | Treatment efficiency based on COD depending on the ozone concentration in the ozone-air mixture and treatment time: (a) experimental data and (b) modeling results.

$$\begin{aligned} Ef_{COD} = {} & -0.8188 + 6.614 \cdot t + 0.1214 \cdot C_{O3} - 4.696 \cdot t^2 \\ & + 0.7712 \cdot t\, C_{O3} + 0.01073 \cdot C_{O3}^2 + 0.9399 \cdot t^3 \\ & - 0.1128 \cdot t^2\, C_{O3} - 0.00531 \cdot t\, C_{O3}^2 - 0.000146 \cdot C_{O3}^3 \\ & - 0.05674 \cdot t^4 + 0.006015 \cdot t^3\, C_{O3} + 0.0002454 \cdot t^2\, C_{O3}^2 \\ & + 1.258 \cdot 10^{-5} \cdot t \cdot C_{O3}^3 \end{aligned} \quad (4)$$

where t is processing time, min; C_{O3} — ozone concentration in the ozone-air mixture, g/m^3.

The results obtained (Figure 7a) show that the use of ultrasound for wastewater treatment gives lower efficiency values compared to air flotation. Even though nano- and micro-sized bubbles (discontinuities in the medium) are formed during ultrasonic treatment, they collapse quite quickly. The main effect on dissolved dyes and surfactants occurs due to the energy released from the collapse of bubbles, due to which the bonds are broken. It is known that heteroatom-heteroatom and carbon-heteroatom bonds have the lowest binding energy. It is these bonds that are responsible for the chromophoric properties of dyes. In the process of pneumatic flotation, a much larger swarm of bubbles is formed, despite their size of several millimeters [58]. Thus, flotation is more effective than ultrasonic treatment. The results for wastewater treatment (at a set flow rate of the ozone-air mixture of 6.25 L/(L·min)) showed a treatment efficiency of 98.8% in terms of optical density and 62.3% in terms of COD. The addition of ultrasonication to the ozone flotation process resulted in

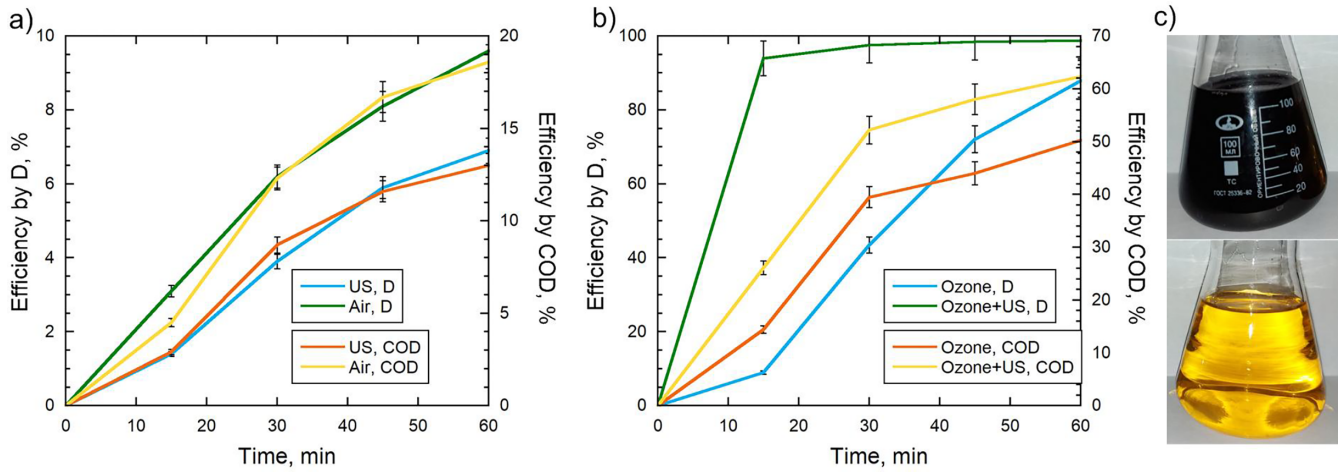

FIGURE 7 | Efficiency of wastewater treatment of the enterprise at a consumption of ozone-air mixture of 8.3 g/m^3: (a) separate US and air as control, (b) by ozone and combination of ozone and US, and (c) samples before and after treatment for a combination of ozone and US for 60 min.

an increase in purification to 10.9% in optical density and 12.0% in COD (Figure 7b). The higher efficiency in terms of optical density in comparison with the efficiency of purification in terms of COD shows that in the process of combined purification under the selected conditions, the chromophoric groups of dyes responsible for coloring are primarily eliminated. At the same time, organic molecules of dyes and surfactants do not decompose completely. In the process of ozonation, oxidation occurs, both by dissolved ozone itself and by the resulting radicals according to the reactions:

$$O_3 + H_2O \rightarrow O_2 + H_2O_2 \quad (5)$$

$$H_2O_2 \rightarrow 2HO^* \quad (6)$$

The increased efficiency of combined application using ultrasonic treatment and ozonation can be explained by the fact that during ultrasonic treatment, flotation bubbles are dispersed, thereby increasing the total area of the bubbles and reducing the efficiency of ozone dissolution in the treated wastewater. Ultrasonic treatment enhances ozone dissolution and bubble dynamics primarily through the generation of acoustic cavitation. Cavitation involves the rapid formation, growth, and violent collapse of microbubbles in a liquid under high-frequency ultrasonic waves. These collapsing bubbles produce intense local pressures and temperatures, which in turn create microturbulence and increase the surface area available for ozone dissolution. The shockwaves from bubble collapse also disrupt the diffusion boundary layer around ozone bubbles, significantly improving mass transfer. This process results in smaller, more uniformly distributed ozone bubbles, which increases the overall gas–liquid interfacial area, further enhancing ozone solubility. Additionally, cavitation-induced microstreaming facilitates the dispersion of dissolved ozone throughout the liquid, preventing concentration gradients and improving the efficiency of the oxidation reactions. Thus, the combination of reduced bubble size, increased mass transfer, and enhanced mixing makes ultrasonic treatment a highly effective method for improving ozone dissolution in various applications [59]. This is reflected in the graphs (Figures 5 and 6). It can be seen that the use of ultrasound results in almost three times shorter ozone dissolution time, from 15 [58] to 5 min, which can be seen from Figure 7b in terms of cleaning efficiency. Also, a synergistic method is associated with the use of O_3 in collapsing bubbles (ultrasonic cavitation) with the formation of additional radicals [60]. The synergistic effect of increasing ozone decomposition during ultrasonic treatment by the authors [61–63]. During ultrasonic processing of high power at frequencies from 20 to 100 kHz, the effect of cavitation occurs—the formation of bubbles due to a break in the continuity of the medium. In addition, in the liquid phase, there are high shear phenomena that can lead to the formation of radicals, including OH* and H*, which oxidize organic pollutants in solution. It should be noted that both ultrasonic power and frequency can significantly influence the cavitation process and thus the overall purification efficiency. We see this as interesting for further investigations.

During ultrasonic cavitation, water decomposes into hydroxyl and hydroperoxyl radicals according to the following reactions:

$$H_2O \rightarrow H^* + HO^* \quad (7)$$

$$H^* + O_2 \rightarrow HO_2^* \quad (8)$$

The combination of ultrasonic cavitation with ozonation increases the formation of OH* radicals due to the decomposition of ozone, which occurs in the vapor phase of the cavitation bubble as follows:

$$O_3 \rightarrow O_2 + O^* \quad (9)$$

$$O^* + H_2O \rightarrow 2HO^* \quad (10)$$

$$2HO^* \rightarrow H_2O_2 \quad (11)$$

The authors of [64, 65] also noted that the high efficiency of ozonation in combination with ultrasound is achieved due to a higher mass transfer effect. In addition, the combination of ultrasound with ozonation can eliminate the formation of highly toxic intermediate compounds [66].

Compared to conventional treatment methods such as coagulation-flocculation, adsorption, and biological treatments, the combined ozone-air flotation and ultrasonic treatment demonstrated superior efficiency in removing dyes and organic pollutants from wastewater. Conventional methods typically achieve dye removal efficiencies ranging from 60% to 85% and COD reductions of about 50%–80%, depending on the specific dye and wastewater characteristics. In contrast, our method achieved up to 98% reduction in optical density and up to 94% COD removal under optimized conditions. The use of an ozone-air mixture in flotation increased the removal efficiency up to 12 times compared to air-only flotation. Furthermore, integrating ultrasonic treatment enhanced the process efficiency by an additional 12%, attributed to improved bubble dispersion and mass transfer kinetics. While conventional methods often face challenges with sludge production, longer treatment times, and limited effectiveness for complex wastewater matrices, our approach offers faster treatment, lower chemical usage, and improved removal of recalcitrant contaminants. To develop this idea, future experiments could explore the integration of nanocatalysts into the combined ozone-air flotation and ultrasonic treatment process to enhance degradation rates and selectivity for persistent organic pollutants [27, 67]. These nanocatalysts can improve reaction kinetics through advanced oxidation processes, potentially increasing overall treatment efficiency and reducing energy consumption. Some of them can allow to efficient adsorption of heavy metals presented in some organic dyes [68, 69]. Future studies could also focus on machine learning for deeper analysis and predictions [70, 71], evaluating operational costs and potential limitations such as energy consumption for ultrasound and ozone generation to provide a more detailed comparative assessment [72].

Long-term stability can be influenced by several factors, including the durability and maintenance of ultrasonic equipment, consistency in ozone generation, and potential fouling or degradation of flotation systems. For industrial scalability, key considerations include the energy costs of continuous ultrasonic treatment, the capacity of ozone generators to handle large volumes of wastewater, and the integration of this combined process into existing treatment facilities. Future work will address these issues by testing the process under continuous flow conditions over extended periods and on a pilot-scale setup to assess operational stability, energy consumption, and overall process feasibility. This will provide a more comprehensive understanding of the potential for implementing this treatment method in industrial-scale wastewater management, ensuring reliable long-term performance and cost-effectiveness [73].

4 | Conclusion

When using ozone flotation, to achieve 90% purification on real wastewater from the enterprise, selected before the treatment unit (electrocoagulation followed by flotation): the recommended treatment time is at least 60 min; consumption of the ozone-air mixture is not less than 5 L/(L·min); the ozone concentration in the ozone-air mixture is not less than 8 g/m^3.

Under experimental conditions, ultrasonic treatment led to an increase in the efficiency of ozone flotation to 12%. This effect may be associated primarily with the dispersion of bubbles of the ozone-air mixture, leading to an increase in their total surface area and, accordingly, an increase in the kinetics of mass transfer—ozone dissolution.

Author Contributions

Valentin Romanovski: conceptualization, investigation, writing – original draft, methodology, validation, visualization, writing – review and editing, formal analysis, data curation, supervision. **Marina Pilipenko:** investigation, writing – original draft, validation, data curation, formal analysis. **Alexandr Dubina:** investigation, resources, data curation, formal analysis. **Vitaly Likhavitski:** formal analysis, data curation, validation, software, investigation. **Sergey Volodko:** investigation, formal analysis, data curation. **Dmitry Moskovskikh:** formal analysis, data curation. **Elena Romanovskaia:** data curation, formal analysis.

Disclosure

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethics Statement

The authors have nothing to report.

Consent

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

All data, models, and code generated or used during the study appear in the submitted article. The data that support the findings of this study are available from the corresponding author upon reasonable request.

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