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Decolouration of Real Textile Wastewater with Advanced Oxidation Processes

Abstract
The efficiency rates of advanced oxidation processes for the decolouration of different types of textile wastewater taken from textile plants in Łódź were compared on the basis of the results obtained. The wastewater had different compositions and concentrations of pollutants, and the dyeing wastewater was of intense colour. The advanced oxidation processes with the use of ozone, gamma radiation, hydrogen peroxide and UV radiation gave good decolouration results. The efficiency of colour removal depended on the type of wastewater and concentration of pollutants contained therein. The effects of wastewater type, pollutant concentrations, the pH of the solution, process temperature and the amount of oxidising agents, in particular of hydrogen peroxide, on the yield of decomposition of dyes during ozonation were investigated. As a result of the treatment, complete decolouration of the wastewater was obtained. Considering both the experimental results and technological problems, it can be presumed that advanced oxidation with a simultaneous application of ozone and hydrogen peroxide is a very promising technique for potential industrial implementation.

Key words*: textile wastewater, decolouration, ozone, gamma radiation, advanced oxidation.*

Introduction

The processes of advanced oxidation have been investigated for many years in numerous research centres. Both laboratory and pilot-scale investigations have been carried out to apply them in industry. Various types of model substances such as dyes, cyanides, detergents, phenols, polycyclic aromatic hydrocarbons, etc., as well as model and real wastewater, both industrial and municipal, were investigated. Much attention was paid to the decolouration of aqueous solutions, which was carried out with the use of various versions of the advanced oxidation.

In pilot-plant and industrial installations, the advanced oxidation processes have mainly been used in the treatment of drinking and industrial water. At present, such installations are used for wastewater treatment in several countries, including Germany, France, Canada and the United States [1]. Textile wastewater is treated using preozonation on an industrial scale only in Japan [2].

The interest in advanced oxidation methods results from their potential. The mechanism of chain reactions which involves hydroxyl and hydroperoxy radicals (due to their high reactivity and low selectivity), enables the application of the process to a large number of compounds present in the wastewater, especially for decolouration. The method's main advantages include the lack of by-products which might cause secondary pollution of the environment, elimination of the hazard of overdosing the oxidising agents, and high process rate and efficiency.

Through primary and secondary products of water radiolysis, the ionising radiation causes the decomposition of organic compounds contained in water. It was found that the presence of oxygen in the solution had a positive effect on the rate of destruction process due to its contribution in the chain processes of oxidation. The mechanism of the process is complex because of various agents that initiate the decomposition and a number of consecutive reactions that follow. As a result, there is a variety of intermediate and final products.

Research on the application of radiation techniques in the protection of natural environment started around 40 years ago. It dealt mainly with model solutions of dyes, detergents, phenol, pesticides and others [3]. In the field of technology, the investigations concerned radiation of the wastewater generated by textile, chemical, pulp and paper, metallurgical and pharmaceutical industries. Recently, much interest has been paid to municipal wastewater and the possibility of using gamma radiation in the treatment of industrial and drinking water [4]. The existing applications of radiation techniques in wastewater treatment on an industrial scale are rather meagre.

Radiation combined with biological processes was used in the treatment of wastewater issuing from antibiotics production, and from metallurgy where large quantities of detergents and fats were used in the production processes [3,5]. For dyehouse wastewater, which has been studied most extensively, no industrial installation has been built so far; only pilot-plant systems are in existence at this time [6].

A growing interest in the advanced oxidation processes caused a return to radiation processes, especially the combination of radiation with chemical oxidants, mainly ozone. Of special importance are the studies on decomposition of phenol, ethylene glycol and halogen derivatives of methane and ethane [7].

The results of research into real textile wastewater treatment with advanced oxidation methods are discussed in this paper. Below, we shall discuss and compare the results of decolouration of real textile wastewater collected in textile factories located in Łódź, Poland.

Material

The decolouration of textile wastewater will be exemplified by the following textile wastewater issuing from knitting plants in Łódź:
wastewater 1: very highly concentrated wastewater from cotton + elastil dyeing process, of intense red colour, CT=-10000. The COD value was 5320 mg O_2/dm^3, whereas BOD_5=480 mg O_2/dm^3. The BOD_5/COD ratio was 0.09. The content of anionic detergents was high = 63 mg/dm^3, the content of suspended matter = 50 mg/dm^3. The dissolved substances = 13970 mg/dm^3;
wastewater 2: very highly concentrated wastewater from cotton + stilon dyeing process of intense green colour, CT= 25000. The COD value was 5280 mg/dm^3, and BOD_5=370 mg O_2/dm^3. The BOD_5/COD ratio was 0.07. The content

of anionic detergents was high = 40 mg/dm^3. The amount of suspended matter reached 30 mg/dm^3. The dissolved substances = 12670 mg/dm^3;
wastewater 3: highly concentrated wastewater coming from cotton + wool dyeing process. This exhibits intense blue colour, CT=3300, high COD=3300 mg O_2/dm^3. The BOD_5 value = 760 mg O_2/dm^3, the content of anionic detergents = 87 mg/dm^3, whereas that of dissolved substances = 4850 mg/dm^3, the BOD_5/COD ratio reached 0.23;
wastewater 4: plant effluents of strong blue-grey colour, CT=670. The COD value was 660 mg O_2/dm^3, whereas BOD_5= 136 mg O_2/dm^3. The BOD_5/COD ratio was 0.21. The content of anionic detergents was 10 mg/dm^3 and dissolved substances = 920 mg/dm^3;
wastewater 5: plant effluents of strong red colour, CT=1000. The COD value was 350 mg O_2/dm^3, whereas BOD_5= 110 mg O_2/dm^3. The BOD_5/COD ratio was 0.31. The dissolved substances = 1670 mg/dm^3;
wastewater 6: plant effluents of strong blue colour, CT=500. The COD value was 620 mg O_2/dm^3, the content of anionic detergents was 16.5 mg/dm^3, non-ionic = 41 mg/dm^3. The dissolved substances = 4550 mg/dm^3;
wastewater 7: plant effluents of green colour, CT=200. The COD value was 550 mg O_2/dm^3, the content of anionic detergents was 4.6 mg/dm^3, non-ionic = 13.2 mg/dm^3. The dissolved substances = 1400 mg/dm^3;
wastewater 8: dyehouse wastewater coming from rinsing operations, of light brown colour, CT=120. The COD value was 120 mg O_2/dm^3, the content of anionic detergents was 0.9 mg/dm^3, non-ionic = 1.0 mg/dm^3. The dissolved substances = 730 mg/dm^3;
wastewater 9: wastewater produced during rinsing after washing, of light grey colour, CT=25. The COD value was 340 mg O_2/dm^3, the content of anionic detergents was 0.2 mg/dm^3, non-ionic = 4.8 mg/dm^3. The dissolved substances = 350 mg/dm^3;
wastewater 10: plant effluents of light grey colour, CT=25. The COD value was 430 mg O_2/dm^3, the content of anionic detergents was 20 mg/dm^3. The dissolved substances = 1500 mg/dm^3;
wastewater 11: dyehouse wastewater produced during cotton + polyester and polyurethane dyeing, of intensive dark blue colour. CT=1700, COD was 415 mg O_2/dm^3, BOD_5 reached 20 mg O_2/dm^3. The concentration of anionic detergent was small, amounting to 3.8 mg/dm^3, the dissolved substances = 570 mg/dm^3;
wastewater 12: dyehouse wastewater from cotton dyeing with reactive dyes, of intensive dark green colour. CT=3300, COD was 430 mg O_2/dm^3, BOD_5 reached 132 mg O_2/dm^3. The concentration of anionic detergents was 2.2 mg/dm^3, the dissolved substances 1150 = mg/dm^3;
wastewater 13: textile wastewater from the process of dyeing of wool with polyester, of intensive grey-blue colour, CT=670, high COD=1310 mg O_2/dm^3, BOD_5=75 mg O_2/dm^3, anionic detergents 5.3 mg/dm^3, dissolved substances = 1040 mg/dm^3;
wastewater 14: dyehouse wastewater of medium concentration and not very intensive green colour. CT=50, COD amounted to 320 mg O_2/dm^3 and BOD_5 to 42 mg O_2/dm^3. The content of anionic detergents was small = 2.6 mg/dm^3. The amount of suspended matter was also small = 10 mg/dm^3. Dry residue = 2270 mg/dm^3, and dissolved substances = 2260 mg/dm^3;
wastewater 15: dyehouse wastewater of medium concentration and intensive blue colour. CT=250. COD was 320 mg O_2/dm^3 and BOD_5 was 64 mg O_2/dm^3. The BOD_5/COD ratio was 0.20. The content of anionic detergents was small 3.9 mg/dm^3. The amount of suspended matter was pretty high reaching 120 mg/dm^3. Dry residue was 1680 mg/dm^3, and dissolved substances 1560 mg/dm^3. TOC was 117 mg/dm^3;
wastewater 16: concentrated wastewater from bistor dyeing, of intensive orange colour, CT=670, high COD=1310 mg O_2/dm^3. The value of BOD_5 was 75 mg O_2/dm^3, the content of anionic detergents was 5.3 mg/dm^3 and dissolved substances = 1040 mg/dm^3.

The aim of the application of such a large number of different textile wastewaters was to check whether the advanced oxidation processes could be a universal method for decomposing the impurities it contained, particularly of decolouration. We also hoped to make some generalisations of the differentiated object which is the wastewater that occurs in the domestic textile industry.

Experimental

The experimental system and experimental methods with and without the use of gamma radiation have been described in our previous studies [8,9]. Both crude and treated wastewater was subjected to complete physicochemical analysis, including the analysis of colouration and colour threshold CT.

Advanced oxidation processes in real dyehouse wastewater

The textile wastewater was subjected to the treatment with the following versions of the advanced oxidation processes: ozone, hydrogen peroxide, photochemical and radiation oxidation and combined processes ozone + hydrogen peroxide, ozone + UV radiation, ozone + γ radiation, hydrogen peroxide + UV radiation and ozone + hydrogen peroxide + UV radiation. The following conclusions on the wastewater decolouration process can be derived from the results obtained:

Ozone

The degree of dye decomposition increases with an increase in ozonation time, i.e. with the dose of ozone administered. Even at a short reaction time (ozone doses) the colour is greatly reduced. Detailed results of the study of ozonation process in relation to solutions and dyebaths have been presented elsewhere [10,11].

Hydrogen peroxide

In dyehouse wastewater treated with hydrogen peroxide, the decolouration ranged from 0 to 66% depending on the amount of H_2O_2 and the exposure time. Detailed results of the study have been presented in our previous articles [12].

UV radiation

In the UV-irradiated dyehouse wastewater, the decolouration reached 0 to 60% depending on the time of irradiation. Detailed results of the study have been discussed in our previous articles [11].

Gamma radiation

The irradiation of wastewater with ionising radiation gave very good results of dye decomposition. The wastewater usually assumed a colour different than the original one, which was a consequence of the formation of coloured products of the original dyestuff radiolysis. In one sample only, the colour of wastewater after irradiation was the same as in non-irradiated wastewater, although its intensity was minimal. This may provide evidence that the dyestuffs present in this wastewater sample do not yield any coloured products after radiolysis.

The degree of wastewater decolouration measured by the values of colour thresh-

old (CT) was high, particularly in the case of very strongly coloured dyehouse wastewater (samples 1-3), and ranged from 94.8 to 99.5%. In plant effluents with less intensive colour (samples 4-5) the decolouration was lower and amounted to 92.5-95%, in one sample even reaching 50%.

Although after the irradiation a practically complete decomposition of dye molecules was obtained, the advantageous effect of oxygen on wastewater decolouration could be observed. In oxygenated wastewater, in all samples colour reduction of 95-99.5% was reported during irradiation (Table 1).

Ozone and UV radiation

In the wastewater subjected to the combined treatment with the use of O_3+UV, the wastewater was already completely decoloured after 60 to 120 minutes depending on the initial value of CT (50-250). The most important factor in this system is ozone and its dose, and consequently the concentration in the gas at the reactor inlet. The effect of the gas flow rate itself is much lesser, because in the experimental conditions the process is not controlled by diffusion. It was found that the assisting impact of UV radiation was related mainly to the power of lamps and their emission spectra. The wastewater reaction is of high importance. In acid solutions, where direct ozonolysis predominates, the assisting effect is lower. A detailed description of all results has been given in our previous studies [11], and examples of the results of wastewater decolouration are shown in a table inserted in this study.

Hydrogen peroxide and UV radiation

At the initial values of CT<50 and doses of H_2O_2<5 cm^3/dm^3, after 60 minutes of the treatment, a complete decolouration of the wastewater has already been achieved. The result of decolouration depends first of all on hydrogen peroxide concentration. However, there is some optimum concentration above which the decolouration effect is weakened. The value of this optimum concentration depends on the composition of wastewater being treated. The intensity and type of light applied affects the generation of hydroxyl radicals, and as a result, the decolouration efficiency. The most advantageous is monochromatic light from the UV range. However, depending on which dyes are present in the solution and wastewater colour intensity, this effect may be hardly visible.

Detailed results of the combined treatment with H_2O_2 and UV radiation are given, among others, in our previous studies [12]. Examples of wastewater decolouration are given in a table inserted in this study.

Hydrogen peroxide and ozone

The results of decolouration obtained by this method were very good. For instance, the wastewater was completely decoloured at the initial value of CT=250 after 1 h of ozonation with hydrogen peroxide doses of 3 cm^3/dm^3. Detailed results of the joint action of ozone and hydrogen peroxide on textile wastewater are given, among others, in our studies [13]. Examples of wastewater decolouration are shown in a table inserted in this study.

Ozone and γ radiation

A combined application of ozone and ionising radiation leads to an increase in the concentration of oxidising agents in the aqueous solutions, including strongly reactive OH hydroxyl radicals, due to interactions between the products of water radiolysis and those of ozone decomposition [14]. This should be reflected in the higher decomposition efficiency of organic pollutants contained in the wastewater, and higher efficiency of decolouration (Figure 1 and Table 2).

The wastewater composition was very differentiated (samples 6 to 10). Figure 1 shows a comparison of exposure of wastewater 6 to gamma radiation, ozone and joint gamma radiation and ozone. The experiments showed that the combined application of ozone and radiation

Table 1. *Decolouration of dyehouse wastewater exposed to gamma irradiation.*

Wastewater type	Radiation dose	Exposure rate	Oxygenation rate	Reaction	Specific colour	Colour threshold number
	kGy	Gy/s	dm^3/h	pH	description	
Dyehouse - 1	0	0	0	8.0	dark red	10000
	100	0.278	0	7.0	light yellow	120
	100	0.556	5	6.7	light yellow	250
Dyehouse - 2	0	0	0	7.5	dark green	25000
	100	0.278	0	6.6	yellow	670
	100	0.556	5	6.8	orange	1000
Dyehouse - 3	0	0	0	9.7	blue	3300
	100	0.556	0	9.3	gray-blue	170
	100	0.556	5	7.6	light blue	17
Dyehouse - 4	0	0	0	8.0	gray-blue	670
	100	0.556	0	6.9	olive green	50
Dyehouse - 5	0	0	0	9.0	red	1000
	100	0.278	0	8.6	light orange	500
	100	0.556	5	7.9	light orange	50

Table 2. *Decolouration of dyehouse wastewater by gamma radiation and ozone.*

Dyehouse wastewater	Treatment time	Ozone dose	Radiation dose	Reaction	Specific colour	Colour threshold
	h	mg O_3/dm^3	kGy	pH	description	
No. 6	0	0	0	8.4	blue	500
	1	145	1.2	7.2	blue	250
	3	435	3.6	7.3	l. yellow-green	50
	5	725	6.0	7.3	light yellow	25
No. 7	0	0	0	7.4	green	200
	1	145	1.2	6.9	colourless	-
	2	290	2.4	6.6	colourless	-
	4	580	4.8	6.5	colourless	-
No. 8	0	0	0	7.7	light brown	120
	1	145	1.2	7.2	colourless	-
	3	435	3.6	7.5	colourless	-
	5	725	6.0	7.5	colourless	-
No. 9	0	0	0	8.0	light grey	25
	1	145	1.2	7.7	colourless	-
	3	435	3.6	7.8	colourless	-
No. 10	0	0	0	8.2	light grey	25
	1	145	1.2	7.8	light grey	17
	3	435	3.6	7.9	light grey	12
	5	725	6.0	7.9	light grey	<5

produced very good decolouration results. Additionally, a positive synergistic effect is observed, especially at low doses of ozone and radiation. The results of decolouration are better than if the results obtained separately by the two methods had been added together. This allows us to significantly decrease the dose necessary to obtain the desired decolouration degree, and in consequence to reduce the time of wastewater treatment.

The results of decolouration obtained in the wastewater treated by the combined radiation and ozonation method depended on the type and concentrations of particular contaminants and applied doses of ozone and radiation. The process of dye decomposition was very quick and efficient. To achieve more than 90% wastewater decolouration, at high initial CT reaching 500, the ozone doses from 150 to 400 mg/dm^3 and radiation doses from 1.2 to 2.4 kGy were required. For the wastewater with less intensive colour (CT from 25 to 100) at the same doses, complete decolouration was obtained.

Ozone, hydrogen peroxide and UV radiation

When the textile wastewater was exposed to three oxidants simultaneously, very good decolouration results were obtained. At large differences in colour intensity (CT from 50 to 33,000), the wastewater was completely decoloured after a maximum of 2 hours of reaction. However, it is worth mentioning that similar or slightly worse results were obtained when the two factors were used together (H_2O_2+O_3, H_2O_2+UV, O_3+UV), and in some cases when only ozone was used. In one case (dyehouse wastewater no. 16) the joint application of O_3, UV and H_2O_2 was much better than all other versions of advanced oxidation. In this only case, a clearly synergistic effect was observed, while in other cases there were at most assisting effects (Figure 2 and Table 3).

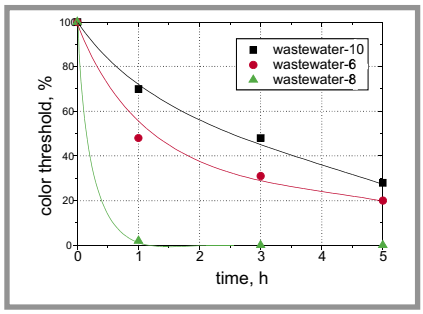

Figure 1. *Changes of the colour threshold number in the wastewater subjected to ozonation and γ irradiation.*

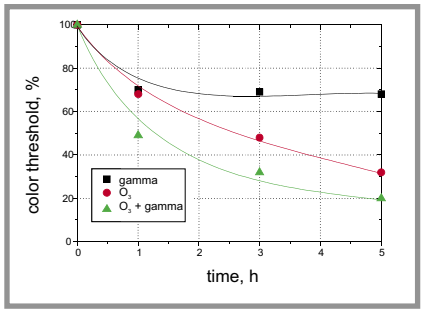

Figure 2. *Changes of the colour threshold number in dyehouse wastewater no. 6 exposed to ozonation, gamma irradiation and combined ozonation with gamma irradiation.*

Optimisation of advanced oxidation process

A significant effect on textile wastewater decolouration was imposed by the pH of the wastewater solution. The best results of dye particle decomposition were obtained in the acid environment (pH ~4), while the worst effects were obtained in the basic one (pH ~10).

The degree of wastewater decolouration increased with an increase in the ozone dose. With reference to hydrogen peroxide, the observed relations were not so explicit. During the combined treatment with O_3 and H_2O_2, in some samples a decrease of pollutant concentration was observed with an increase in the amount of hydrogen peroxide added. However, in several samples the increase of H_2O_2 in the system significantly hampered the decomposition of organic compounds, which decreased the process yield remarkably. It seems that this could be a result of scavenging hydroxyl radicals by hydrogen peroxide, and also of a decrease of hydroxyl concentration in the system. The type and structure of pollutants occurring in the wastewater analysed had a very pronounced effect on the decomposition processes. Hence, to obtain satisfactory results of the treatment, an optimum amount of hydrogen peroxide should be selected individually during the process.

As the temperature of textile wastewater flowing out from the dyehouse is often above the ambient temperature, the question arises of whether it is reasonable to oxidise the wastewater immediately at the outlet. As expected, temperature affects the rate of decomposition of hydrogen peroxide added to the wastewater. Therefore, the effect of temperature on the yield of textile wastewater decolouration was investigated. It was found that at H_2O_2+O_3 treatment, the process temperature had a relatively small effect on changes in the wastewater parameters. At higher temperatures (the range from 25 to 55°C was investigated), the run of degradation processes was slightly better, although not significantly so.

Despite significant differences in composition, all types of wastewater subjected to advanced oxidation processes generally behaved in a similar way. The treatment process that included a simultaneous action of all three factors appeared most efficient from the point of view of pollutant decomposition yield. Differences in the application of particular AOP versions are most visible in the concentrated wastewater at high values of the colour threshold (CT). The decolouration degrees were very high, amounting even to 100%. In the case of radiation, sometimes stable colouration occurred that could not be removed even upon prolonged oxidation of the wastewater.

In weakly coloured wastewater, complete decolouration is achieved both during the simultaneous action of three factors and when all combinations of two oxidants are applied. It is interesting that some dyehouse wastewater of more intensive colour is decoloured at practically the same efficiency as the wastewater of low CT. This is undoubtedly evidence of a significant degradability of dyes present in the wastewater caused by the applied oxidising agents.

Regarding the action of single oxidants such as ozone, UV radiation and hydrogen peroxide, different decolouration effects were obtained depending on the type of treated wastewater. However, in general, the process of ozonation appeared to be the most efficient, and the photochemical decomposition the least so [11-13,15].

The increase in the decolouration yield CT when all three factors were applied simultaneously, in comparison with the simultaneous use of two agents, was very small in many cases. When two agents are used simultaneously, it is not possible to make an explicit choice of the most efficient version. In reference to given wastewater, this can prove to be both the worst and the best version. The advanced oxidation processes with the use of UV radiation are easy to perform under labo-

Table 3. *Decolouration of textile wastewater exposed to ozone, hydrogen peroxide and UV radiation in optimum conditions.*

Dyehouse wastewater	Treatment type	Treatment parameters	Colour	CT	pH
Dyehouse - 11	none	-	dark blue	1700	6.1
	O_3	2 h	yellow	120	6.6
	H_2O_2	1 cm^3/dm^3	dark blue	800	7.5
	UV	10 h	brown	330	7.4
	$O_3+H_2O_2$	2 h + 1 cm^3/dm^3	light grey	50	6.5
	H_2O_2+UV	1.25 cm^3/dm^3 + 2.5 h	brown	330	6.2
	$O_3+H_2O_2$+UV	3 cm^3/dm^3 + 2 h	light grey	8	6.4
Dyehouse - 12	none	-	dark green	3300	7.4
	O_3	2 h	light green	17	7.3
	UV	5 h	dark green	3300	7.9
	H_2O_2	2 cm^3/dm^3	dark green	3300	6.9
	$H_2O_2+O_3$	1 cm^3/dm^3 + 2 h	light green	50	6.9
	O_3+UV	2 h	colourless	-	7.5
	$H_2O_2+O_3$+UV	1 cm^3/dm^3 + 2 h	colourless	-	6.8
Dyehouse - 13	none	-	grey-blue	670	6.7
	H_2O_2	1 cm^3/dm^3	grey-blue	500	8.0
	$H_2O_2+O_3$	1 cm^3/dm^3 + 2 h	light yellow	67	6.9
	H_2O_2+UV	2 cm^3/dm^3 + 1 h	grey-blue	500	7.3
	$H_2O_2+O_3$+UV	2 cm^3/dm^3 + 1 h	light grey	67	5.9
Dyehouse - 14	none	-	green	50	9.0
	O_3	1.5 h	colourless	-	8.6
	H_2O_2	20 cm^3/dm^3	light green	17	9.3
	UV	6 h	light green	17	9.0
	$O_3+ H_2O_2$	20 cm^3/dm^3	colourless	-	8.7
	H_2O_2+UV	5 cm^3/dm^3 + 1 h	colourless	-	8.0
	$O_3+H_2O_2$+UV	5 cm^3/dm^3 + 1 h	colourless	-	8.4
Dyehouse - 15	none	-	blue	250	8.2
	O_3	1 h	colourless	-	7.8
	UV	2 h	light yellow	33	8.3
	H_2O_2	10 cm^3/dm^3	light violet	100	8.5
	$H_2O_2+O_3$	5 cm^3/dm^3 + 1 h	colourless	-	7.9
	O_3+UV	1 h	colourless	-	7.6
	H_2O_2+UV	5 cm^3/dm^3 + 1 h	colourless	-	8.3
	$H_2O_2+O_3$+UV	5 cm^3/dm^3 + 1 h	colourless	-	7.8
Dyehouse - 16	none	-	orange	670	6.6
	O_3	2 h	orange	500	7.1
	UV	2 h	orange	670	7.5
	H_2O_2	10 cm^3/dm^3	orange	330	7.5
	$H_2O_2+O_3$	10 cm^3/dm^3 + 2 h	light yellow	67	6.8
	O_3+UV	2 h	light yellow	100	7.0
	H_2O_2+UV	10 cm^3/dm^3 + 2 h	yellow	120	7.3
	$H_2O_2+O_3$+UV	10 cm^3/dm^3 + 2 h	light yellow	17	7.0

ratory conditions, but require specific equipment on an industrial scale. A small range of UV radiation, particularly in the case of strongly coloured wastewater, requires irradiation to be carried out in thin layers of the solution, which calls for specially designed reactors. It was observed that most advantage is obtained by the use of UV radiation at short wavelengths of around 250 nm. This enables the application of low-pressure low-power lamps. Recently, however, despite a significant prolongation of UV lamp operation and efficiency, this still proves to be an energy-consuming and expensive device.

Taking into account technological and economic aspects, it seems that if particular versions of advanced oxidation processes lead to similar results of decolouration, then ozone and hydrogen peroxide should be used in combination. In the case of significant differences in the process yield, a thorough economic analysis should be made.

Conclusions

The application of combined methods of wastewater treatment with ozone, gamma irradiation, hydrogen peroxide and UV irradiation is advantageous. These methods allow us both to obtain better efficiency of decolouration, and to reduce doses of oxidants, thanks to which the wastewater treatment costs may be reduced. The effects of dye degradation depend on the type and quantities of oxidants used and on the type and concentration of pollutants present in the wastewater. Hence, the choice of optimum doses of all oxidants and their interaction should be established separately. In view of the degradation of toxic and hardly biodegradable compounds and their transition into easily recoverable compounds, it is desirable to combine the processes of advanced oxidation with further treatment of wastewater with biological methods.

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Received 20.12.2002 Reviewed 10.03.2003