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An evaluation of the effectiveness of supporting chemical disinfection with UV irradiation

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ABSTRACT

The presented study aimed to determine the transformation of organic substances and to compare the effectiveness of deactivating microorganisms in the chemical disinfection with sodium hypochlorite and chemical disinfection process supported by UV radiation. The study was conducted in two flow-type water treatment systems: the reference and the test system with a throughput of 1 m^3/h each. Prior to disinfection, both systems contained processes of coagulation, sedimentation, sand filtration, and adsorption on activated carbon. The study has shown that during chemical disinfection not supported by UV radiation, microorganisms did not be completely removed. To increase the efficiency of the process, it is necessary to use higher doses of sodium hypochlorite or additionally the use of UV radiation.

Keywords: Sodium hypochlorite; Psychrophilic microorganisms; Mesophilic microorganisms; Organic substances; Flow cytometry

1. Introduction

The necessity of providing water of appropriate quality at its point of use means that it is not only required to treat it, but also to protect it against secondary contamination in the distribution system. The change in water composition, that is one of two main aims of disinfection [1,2] used in all water treatment plants. Chemical disinfection is the most commonly used method, [3,4] with examples of the most popular disinfectants being chlorine compounds [5,6], including gaseous chlorine and sodium hypochlorite. The choice of the appropriate disinfectant type and dosage is the subject of many studies [7–9]. The type of oxidizer used determines the type of physicochemical changes in water, including, above all, the types of disinfection by-products that are formed [10,11]. Research conducted around the world mainly focuses on the formation of THMs [12,13], which are the main group of chlorine disinfection by-products. The amount and type of chlorinated organic substances formed, in particular THMs, depend on the composition of the water being purified, its temperature and pH [14] and the used chlorine dose [15]. Due to the necessity of deactivating microorganisms, which is the primary aim of disinfection, the disinfectant doses that are used are large. As a consequence, conditions are created for the formation of disinfection by-products. On the other hand, precursors of disinfection by-products are typically organic compounds [16], mainly refractive substances [17], which are characterized by a high reactivity with disinfectants.

Therefore, limiting the amount of formed disinfection by-products while simultaneously deactivating microorganisms requires the use of large disinfectant doses or limiting the concentration of organic substances in water undergoing disinfection. Reducing the required disinfectant dose, and

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therefore limiting the probability of the formation of disinfection by-products, is possible by using another method to supplement disinfection [18]. To this end, UV radiation is most commonly used as a local disinfection method, together with chemical disinfection, which allows for ensuring the presence of disinfectant in water introduced into the distribution network [19,20]. The most information about UV used in water treatment is about its disinfection potential but there is a lack of information about changes in chemical compounds transformation. The use of a physical disinfection factor provides almost 100% effective water sterilization [21–23] and in addition does not significantly affect the composition of the treated water. There is also no information on the impact of UV radiation on the cells of microorganisms, whose numbers are determined using a flow cytometer. However, during water irradiation, the transformation of high molecular weight organic substances to low molecular weight one may take place [24], which increases the Trihalomethans (THM) formation potential [25].

Therefore, it was justified to carry out studies which had as their aim determining the transformation of organic substances and the effectiveness of deactivating microorganisms during chemical disinfection alone and chemical disinfection supplemented by flow UV irradiation.

2. Subject and methods of study

Studies were conducted in two flow-type water treatment systems with a throughput of 1 m^3/h. The systems consisted of coagulation, sedimentation, sand bed filtration, adsorption on activated carbon, and disinfection. In one of the systems, water after adsorption underwent disinfection by sodium hypochlorite, while in the other it was irradiated by UV radiation, and then chemically disinfected with sodium hypochlorite. In both systems, a constant sodium hypochlorite dose of 0.5 g Cl_2/m^3 was used. UV irradiation was carried out using a low-pressure lamp with a power of 130 W with the water flow time through the lamp being 1.5 min. On the other hand, the sodium hypochlorite - treated water contact time was in the range of 15–17 min.

The objects of research of further analysis were water samples taken at the outflow from adsorption filters (FWO) and after disinfection (DO1) and (DO2), and in the second system also at the outflow from the UV Lamp (UVO).

Water samples were taken once a week, and the study was carried out for a period of 4 months. The number of analyzed water samples was 16 in every stage of the treatment. For all water samples, the following were determined: temperature, pH, turbidity, color at wavelengths of 340 and 410 nm (C_{340}, C_{410}), total organic carbon (TOC), dissolved organic carbon (DOC) and biodegradable dissolved organic carbon (BDOC) organic carbon, and UV absorbance at wavelengths of 254 and 272 nm (UV_{254}, UV_{272}). The total number of psychrophilic (TN psychrophilic) and mesophilic (TN mesophilic) microorganisms and the total number of cells (TCC) and the number of intact cells (ICC) were also determined.

All analysis was carried out in accordance with applicable Polish Norm. BDOC was determined by a modified Van der Kooij method, the incubation of samples with microorganisms characteristic to a given environment. It is the most common method for BDOC analysis.

The total microorganism count was determined by a culture method on nutrient agar. The total cell count and the intact cell count was determined with the aid of a flow cytometer using the Deoxyribonucleic acid dying method. The total cell count was determined with the use of SYBR Green (SG), while the number of damaged cells was determined by using pyridine iodide (PI). The number of undamaged cells was determined by the difference between these two numbers.

This study aimed to determine the effectiveness of disinfection and to evaluate the transformations of organic substances during chemical disinfection and chemical disinfection supplemented by UV radiation. The novelty of this paper is the changes in chemical compounds and the number of microorganisms determined. In addition it determined the efficiency of chemical disinfection and disinfection with UV irradiation in the removal of total cell count and damage cell number.

3. Results and discussion

Water undergoing disinfection was characterized by a small variability of physicochemical composition (Table 1), which resulted from surface water pre-treatment. Among organic substances, the dissolved fraction dominated, making up 54.4%–100.0% of TOC. A consequence of the presence of low levels of insoluble organic substances was low water turbidity, which increased the effectiveness of the disinfection process [26]. It should also be noted that in water undergoing disinfection, biodegradable substances made up on average 31.8% of the dissolved fraction, which exceeds values typically found in surface waters [27].

At the same time, it was found that the DOC content was directly proportional to UV absorbance at both wavelengths of 254 and 272 nm (Fig. 1). This means that DOC concentration is determined by the presence of refractive substances and precursors of organic disinfection by-products [28].

On the other hand, the UV absorbance value was directly proportional to the watercolor intensity values that were found (Table 2), which indicates a dominance of colored organic substances, especially humic substances.

Apart from organic substances, microorganisms were present in water undergoing disinfection, and their numbers varied significantly (Table 1). The total microorganism count, both psychrophilic and mesophilic, was significantly smaller than the total cell count and the intact cell count, as determined by the cytometric method. This is due to the marking of all bacteria cells, and not only colony-forming ones [29,30]. The variability in the number of microorganisms and cells was similar, and their number resulted from the intense flushing of microorganisms from fresh absorption beds [31]. The large variation in the number of microorganisms and cells contributed to an increased demand for disinfectant, and thus a larger required dose of disinfectant.

In the first analyzed system, the disinfection by sodium hypochlorite allowed for a deactivation of microorganisms, which is evidenced by decreases in the total psychrophilic microorganism count and the total cell count of on average 87.0% and 77.2%, respectively. The lack of complete elimination of microorganisms during chemical disinfection may result from an insufficient disinfectant dose [32] or insufficient reactivity of sodium hypochlorite. Due to the

Table 1
Ranges of water quality indicator values before and after disinfection

Parameter	FWO	DO1	UVO	DO2
Temperature, °C	15.4–23.8	15.8–24.5	15.7–24.4	15.6–24.3
pH	7.45–8.59	6.77–8.63	7.49–8.65	7.52–8.67
Turbidity, NTU	0.01–0.19	0.02–0.42	0.01–0.25	0.01–0.63
TOC, g C/m^3	0.16–3.93	0.17–4.01	0.08–3.03	0.12–3.00
DOC, g C/m^3	0.09–2.65	0.13–2.68	0.09–2.72	0.13–2.65
BDOC, g C/m^3	0.06–0.73	0.03–0.51	0.03–0.51	0.01–0.57
C_{410}, g/m^3	0–4.26	0–3.83	0.07–5.15	0.03–4.16
C_{340}, g/m^3	0.02–3.57	0.11–3.16	0.10–4.33	0.13–3.80
UV_{272}, m^{-1}	0.09–4.05	0.15–3.65	0.11–4.16	0.11–3.69
UV_{254}, m^{-1}	0.11–5.09	0.17–4.62	0.12–5.03	0.16–4.59
TN psychrophilic, cfu/1 mL	16–2,940	0–27	3–43	0–36
TN mesophilic, cfu/1 mL	1–2,560	1–15	1–27	0–11
TCC cell/mL	622–5,865	95–17,610	150–8,190	69–7,564
ICC cell/mL	600–5,794	87–17,511	99–8,094	57–7,487

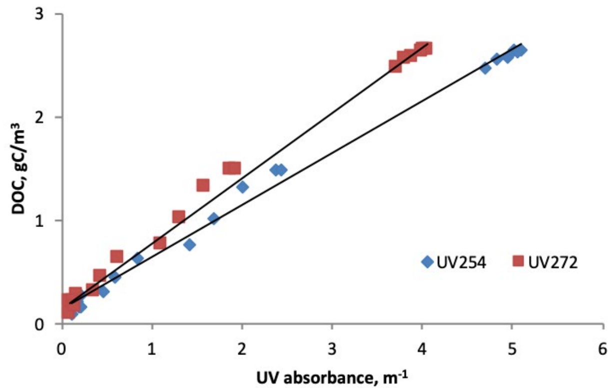

Fig. 1. Relationship between DOC concentration and UV absorbance in water undergoing disinfection.

Table 2
Relationships between color intensity and UV absorbance

No.	Equation	*R*
1	$C_{340} = 0.6968 \times UV_{254} - 0.0104$	0.999
2	$C_{340} = 0.876 \times UV_{272} - 0.0005$	0.999
3	$C_{410} = 0.9258 \times UV_{254} - 0.197$	0.982
4	$C_{410} = 0.7364 \times UV_{272} - 0.184$	0.982

lower oxidative potential of this oxidant, higher doses are required in comparison to using gaseous chlorine.

The significant reduction in the number of microorganisms and cells was accompanied by transformations of organic substances (Table 3).

No single direction of changes was found for concentrations of TOC, DOC, and BDOC. This was the result of, on the one hand, oxidation of organic substances, and on the other, the release of these substances from microorganism cells damaged during the disinfection process. The increase in BDOC could have also been caused by the transformation of large-molecule substances into smaller ones, which was also found in other studies [33].

No relationship was found between changes in the DOC content and UV absorbance. However, changes in UV absorbance at both wavelengths of 254 and 272 nm determined the change in color intensity at wavelengths of 340 (Fig. 2) or the maximum absorbance of humic substances [34].

In the second system, an effective deactivation of microorganisms was achieved by UV irradiation, which resulted in the decrease of the number of psychrophilic and mesophilic microorganisms, and the total cell count (Table 3). The average effectiveness in reducing microorganisms/cells was larger than that found for chemical disinfection, which shows the higher effectiveness of UV radiation as compared to sodium hypochlorite, which is confirmed by other studies [35].

The reduction in the number of microorganisms was accompanied by the reduction of DOC in half of all water samples, and a significant reduction in UV_{254} absorbance in 80% of water samples. During irradiation, an increase in BDOC was found in half of the water samples, which testifies to breaking down of organic substances. Like in the case of using chemical disinfection, UV irradiation showed that changes in UV absorbance cause changes in color intensity at the maximum for humic substances, which testifies to the transformation of mainly this group of substances during irradiation [36].

Changes in water composition during physical disinfection showed that the used dose of sodium hypochlorite ensured an effective elimination of microorganisms and cells (Table 3), which is illustrated by a comparison of cell numbers in water after disinfection in both systems (Fig. 3).

Additionally, the use of an oxidant after water irradiation caused further changes in organic substances, as evidenced by the reduction in TOC and DOC in the majority of water samples after chemical disinfection. On the other hand, an increase in BDOC concentration was found, and therefore probably a transformation of high molecular weight organic

Table 3
Ranges of the effectiveness of water quality indicators after the disinfection process

Parameter	Water treatment system with chemical disinfection alone	Water treatment system with chemical disinfection assisted by UV radiation		
	Chemical disinfection	Physical disinfection	Chemical disinfection	Total disinfection
Turbidity, %	–732.45 – 56.21	–411.86 – 71.29	–873.30 – 64.29	–295.04 – 56.96
TOC, %	–257.76 – 38.69	–27.23 – 52.29	–254.00 – 71.06	–350.38 – 49.58
DOC, %	–310.29 – 42.26	–230.16 – 37.92	–274.27 – 67.22	–79.78 – 47.21
BDOC, %	–151.72 – 93.05	–171.43 – 73.95	–128.57 – 96.92	–108.06 – 96.65
$Color_{410}$, %	–73.81 – 53.62	–62.25 – 81.75	–128.57 – 96.92	–232.57 – 93.83
$Color_{340}$, %	–117.32 – 43.33	–56.81 – 38.71	–370.11 – 78.58	–729.79 – 42.10
UV_{272}, %	–271.52 – 20.28	–33.33 – 28.79	–315.96 – 26.53	–417.88 – 35.31
UV_{254}, %	–97.52 – 14.55	–36.36 – 27.97	–380.85 – 16.64	–479.49 – 29.22
TN psychrophilic, %	19.40 – 99.80	53.68 – 99.86	–80.00 – 100.00	76.12 – 100.00
TN mesophilic, %	0 – 99.92	36 – 99.91	–600.00 – 100.00	0 – 100.00
TCC (all), %	40.14 – 96.05	29.52 – 93.77	–660.20 – 76.77	–133.42 – 97.13
ICC (undamaged), %	44.59 – 96.37	34.26 – 95.87	–705.92 – 77.42	–139.80 – 97.62

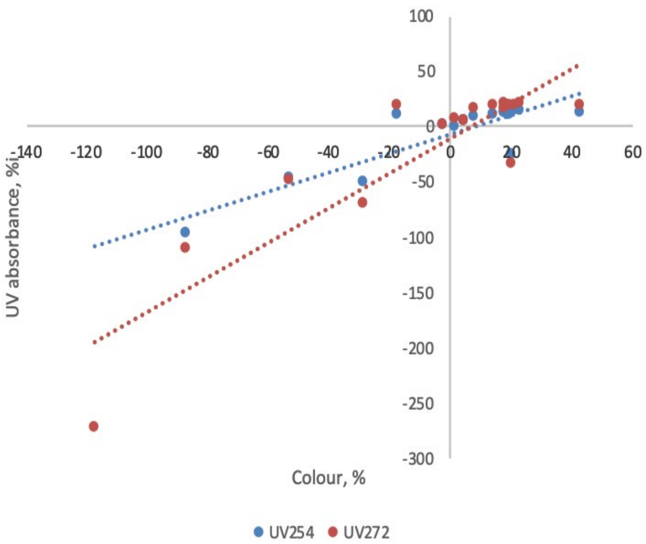

Fig. 2. Relationship between changes in UV absorbance and color intensity.

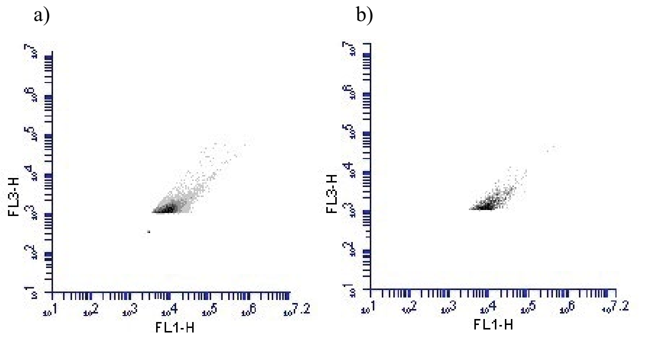

Fig. 3. Total number of cells in water after (a) chemical disinfection assisted by UV radiation and (b) chemical disinfection alone.

substances to lower ones took place. The breaking of the carbon–carbon bonds of an organic compound took place.

The transformation of organic substances was accompanied by changes in color and absorbance. In the majority of water samples, a reduction in these indicator values took place, apart from the period of deterioration in input water quality, that is, during the refilling of the adsorption beds with fresh activated carbon. This may be related to the flushing of microorganisms from the beds and therefore the release of organic substances into the treated water.

In both systems analogous changes took place, yet in the case of chemical disinfection assisted by UV radiation, there was a greater intensity of these changes along with a greater intensity of microorganism/cell deactivation. Consequently, water after chemical disinfection assisted by UV radiation was characterized by lower contamination levels (Table 1). Above all, a much smaller number of intact cells was found. This is mainly a confirmation of the disinfecting effect of UV radiation [33].

As a result of the use of the chemical agent, no significant changes in the TOC content were found, but the supplementing of disinfection by UV radiation caused a decrease in the value of this parameter as compared to water undergoing only chemical disinfection. Such a relationship was not found with respect to the dissolved fraction, which testifies to the dominance of the transformation of organic substances over their mineralization. The transformation of organic substances is also confirmed by the correlation that was found between changes in UV absorbance and watercolor. More intense transformations in the system with UV radiation caused that the color intensity in some samples was larger in the system with UV radiation than in the system without (Table 1).

Changes in the UV absorbance and watercolor were not dependent on the effectiveness of removing DOC that was

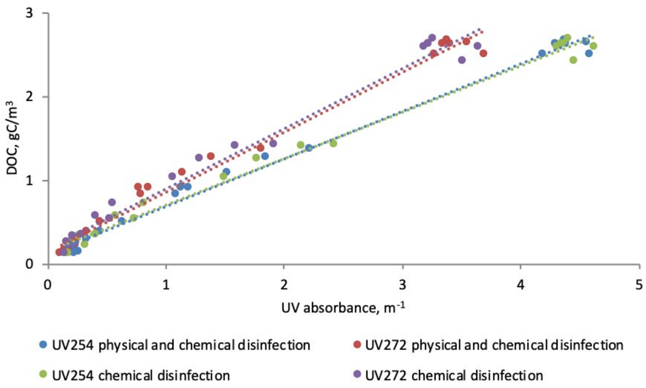

Fig. 4. Relationship between changes in DOC content and UV absorbance.

found, which resulted from the lack of organic substance mineralization and insignificant changes in DOC concentrations. On the other hand, in water after disinfection in both systems, a relationship was found between the DOC content and UV absorbance (Fig. 4).

This relationship initiates that, despite the chemical changes taking place during pure chemical disinfection and chemical disinfection assisted by UV radiation, refractive substances dominate in treated water. Above all, humic substances dominate, whose absorption maximum is at 340 nm.

Adding UV radiation before chemical disinfection, therefore, caused an intensification of biological and chemical transformations, and consequently led to lower microorganism numbers, decreases in TOC concentrations and frequently greater watercolor intensities.

3. Conclusions

The DOC content in water, both before and after disinfection in both processes was directly proportional to UV absorbance.

The use of only a chemical oxidizer for disinfection did not ensure complete elimination of microorganisms or a sufficient reduction in the number of cells. During chemical disinfection, no organic substance mineralization was found, but only a transformation of their structures. Transformations of organic substances during chemical and assisted disinfection mainly concern colored UV-absorbing humic substances.

Supplementing of disinfection by UV radiation allowed for an insignificant reduction in organic substance content and an intense transformation of these substances during disinfection. Supplementing disinfection by UV radiation allowed for effective elimination of microorganisms and cells at the same sodium hypochlorite dose.

Lack of UV disinfection support contributes to increased demand for disinfectant, and therefore it is necessary to use higher doses of oxidant to obtain the same effect of removing microorganisms.

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