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ANALYSIS OF CHLORINE DISTRIBUTION IN RURAL WATER SUPPLY NETWORK

ANALIZA ROZPRZESTRZENIANIA SIĘ CHLORU W GMINNEJ SIECI WODOCIĄGOWEJ

Abstract: Tap water delivered to customers should meet the drinking water requirements determined by EU and Polish biding law. Assuring the proper qualitative parameters of drinking water requires the necessary control of water quality along all length of distribution system, selection of proper methods of water treatment, application of suitable piping materials as well as countermeasures in case of water quality deterioration, i.e. performing permanent or periodical disinfection.

The aim of this paper was to analyze chlorine distribution in rural water supply system. Our studies were based on numerical hydraulic model of the studied network developed in Epanet 2.0 modeling software.

The first order chlorine decay reaction was assumed to modeling studies, with applied literature values of decay rate in water mass k_b = 0.09 h^{-1} and in boundary layer k_w = 0.041 h^{-1}. It was also assumed that chlorine in dose of 0.3 mg · dm^{-3} was introduced to the network during time duration of simulation. Additionally, the simulations of water age for various variants of water supply network operation were performed. Time duration assumed for modeling of chlorine decay was equal to 120 h and for water age analysis 480 h.

The obtained results of chlorine decay simulation showed that even after 5 days there were observed pipelines in which the observed calculated concentration of free chlorine was lower than 0.01 mg/dm^3. Thus, the required microbiological protection of water quality in these pipelines is unavailable. The determined water age in the studied rural network was in age from 12 hours in water supply station to over 192 hours in the end parts of the system.

Keywords: water age, chlorine distribution in water

Introduction

The tap water delivered to consumer should meet the requirements for drinking water determined by European and local standards [1, 2]. The determined proper quality characteristics of water require the water quality monitoring along the whole distribution system, selection of suitable methods of water treatment, usage of the appropriate

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materials in network construction as well as undertaking the necessary actions preventing deterioration of water quality by i.e. constant or periodical application of disinfectants such as chlorine or its compounds. The physicochemical properties of water and efficiency of the applied disinfection are directly influencing the intensity of chemical and biological processes occurring in tap water [3].

Chlorine is one of the most popular disinfectants used in water purification, added to water destroys microorganisms present in it. But, on the other hand, chlorine added to tap water reacts with organic compounds, which may result in appearance of the disinfection process by-products, responsible for the secondary deterioration of water quality [4–8]. The above shows the importance of proper determination of the chlorine dose. According to the WHO's requirements, the concentration of free chlorine at the tap water receivers should be in the range of 0.2–0.5 mg $\cdot$ dm^{-3} [9]. The Polish national standards [2] presents the allowable concentration of chlorine in drinking water as 0.3 mg $\cdot$ dm^{-3}.

The main indicators of water quality influencing usage of the free chlorine include: temperature and pH of water, content of reduced inorganic and organic compounds as well as inorganic forms of phosphorus and nitrogen [10–15]. The free chlorine production is also significantly influenced by velocity of flow as well as diameter, material and age of pipeline [16–18]. The studies performed by Hallama et al. [19] showed increase in constant of chlorine usage in relation to increase in water flow velocity inside the cast iron pipes. The opposite relation was however observed for water supply pipeline. Chlorine present in drinking water is used in numerous chemical reactions with microorganisms, organic and inorganic compounds and material of the pipe. Thus, the constant of chlorine decay is being defined as sum of two components, constant of chlorine decay speed in waterbody mass, k_b, and on the pipe wall, k_w, according to the following equation:

$$k = k_b - k_w \tag{1}$$

The available literature studies suggest that the most important influence on ratio of chlorine decay in waterbody have the following factors: temperature and pH of water, initial chlorine dose and hydraulic conditions. Results of the studies performed by Clark [20], Powela et al. [21], Al-Jasera [16] presented value of chlorine decay constants in water as 0.07–0.74 h^{-1}. However, the constant of chlorine decay in the boundary layer depends mainly to the amount of biomass deposited on the pipe wall and the material of pipeline. The laboratory studies performed by Hallama et al. [19] showed the significant influence of pipe material on k_w. The determined k_w values were in range 0.03–1.64 h^{-1} for different materials [19].

The literature reports [5, 20, 22–23] deliver numerous examples of modeling of the chlorine decay ratio in water. The most popular mathematical model describing chlorine decay is a first-order model, according to the following equation:

$$c = c_0 e^{-kt} \tag{2}$$

where: c – chlorine concentration in time t [mg $\cdot$ dm^{-3}];
c_0 – initial chlorine concentration [mg $\cdot$ dm^{-3}];

k – constant of chlorine decay rate [min^{-1}];
t – time [min].

The other model used in researches considering chlorine decay is the second-order model, based on the concept of competitive reacting substances. The model described in literature by Clark [24] assumes that the reaction speed is proportional to concentrations of chlorine and the substance reacting with it:

$$aA + bB \rightarrow pP \tag{3}$$

where: A – chlorine;
B – compounds reacting with chlorine;
P – disinfection by-products;
a, b, p – stechiometric coefficients.

Taking into account that both first- and second-order models do not include all factors affecting ratio of chlorine decay in water supply network, the literature delivers the modified versions of standard, basic models [23–25], e.g. mixed fist- and second-order model, kinetic model of n-order, limited first-order model and parallel first-order model.

The aim of this paper was to analyze the water age and distribution of chlorine in the selected rural water supply system. The studies were performed by Epanet 2.0, with application of the hydraulic model of researched distribution network.

Materials and methods

Study area

The studies considering age of water and chlorine distribution in rural water supply network were performed by Epanet 2.0, EPA, USA modeling software, with application of hydraulic model of the researched network. Our Epanet simulation model used the first-order chlorine decay for prediction of residual chlorine concentration in the modeled drinking water distribution system [26–31].

The length of studied network was approx. 87 km, of which 47 km were the connection pipes. The oldest parts of the studied network, built about year 2000, were constructed of PVC pipes, the younger parts were mainly made of PE pipelines. The applied diameters of distribution pipes were in range 90–200 mm, while connection pipes 25–63 mm. The described rural water supply system was developed as a mixed, ring- and branched-system, supplied from two water supply stations. The regions supplied with water by each station have no common zones.

Hydraulic model

The applied hydraulic model, developed in Epanet 2.0, consisted of 655 lines and 641 nodes (see Fig. 1).

Fig. 1. Scheme of modeled network with marked characteristic nodes and pipelines

The following physical and hydraulic input data were introduced to the model: length of pipes, diameters, absolute roughness, geometrical elevation of nodes as well as computational water demands. The required pressure losses were determined according to the standard equation by Darcy-Weisbach.

The assumed water demand values were determined on the basis of readings of the domestic water-meters (0.006–0.250 $dm^3 \cdot s^{-1}$). The water demand patterns were based on readings of the main water-meter localized in the water supply station. The assumed values of absolute roughness were determined according to the available literature as $k = 0.1$ mm for PE pipelines used in water distribution systems for a period shorter than 15 years [32].

Qualitative model

The fist-order chlorine decay reaction, according to equation (1), and literature values of chlorine decay rates $k_b = 0.09$ h^{-1} and $k_w = 0.041$ h^{-1} [20], were adopted to our numerical calculations of chlorine distribution. Water in the studied network undergoes disinfection by chlorine periodically, in cases of the possible threat of bacteriological pollution or after restoration works. According to the local water supply company the chlorine concentration at the outflow form pumping station is equal to 0.3 $mg \cdot dm^{-3}$. It was assumed in our numerical calculations that chlorine is being introduced to the network with the same concentration (0.3 mg · dm^{-3}) through the full time duration of the simulation. The assumed initial concentration (c_0) of chlorine in tap water was assumed as 0 mg · dm^{-3}. Additionally, the simulation of water age in the distribution pipes was performed. The applied time duration for chlorine distribution and water age determination were equal 120 h and 480 h, respectively.

Results of numerical modeling

In order to present the chlorine distribution and determined water age in the studied rural water supply network, 10 characteristic points and 10 pipelines were selected. Their choice was determined by the distance from the pumping station, magnitude of daily changes in values of the hydraulic parameters and the location in the distribution network. The following nodes and lines were selected as the representative: H243 (1), HZ550 (2), w711 (3), H709 (4), w615 (5), z281 (6), H315 (7), H2 (8), w29 (9), H160 (10) and R734, R519, R689, R631, R717, R228, R347, R733, R125, R13. Their spatial distribution is presented in Fig. 1.

The schematic contour plot presenting isolines of chlorine distribution and water age are presented in Fig. 2.

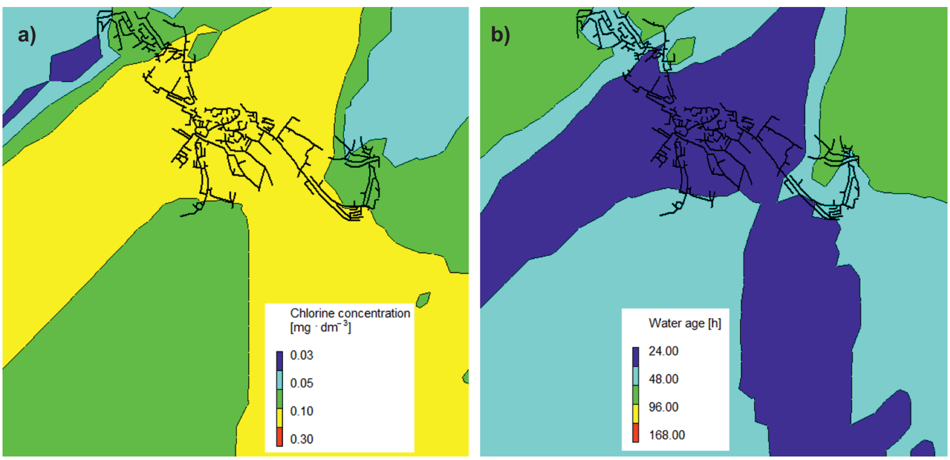


Fig. 2. Scheme of counter lines dividing: a) chlorine concentration in water and b) the water age in pipelines

Table 1 shows determined changes of free chlorine distribution in nodes of network, during the consecutive hours of simulation.

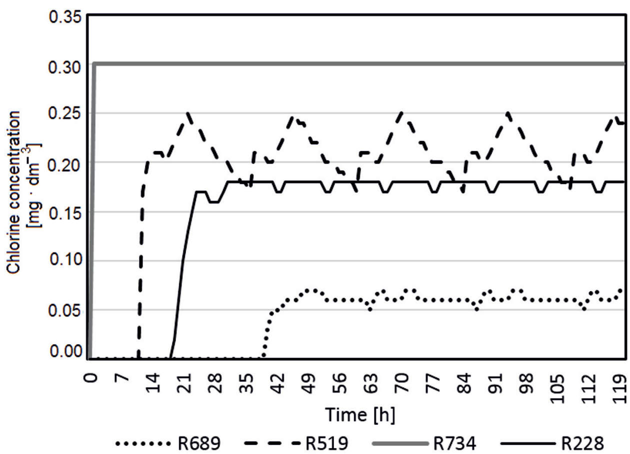
Figure 3 shows changes of free chlorine concentration in time for selected pipelines of the studied network.

The obtained results of chlorine distribution simulation indicate than the applied parameters of disinfection (i.e. the assumed time duration of disinfectant dosing) do not allow chlorine to reach all the pipelines. The zero concentrations of free chlorine were observed in several nodes, including H709, w615, w160 (see Table 1). The contour graph of chlorine distribution isolines presented in Figure 3 and time-related changes of

Table 1

Chlorine concentration on selected nodes of the network

Hour of simulation / Node No / Point No	Chlorine concentration [mg · dm^{-3}]									
Node No	H243	HZ550	w711	H709	w615	z281	H315	H2	w29	w160
Point No	1	2	3	4	5	6	7	8	9	10
0	0.30	0.00	0.00	0.00	0.00	0.00	0.00	0.30	0.00	0.00
24	0.30	0.22	0.00	0.00	0.00	0.16	0.00	0.30	0.20	0.00
48	0.30	0.22	0.03	0.00	0.00	0.17	0.00	0.30	0.20	0.00
72	0.30	0.22	0.01	0.00	0.00	0.17	0.00	0.30	0.20	0.00
96	0.30	0.22	0.01	0.00	0.00	0.17	0.00	0.30	0.20	0.00
120	0.30	0.22	0.00	0.00	0.00	0.17	0,01	0.30	0.20	0.00



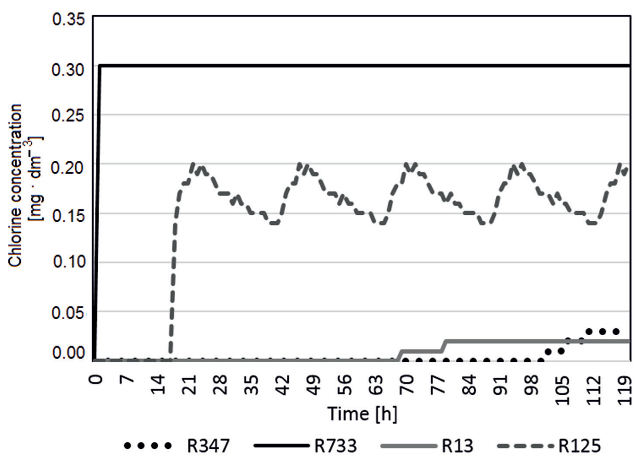


Fig. 3. Changes of free chlorine concentration in time in selected pipes of water distribution

chlorine concentration shown in Figure 3 indicate that the highest modeled concentrations of chlorine were noted in pipelines localized in close distance to the pumping station – R733 and R734, while the lowest were observed at the perimeter of the network. The required time duration between dosing the disinfectant and its arrival to the modeled node varied between 0 h (nodes at pumping station) and even 114 h (e.g. node H315) for nodes located at the perimeter. Despite the fact that chlorine in our model was dosed constantly during the time of 5 days, its concentration in none of the nodes did not exceed the allowed value of 0.3 mg · dm^{-3} [2].

The determined values of water age in the selected nodes of water supply system are presented in Fig. 4.

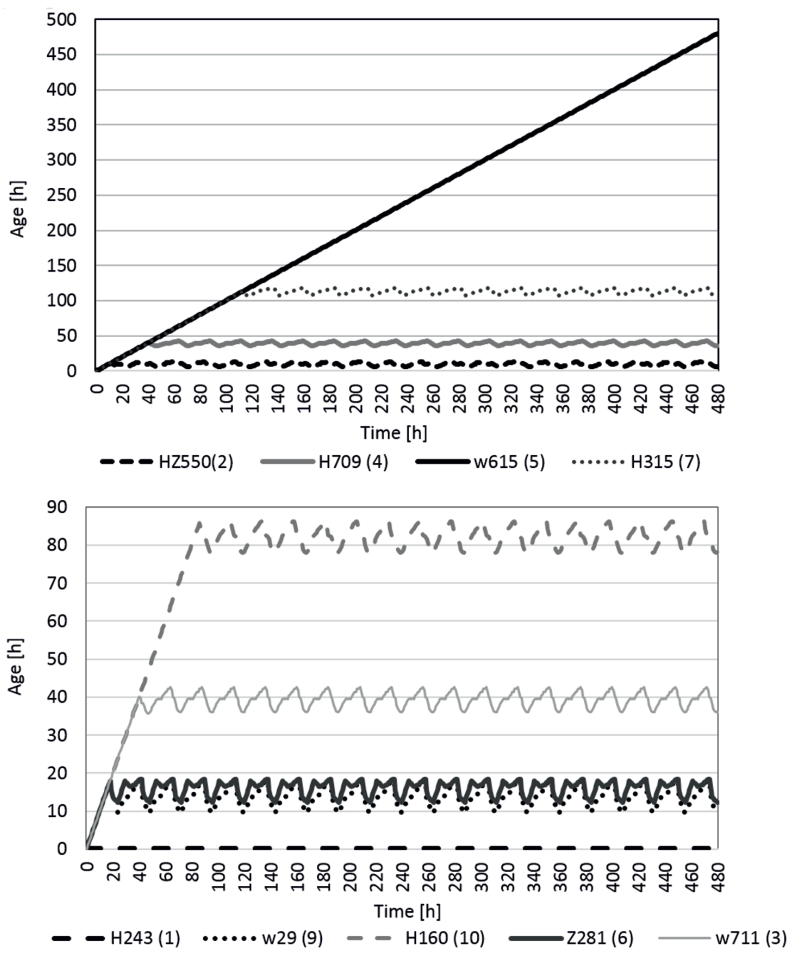


Fig. 4. Water age in selected nodes of water distribution system

Table 2 presents the modeled water age and several characteristics of flow for selected pipelines of distribution system.

Table 2

Water age and parameters of flow in selected pipes after 480 hours of modeling time duration

Pipeline	Pipe diameter [mm]	Volumetric flow rate $[dm^3 \cdot s^{-1}]$	Velocity $[m \cdot s^{-1}]$	Water age [h]
R734	160	1.69	0.10	0.80
R519	160	0.40	0.20	4.73
R717	90	0.00	0.00	474.00
R692	110	0.09	0.01	33.31
R631	90	0.00	0.00	473.60
R228	150	0.00	0.00	17.30
R347	90	0.01	0.00	103.94
R733	200	1.10	0.05	0.80
R125	160	0.46	0.03	9.62
R13	90	0.00	0.00	69.62

Analysis of data obtained after time duration of 489 hours simulation of water age shows that the determined water age increased in relation to the distance of pipeline to the water supply station (Table 2, Figure 2 and 4). The longest water age, between 4 and almost 20 days, was noted for the pipelines at the perimeter of the network, with the minimal water demand. The shortest water age was observed in pipelines in the central region of the network, where the determined water age varied in the range from 0.8 h to approx. 24 h (Fig. 4). Such long time of water retention, combined with the lack of disinfectant (see Table 1, Fig. 3) may result in growth of microorganisms, sediments deposition and deterioration of organoleptic characteristics of water.

Summary and conclusions

The asseveration of the minimal free chlorine content in tap water, combined with conservation of the required hydraulic parameters of water flow in the pipelines, is a crucial factor limiting the secondary deterioration of drinking water quality. Our analysis showed that in the studied network there are locations in distribution system which are unreachable for chlorine. These are mainly pipelines at the perimeter of the network, characterized by the minimal water demands. Only in the close proximity of the modeled water supply stations the determined numerically concentration of free chlorine reached the values 0.2–0.3 $mg \cdot dm^{-3}$. Studies concerning the water retention time in the modeled distribution system showed that there are numerous regions in the studied network, where water age reached clearly unacceptable values, posing a huge threat to water quality due to risk of microorganisms growth, development of disinfection by-products, appearance of unacceptable taste and smell as well as deposition of sediments [6]. The determined water age in the distant parts of the distribution network, where calculated water flow velocity was commonly below 0.01 $m \cdot s^{-1}$, reached even values of 473 hours.

Taking into account the fact that numerical model used in our studies was not calibrated and our calculations were based on the literature values of chlorine decay constants, our results should be treated as preliminary. However, they may serve as valuable source of information about operation conditions of the tested network.

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ANALIZA ROZPRZESTRZENIANIA SIĘ CHLORU W GMINNEJ SIECI WODOCIĄGOWEJ

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Abstrakt: Woda dostarczana odbiorcom powinna spełniać wymagania stawiane wodzie do picia podane w dyrektywie europejskiej 2015 r. oraz Rozporządzeniu Ministra Zdrowia z dnia 13 listopada 2015r. w sprawie jakości wody przeznaczonej do spożycia przez ludzi. Zapewnienie odpowiednich parametrów wody pitnej wymaga odpowiedniej kontroli jej jakości na całej długości systemu dystrybucji, doboru odpowiednich metod jej uzdatniania, stosowania odpowiednich materiałów w całych systemie jej dystrybucji a także podejmowania stosownych działań w sytuacji wystąpienia jej zanieczyszczenia np. prowadzenie stałej lub okresowej dezynfekcji.

Celem prezentowanych badań jest analiza rozprzestrzeniania chloru w gminnej sieci wodociągowej. Badania przeprowadzono w programie Epanet 2,0 przy zastosowaniu modelu hydraulicznego badanej sieci. Do obliczeń symulacyjnych rozkładu chloru przyjęto pierwszorzędową reakcję jego rozkładu oraz literaturowe wartości stałych szybkości rozkładu w masie wody k_b = 0,09 h^{-1} oraz w warstwie przyściennej przewodu k_w = 0,041 h^{-1}. Założono również, iż dawka chloru w wysokości 0,3 mg · dm^{-3} wprowadzana jest do sieci przez założony czas trwania symulacji. Dodatkowo przeprowadzono symulację wieku wody dla różnych wariantów pracy sieci wodociągowej. Czas trwania symulacji wynosił odpowiednio 120 h dla badań rozkładu chloru oraz 480 h dla analiz wieku wody.

Wyniki badań symulacyjnych rozprzestrzeniania chloru w sieci wykazały, iż nawet po 5 dobach istnieją w sieci przewody, w których stężenie chloru wolnego jest mniejsze od 0,01 mg/dm^3. W przewodach tych nie ma zapewnionej wymaganej ochrony mikrobiologicznej wody. Wiek wody w badanej sieci kształtuje się od 12 h w obrębie stacji wodociągowej do ponad 192 h, w końcowych fragmentach sieci.

Słowa kluczowe: wiek wody, rozprzestrzenianie chloru w wodzie