Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2023.29385

288 (2023) 37–44
March

Novel solution of water disinfection for a branched water supply network

Dariusz Kowalski*, Beata Kowalska

Wydział Inżynierii Środowiska, Politechnika Lubelska, ul. Nadbystrzycka 40B, 20-618 Lublin, Poland, emails: d.kowalski@pollub.pl (D. Kowalski), b.kowalska@pollub.pl (B. Kowalska)

Received 7 November 2022; Accepted 7 February 2023

ABSTRACT

Re-contamination of water supplied through a water supply network most frequently occurs in its dead-ends. In many cases, these are located in the least urbanized areas of settlement units. Usually, the water intake from these pipelines is small, which leads to stagnation of the stored water and issues related to its deteriorating quality, especially in terms of microbiology. Traditionally, this problem has been solved by increasing the dosage of disinfectant in water supply stations, periodically flushing the pipelines or using network disinfection stations. Each of these methods has certain disadvantages and does not fully solve the indicated problem. The purpose of the current study is to present a novel disinfection solution of dead-end pipes. The solution developed herein combines a network disinfection station with forced circulation of water in the water supply pipe. The proposed solution was tested using the hydraulic and quality calculations presented in the paper. As a result, the conditions for the application of the developed solution in actual water supply networks were indicated.

Keywords: Water supply networks; Re-contamination; Disinfection

1. Introduction

The issue of water re-contamination, especially at dead-ends of the water supply network, is well known and addressed in numerous publications [1–7]. For many years, changes have been observed regarding the rational use of water in water distribution systems, resulting in a significant reduction in the amount of water consumed [8,9]. This phenomenon results in a decreased velocity of water flow in pipes, sometimes leading to water stagnation. One way to reduce this problem is to establish DMAs (District Metered Areas) in water supply networks [10–12]. However, the use of these areas does not fully solve the problems of long water stagnation and the lack of water circulation in dead-end pipelines. In these locations, the increased the risk of re-contamination, can manifest itself as a change in the color, taste or turbidity of the water. Deterioration of microbiological and chemical parameters of water, sedimentation of organic matter and biofilm formation may also occur [13–18]. Dead-ends are also most often the places where disinfectant (residual chlorine) disappears, posing a high health risk to water consumers [15,19–21]. Typical measures taken by water utilities to counteract secondary water contamination in the distribution system are the use of additional network disinfection (booster chlorination) stations and pipe flushing.

In the case of conventional chlorination, it is extremely important to select the appropriate chlorine dosage, ensuring that effective disinfection is achieved throughout the distribution system, while preventing the formation of disinfection by-products. Chlorine reacts with natural organic matter found in the transmitted water forming halogenated disinfection by-products (DBPs), such as trihalomethane and haloacetic acids [10,14–17]. These compounds have a negative impact on the health of water consumers [10,22–26], which is why the World Health Organization (WHO) has set acceptable limits on the concentrations of chlorination by-products in drinking water [27]. Unfortunately, disinfection carried out at water supply stations is not always able

* Corresponding author.

Presented at the 15th Scientific Conference on Micropollutants in the Human Environment, 14–16 September 2022, Częstochowa, Poland

1944-3994/1944-3986

to provide sufficient chlorine concentrations throughout the distribution system, which is the result of too high an age of water or too high a reactivity of both water and pipe material. In turn, increasing the dose of disinfectant at the entrance to the network can lead to the formation of disinfection byproducts that are harmful to health. When this happens, it is necessary to carry out disinfection directly on the water supply network or dose chlorine to network water supply tanks. This process is usually carried out using mobile dosing equipment equipped with metering devices. Booster chlorination helps minimize not only biofilm growth but also fluctuations in chlorine concentration in the water supply network. Chlorine booster stations are typically used in larger systems with large water intakes. There are many publications in the literature that address the issue of booster chlorination in a water supply system, and they focus primarily on optimizing the location of chlorine booster stations within the network and determining optimal doses of dosed chlorine [28–38]. However, there are few publications that include a description of the equipment used in booster chlorination and they mainly refer to local improvement of water quality [39–41]. The devices described therein are installed on water supply systems in buildings (e.g., Klorman, Siperior®) or at residential water tanks (e.g., Aquatabs Flo).

Another way to improve water quality in the distribution system is to flush the pipes. This is a common measure in small towns with extensive water supply systems feeding areas with low population density. However, flushing is associated with high water losses and significant costs. In addition, there are no conclusive research results confirming the effectiveness of flushing for dead-ends, which, according to research [42], can account for 25% or more of all water supply pipes. A study by Barbeau et al. [15] using spot flushing dead-end locations showed that even with nearly identical configurations of dead-ends (water flowing in from the same source, identical pipe material and diameter, etc.), microbiological water quality varies. The authors also noted that using the HPC analysis method to characterize the microbiological quality of water is insufficient. Simunič et al. [43] developed a model of biofilm formation and removal in dead-ends during network flushing at different water flow rates and velocities. They pointed out the ineffectiveness of biofilm removal in dead-ends of the network using flushing, especially when the length of these sections is significantly greater than their diameter. The simulations conducted by these authors showed that laminar movement often occurred in dead-ends, while turbulent movement occurred in the main pipes. With a constant supply of nutrients, this creates conditions for faster biofilm growth in dead ends [44]. As the thickness of the biofilm layer formed in dead-ends increases, so does its resistance to chemical agents, including disinfectants [45,46].

The current paper presents a novel solution, in which a system was designed to achieve circulation and simultaneous disinfection of water in the final, dead-end, water distribution pipes. The solution was developed under the assumption of minimizing the necessary *in-situ* construction works and maximizing the use of already existing water distribution pipes. The paper also presents a method for determining the required flow velocities in circulation pipes and their allowable lengths, depending on the head of the circulator pumps used. The proposed solution enables to maintain the required concentration of disinfectant in the final pipes of the water distribution network. Its application can contribute to preventing and mitigating the effects of water quality deterioration and will also have an impact on reducing the loss of water used for flushing the pipes.

2. Novel solution

The proposed solution combines a network disinfection station, with forced circulation of water in a dead-end. The conceptual scheme of the method is shown in Fig. 1. A pressure circulation pipe fed by a pump and a water disinfection device was introduced into the water supply pipe. Starting the pump causes it to suck water from the water main and then inject it into the circulation pipe, which forces water to circulate through the resulting hydraulic system. The presence of a disinfection device behind the pump enables to dose the required dose of disinfectant into the circulating water and deliver it with the water into the disinfected water supply pipe.

The following assumptions were made while developing the presented solution:

- minimizing the necessary earthworks by inserting the circulation pipe inside the existing water supply pipe,
- placing both the circulator pump and the disinfection device outside the water supply pipe, which facilitates their operation and enables installing additional devices, such as a suspended solids capture filter, a control block for system operation, etc,
- allowing the water flow to be closed through the water supply pipe and through the circulation pipe at the same time,
- manufacturing the circulation pipe from a flexible material, such as thin-walled PE pipe, allowing easy insertion into the water supply pipe and overcoming changes in the direction of the pipe.

Taking into account the above, additional technical solutions had to be developed (Figs. 2 and 3).

The solution shown in Fig. 2 allows using existing mains gate valves installed on the water supply pipe, while maintaining the ability to close the flow in the circulation pipe. This enables to carry out maintenance work (repairs, renovations) below the gate valves. This solution would not be possible without the use of specialized T-connections (Fig. 3). The branch of the T-connection is a pipe stub, terminated on

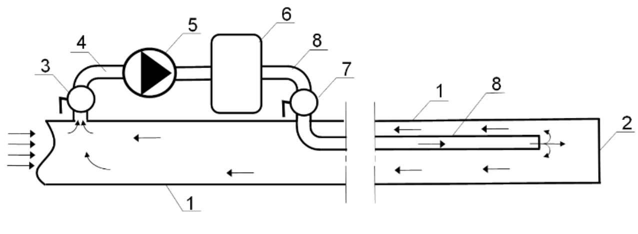

Fig. 1. Schematic diagram of the proposed water disinfection system. 1 – Water supply pipe, 2 –pipe cap, 3 – suction valve, 4 – pump suction pipe, 5 – pump, 6 – water disinfection device, 7 – valve, and 8 –pressure circulation pipe [47].

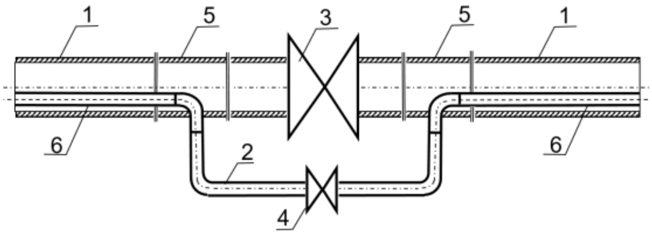

Fig. 2. Schematic diagram of the system that allows shutting off the flow of water in the mains and circulation pipe [48]. 1 – Water supply pipe, 2 – bypass pipe, 3 – mains gate valve, 4 – valve or gate valve, 5 – T-connection, and 6 – circulation pipe.

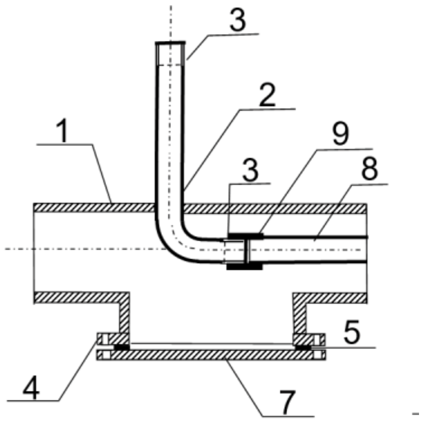

Fig. 3. Schematic diagram of a tee that allows safe routing of the circulation pipe outside/inside the water supply pipe [49]. 1 – Housing, 2 – side pipe, 3 – thread, 4 – flange, 5 – gasket, 7 – inspection cover, 8 – circulation pipe, and 9 – connector.

both sides with a thread that allows the connection of the circulation pipe. Closed by an inspection cover, the chamber of the T-connection allows the circulation pipe to enter the water supply pipe. The circulation pipe connecting to the main pipe is designed to be mechanically rigid. In case of some displacements caused by pump motor, a compensating fitting will be necessary.

3. Research methodology

The feasibility of the proposed water disinfection solution in the dead-end branch of the water supply network was evaluated using hydraulic and quality calculations, which included:

- calculation of the maximum length of the circulation pipe L_{max}, allowing the hydraulic circulation process,
- evaluation of the degree of reduction in the capacity of the water supply pipe due to the placement of the circulation pipe,
- calculation of changes in the concentration of disinfectant in the water supply pipe when using a circulation pipe of this length,
- calculation of the maximum length of the circulation pipe $L_{max\,Cl}$ to achieve the required disinfectant concentration in the water supply pipe

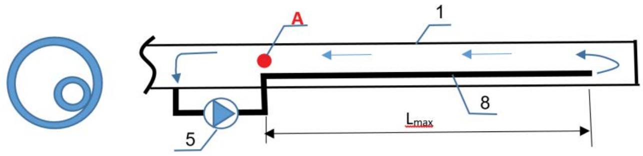

Fig. 4. Design diagram of the circulating hydraulic system. The cross-section is presented on the left-hand side, whereas longitudinal profile is show on the right-hand side. A – calculation point of disinfectant concentration, other designations as in Fig. 1.

3.1. Hydraulic calculation of the circulation pipe length

Hydraulic calculations of the maximum length of the circulation pipe to maintain the circulation process were carried out using the Collebrook–White and Darcy–Weisbach equations, for a pipe-in-pipe system (Fig. 4). Local and linear resistances of the pump connection system were omitted in the calculations.

The calculations involved a cast-iron water pipe with an internal diameter of 80 mm and a PEHD circulating pipe with a nominal diameter of 25 mm × 2 mm, with a roughness of k = 0.1 mm. The roughness of the water pipe was changed during the calculations in the range of 0.1–5 mm, which enabled to check the effect of the size of this roughness on the desired L_{max}. The head of the circulating pump was changed during the calculations from 10 to 60 mH$_2$O. In the calculations, it was assumed that this height would be used entirely to overcome the resistance in both the circulation pipe and the water supply pipe, with a length of L_{max}. The calculated capacity of the pump depended on the assumed speed of water flow in the circulation pipe. This velocity was assumed in the range of 0.1–3.0 m/s.

The effect of changes in the roughness of the water pipe on the length of L_{max} was calculated as a percentage, taking as a reference the length determined for a roughness of 0.1 mm, according to the following formula:

$$L_{\max\text{difference}} = \frac{L_{\max} - L_{\max k=0.1}}{L_{\max k=0.1}} \times 100\% \quad (1)$$

where $L_{\max\ \text{difference}}$ – percentage of difference in length, $L_{\max\ k}$ – length determined for changed roughness k, $L_{\max}$ k = 0.1 – length determined for roughness k = 0.1 mm.

The calculations were carried out for a circulating pump head of 60 mH$_2$O, at which the changes in length L_{max} were the largest.

3.2. Evaluation of the reduction in capacity of the water supply pipe

The introduction of a circulation pipe into the interior of a water supply pipe reduces its active cross-sectional area and thus leads to a reduction in its capacity. This problem can be ignored under the conditions of household water intake provided that pipes are oversized, which is typical for dead-ends in a water supply network. However, the situation changes when fire flow is required. In order to estimate the degree of reduction in the capacity of the pipe under these conditions, a model built in the EPANET 2.0 program was used. The calculation scheme of the model is shown in Fig. 5. In the calculations, the equivalent diameter of the water supply pipe was calculated from the following formula:

$$d_z = \sqrt{\frac{4 \cdot F}{\pi}} = \sqrt{D^2 - d^2} \tag{2}$$

where d_z – equivalent diameter, F – active cross-sectional area, D – internal diameter of the water pipe, d – external diameter of the circulation pipe.

Simulation calculations were carried out comparing the size of the water supply to the H-node, both in the absence and presence of circulation. The length of all pipes was assumed to correspond to the size of $L_{\max\,\mathrm{Cl}}$ determined for circulator pump head of 10 and 60 $m\mathrm{H_2O}$. These heights also corresponded to the characteristics of the pump connected to the calculation system. The reservoir and intake node pressure heights of 60 and 10 $m\mathrm{H_2O}$, respectively, were used as boundary conditions.

3.3. Calculation of changes in disinfectant concentration in circulating water

Calculations of changes in disinfectant concentration in circulating water were carried out assuming the use of residual chlorine as a disinfectant. They were realized with the following assumptions:

– a first-order model of residual chlorine disappearance was used:

$$\frac{C_e}{C_o} = \exp(-kt) \tag{3}$$

where C_o denotes the concentration of residual chlorine at the inlet to the circulation system, assumed to be 0.3 mg·Cl/dm^3, C_e – the concentration of residual chlorine at point A (Fig. 4), after one cycle of water circulation,

– time t was calculated from the following formula:

$$t = \frac{L_{\max}}{v_1} + \frac{L_{\max}}{v_2} \tag{4}$$

where $L_{\max}$ – length determined for the velocity in the circulation pipe according to section 3.1, v_1 – velocity of water flow in the water supply pipe, v_2 – velocity of water flow in the circulation pipe, – the coefficient k denoting disappearance of residual chlorine concentration was taken as the sum of the coefficients of disappearance in the bulk k_b and at pipe walls k_v. The values of these coefficients were adopted using literature data: k_b = 0.036 L/h [50] and k_v = 0.050 L/h – for HDPE pipe and k_{v1} = 0.130 L/h – for cement-coated cast iron pipe [51], calculations were carried out for one cycle of water circulation in the system under study.

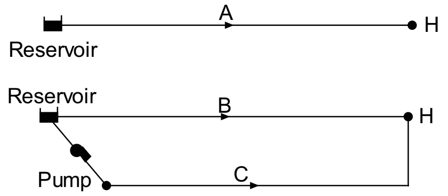

Fig. 5. Diagram of the calculation model in EPANET. A – Water supply pipe without circulation, B – water supply pipe with replacement diameter d_z, C – circulation pipe, H – H-node – fire hydrant.

The water flow time in the system depended on the predetermined lengths of $L_{\max}$, the circulation and water supply pipes, and the assumed flow velocity of the water in the circulator pipe. In the verification calculations, the lengths of $L_{\max}$ and flow velocities determined in accordance with the methodology presented in Section 3.1.

3.4. Calculation of the maximum length of the circulation pipe $L_{max\,Cl}$

The maximum usable length of the circulation pipe is determined not only by the hydraulics of the system, but also by the progressive disappearance of the disinfectant concentration. Taking into account the latter factor, length $L_{\max\,\mathrm{Cl}}$, was calculated, ensuring the achievement of its minimum acceptable concentration. For the calculations, this value was taken as 0.02 mg·Cl/dm^3 [50]. Length $L_{\max\,\mathrm{Cl}}$ was determined graphically in two steps. In the first, the speed in the circulation pipe at which the residual chlorine concentration reached the assumed minimum permissible value was determined using graphs of changes in residual chlorine concentration drawn up as a function of the speed of water flow in the circulation pipe and the head of the circulator pump (section 3.3). In the second step, the length of the circulation pipe corresponding to this velocity was determined (section 3.1). This length was determined as $L_{\max\,\mathrm{Cl}}$. The calculation was carried out by changing the head of the circulating pump, similarly as in section 3.1.

4. Results and discussion

Fig. 6 shows the results of calculating the length of $L_{\max}$ to ensure the realization of the hydraulic circulation process, assuming a water pipe roughness of 0.1 and 5.0 mm.

The graphs indicate that the higher the flow velocity in the circulation pipe, the smaller the length $L_{\max}$. An increase in the head of the circulator increases this length. Using calculations for different roughness of the main pipe, its effect on the length of the circulation pipe was determined. The results of the calculations are shown in Fig. 7.

The calculation results shown in Fig. 7 indicate a relatively small effect of changes in the roughness of the water supply pipe on the maximum length of the circulation pipe. This is due to the fact that the water flow velocity in this pipe is significantly lower than in the circulation pipe. Taking this into account, further calculations were limited to the roughness of the water supply pipe k = 5.0 mm, as the most unfavorable.

The results of calculating the degree of capacity reduction of the proposed hydraulic system are summarized in Table 1.

The introduction of the circulation pipe has reduced the capacity of the water supply pipe. This reduction is partially compensated for by the flow of water in the circulation

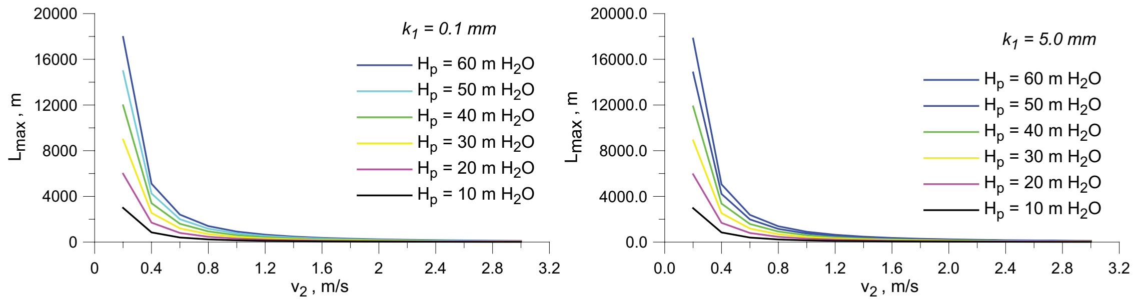

Fig. 6. Calculated maximum length of the circulation pipe to ensure the maintenance of the circulation process, assuming a roughness of the main water pipe of 0.1 mm (a) and 5.0 mm (b).

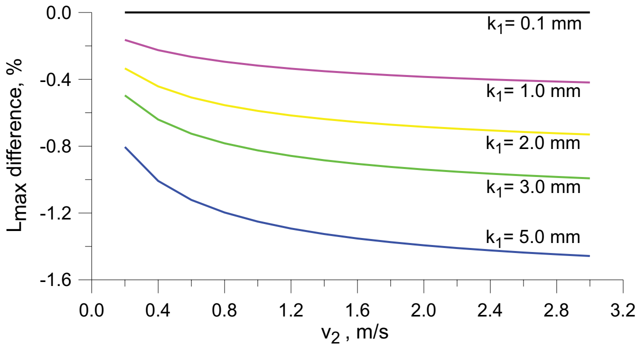

Fig. 7. Graph of the percentage change in the length of L_{max}, depending on the roughness of the main water pipe. Circulator pump head of 60 $m H_2O$.

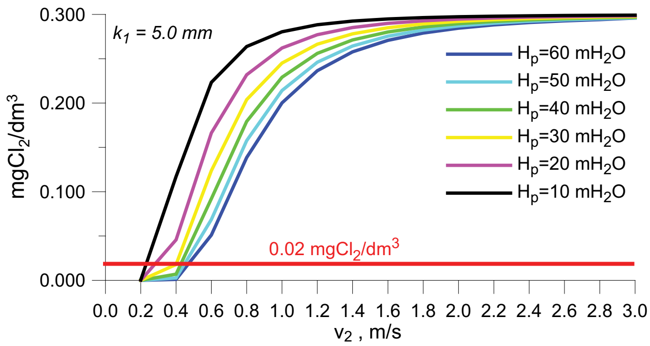

Fig. 8. Calculated concentration of residual chlorine after one circulation, depending on the velocity of water flow in the circulation pipe and the head of the circulator pump.

Table 1
Results of simulation calculations of the reduction of the hydraulic system capacity after the insertion of a circulating pipe inside the water pipe

H_p ($m H_2O$)	L_{max}	Q (dm^3/s)		Reduction %
		Without circulation	With circulation	
10	2,720	3.00	2.80	6.7
60	4,150	2.42	2.30	4.9

pipe, forced by the operation of the pump connected to it. However, it is worth noting that the magnitude of this decrease does not exceed 7%, which does not exclude the proposed solution in practice. The solution presented in Fig. 2 causes an increase in local hydraulic resistance. Assuming the calculation methodology contained in the PN-76/M34034 standard, the total value of the coefficient characterizing these resistance is 2.28, which at the speed of 1.0 m/s and PE pipes corresponds to 2.2 m in length.

Subsequently, the values of residual chlorine concentration were calculated after the water flowed through the circulation and water supply pipes. The results of the calculations are shown in Fig. 8.

An increase in the flow velocity in the circulation pipe results in a reduction of L_{max} (Fig. 6). The time for water to flow through the entire circulation decreases and, at the same time, the residual chlorine concentration increases after a full flow cycle. It is worth noting that there are limiting velocities below which the residual chlorine concentration falls below the assumed minimum value. This suggests that the maximum length of the circulation pipe may be less than the L_{max} calculated from hydraulic flow parameters alone. Therefore, an attempt was made to determine a new maximum length $L_{max\ Cl}$, ensuring that the required disinfectant concentration is achieved. Exemplary calculation charts, for the circulator pump head of 10 and 60 $m H_2O$ are shown in Fig. 9. The results of calculating the maximum length $L_{max\ Cl}$, depending on the obtainable disinfectant concentration, are summarized in Fig. 10.

As expected, maximum lengths $L_{max\ Cl}$ of the circulation line to ensure the minimum assumed residual chlorine concentration were found to be significantly lower than those calculated using the L_{max} hydraulic flow condition. The obtained lengths $L_{max\ Cl}$ range from 2,720 m using a circulator pump with a head of 10 $m H_2O$ to 4,150 m using a pump with a head of 60 $m H_2O$.

Increasing the diameter of the circulation pipe increases its possible length $L_{max\ Cl}$. This is due to the fact that the age of water in the main pipe has been shortened. The results of the calculations carried out for the main pipe with a diameter of 80 mm and circulation pipes with a diameter of 25 mm × 2.0 mm, 32 mm × 2.3 mm and 40 mm × 2.3 mm are summarized in new Table 2.

Presented in Table 2 lengths are very significant and larger than the numerous dead-ends of water supply

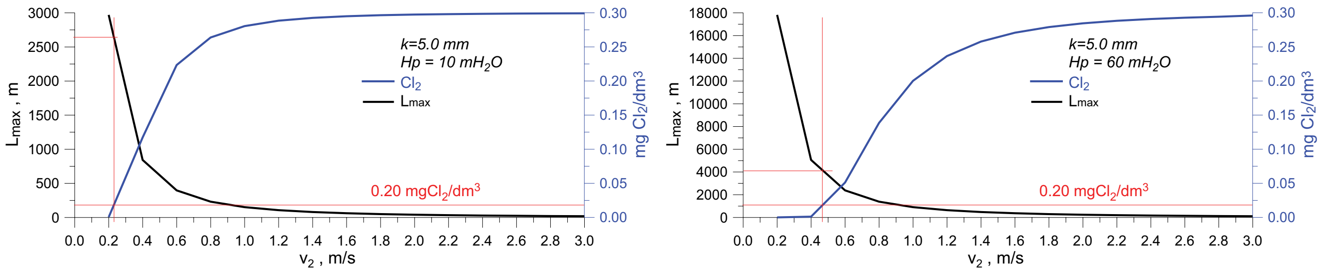

Fig. 9. Design charts of $L_{max\ Cl}$ length, with circulator pump head of 10 (a) and 60 mH$_2$O (b).

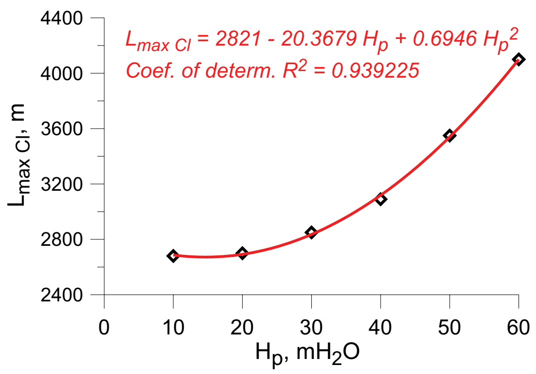

Fig. 10. Graph of the variation of the maximum length, $L_{max\ Cl}$, as a function of the circulator pump head.

Table 2
Maximum lengths $L_{max\ Cl}$ depending on the diameter of the circulation pipe

H_p, mH$_2$O	$L_{max\ Cl}$, m		
	D80/25	D80/32	D80/40
10	2,720	4,186	5,433
60	4,150	6,181	8,180

networks, treating as length from the last branch to the dead end of main pipe. Therefore, this confirms at least the theoretical suitability of applying the proposed solution to the conditions of an actual water supply network.

5. Conclusions

The issue of maintaining the required water quality in the dead-end pipes of water supply networks is highly significant. Insufficient disinfectant concentration in water flowing through these pipes can potentially lead to the growth of undesirable microorganisms and thus endanger the health of water consumers. The methods used so far to solve this problem are not fully effective or are too expensive. In this context, the use of the solution proposed by the authors, combining secondary disinfection stations and forcing circulation in dead-end water pipes, seems expedient. The advantage of this solution is the independence of the disinfection process from stagnant water in the pipelines, the reduction of the amount of water lost to traditional flushing of such pipes, and the possibility of controlling the concentration of disinfectant in dead-end pipes. The simulation calculations carried out in the paper included both hydraulic conditions of water flow and changes in residual chlorine concentration. They showed that the potential feasible length of circulating pipes depends on a number of factors, including: the total decay rate of residual chlorine, its concentration at the point where the circulating pump is turned on, and the capacity and head of the pump. Under the assumed conditions (80 mm diameter cast iron main line and 25 mm × 2.0 mm PEHD circulating line), the length varied from 2,720 to 4,150 m. This is greater than the length of a significant portion of the dead-end pipes of settlement and village water supply networks. This proves, at least in theory, the desirability of applying the proposed solution to these networks. Empirical verification of the solution in an actual water supply network will be necessary before its widespread use. Certainly, the use of repeated water disinfection and forced circulation of water in dead-end water pipes does not fully solve the problem of maintaining a safe concentration of disinfectant in distributed water for users. From other side, turning off the circulation pump will lead to stagnation of water in the circulation pipe. However, presented solution can be a good complement to other methods, such as distributed disinfection stations or established DMAs combined with directed water flow.

References

[1] A.A. Abokifa, Y.J. Yang. C.S. Lo, P. Biswas, Water quality modeling in the dead end sections of drinking water distribution networks, Water Res., 89 (2015) 107–117.
[2] A.A. Abokifa, A. Maheshwari, R.D. Gudi, P. Biswas, Influence of dead-end sections of drinking water distribution networks on optimization of booster chlorination systems, J. Water Resour. Plann. Manage., 145 (2019) 04019053, doi: 10.1061/(ASCE)WR.1943-5452.0001125.
[3] M. Mrowiec. T. Herczyk, E. Kuliński, Analysis of the variability of drinking water quality parameters in the distribution system, Inżynieria i Ochr Środ, 19 (2016) 2735 (in Polish).
[4] U. Olsińska, K. Skibińska, Modeling of water quality changes in the system, Ochr. Środ., 29 (2007) 33–40 (in Polish).
[5] N. New, Z.S. Kazama, S. Takizawa, Network model analysis of residual chlorine to reduce disinfection byproducts in water supply systems in Yangon city, Myanmar, Water, 13 (2021) 2921, doi: 10.3390/w13202921.
[6] Y. Im, G. Song, J. Lee, M. Cho, Deep learning methods for predicting tap-water quality time series in South Korea, Water, 14 (2022) 3766, doi: 10.3390/w14223766.
[7] D. Papciak, A. Domoń, M. Zdeb, B. Tchórzewska-Cieślak, J. Konkol, E. Sočo, Mechanism of biofilm formation on installation materials and its impact on the quality of tap water, Water, 14 (2022) 2401, doi: 10.3390/w14152401.

[8] H. Hotloś, Research on changes in water consumption in selected Polish cities in the years 1990–2008, Ochr. Środ., 32 (2010) 39–42 (in Polish).
[9] H. Kłoss-Trębaczkiewicz, E. Osuch-Pajdzińska, Analysis of trends in water consumption in Polish cities, Ochr. Środ., 27 (2005) 63–67 (in Polish).
[10] K. Gonelas, A. Chondronasios, V. Kanakoudis, M. Patelis, P. Korkana, Forming DMAs in a water distribution network considering the operating pressure and the chlorine residual concentration as the design parameters, Hydroinformatics, 19 (2017) 900–910.
[11] A. Chondronasios, K. Gonelas, V. Kanakoudis, M. Patelis, P. Korkana, Optimizing DMAs' formation in a water pipe network: the water aging and the operating pressure factors, Hydroinformatics, 19 (2017) 890–899.
[12] M. Patelis, V. Kanakoudis, A. Kravvari, Pressure regulation vs. water aging in water distribution networks, Water, 12 (2020) 1323, doi: 10.3390/w12051323.
[13] N. Liu, T. Skauge, D. Landa-Marbán, B. Hovland, B. Thorbjørnsen, F.A. Radu, B.F. Vik, T. Baumann, G. Bødtker, Microfluidic study of effects of flow velocity and nutrient concentration on biofilm accumulation and adhesive strength in the flowing and no-flowing microchannels, J. Ind. Microbiol. Biotechnol., 46 (2019) 855–868.
[14] S.E. Smith, D.M. Holt, A. Delanoue, J.S. Colbourne, A.H.L. Chamberlain, B.J. Lloyd, A pipeline testing facility for the examination of pipe-wall deposits and red-water events in drinking water, Water Environ. J. Promot. Sustainable Solut., 13 (1999) 7–15.
[15] B. Barbeau, K. Julienne, A. Carriere, V. Gauthier, Dead-end flushing of a distribution system: short and long-term effects on water quality, J. Water Supply Res. Technol. AQUA, 54 (2005) 371–383.
[16] F. Ling, R. Whitaker, M.W. LeChevallier, W.T. Liu, Drinking water microbiome assembly induced by water stagnation, ISME J., 12 (2018) 1520–1531.
[17] Z. Liu, Y.E. Lin, J.E. Stout, C.C. Hwang, R.D. Vidic, V.L. Yu, Effect of flow regimes on the presence of *Legionella* within the biofilm of a model plumbing system, J. Appl. Microbiol., 101 (2006) 437–442.
[18] L. Zlatanović, J.P. van der Hoek, J.H.G. Vreeburg, An experimental study on the influence of water stagnation and temperature change on water quality in a full-scale domestic drinking water system, Water Res., 123 (2017) 761–772.
[19] J.T. Carter, Y. Lee, S.G. Buchberger, Correlations between travel time and water quality in a dead end loop, Proc. Wat. Qual. Technol. Conf. Am. Wat. Wks Assoc., Denver, Co, USA, November 9–12 (1997).
[20] V. Kanakoudis, S. Tsitsifli, Potable water security assessment – a review on monitoring, modelling and optimization techniques, applied to water distribution networks, Desal. Water Treat., 99 (2017) 18–26.
[21] V. Kanakoudis, Determining hazards' prevention critical control points in water supply systems, Environ. Sci. Proc., 2 (2020) 53, doi: 10.3390/environsciproc2020002053.
[22] S, Monarca, C. Zani, S. Richardson, A.D. Thruston Jr., M. Moretti, D. Feretti, M. Villarini, A new approach to evaluating the toxicity and genotoxicity of disinfected drinking water, Water Res., 38 (2004) 3809–3819.
[23] M.A. Brown, G.L. Emmert, On-line monitoring of trihalomethane concentrations in drinking water distribution systems using capillary membrane sampling-gas chromatography, Anal. Chim. Acta, 555 (2006) 75–83.
[24] G. Hua, D.A. Reckhow, Comparison of disinfection by-product formation from chlorine and alternative disinfectants, Water Res., 41 (2007) 1667–1678.
[25] V. Uyak, K Ozdemir, I. Toroz, Multiple linear regression modeling of disinfection by-products formation in Istanbul drinking water reservoirs, Sci. Total Environ., 378 (2007) 269–280.
[26] K.P. Cantor, D.F. Lynch, M.E. Hildesheim, M. Dosemeci, J. Lubin, M. Alvanja, G. Craun, Drinking water source and chlorination by products, risk bladder cancer, Epidemiology, 9 (1998) 21–28.
[27] WHO, Guidelines for Drinking-Water Quality, Vol. 1, Recommendations, 3rd ed., World Health Organization, Geneva, 2004.
[28] S.W. Krasner, H.S. Weinberg, S.D. Richardson, S.J. Pastor, R. Chinn, M.J. Sclimenti, G.D. Onstad, A.D. Thruston Jr., Occurrence of a new generation of disinfection by-products, Environ. Sci. Technol., 40 (2006) 75–85.
[29] S.D. Richardson, M.J. Plewal, E.D. Wagner, R. Schoeny, D.M. Demarini, Occurrence, genotoxicity, and carcinogenicity of regulated and emerging disinfection by-products in drinking water: a review and roadmap for research, Mutat. Res., 636 (2007) 178–242.
[30] J.G. Uber, R.S. Summers, D.L. Boccelli, M.E. Tryby, Maintaining Distribution System Residuals Through Booster Chlorination, AWWA Research Foundation, Denver, 2001.
[31] M.E. Tryby, D.M. Boccelli, J. Uber, L.A. Rossman, A facility location model for booster disinfection of water supply networks, J. Water Resour. Plann. Manage., 128 (2002) 322–333.
[32] M. Propato, J.G. Uber, Linear least-squares formulation for operation of booster disinfection systems, J. Water Resour. Plann. Manage., 130 (2004) 53–62.
[33] I. Nouiri, F. Lebdi, Genetic algorithm (GA) for optimal choice of chlorine booster stations in drinking water networks, J. Water Sci., 19 (2006) 47–55.
[34] I. Nouiri, Optimal design and management of chlorination in drinking water networks: a multi-objective approach using Genetic Algorithms and the Pareto optimality concept, Appl. Water Sci., 7 (2017) 3527–3538.
[35] J.D.P. Sandoval, B.M. Brentan, G.M. Lima, D.H. Cervantes, D.A. García Cervantes, H.M. Ramos, X. Delgado Galván, J. de Jesús Mora Rodríguez, Optimal placement and operation of chlorine booster stations: a multi-level optimization approach, Energies, 14 (2021) 5806, doi: 10.3390/en14185806.
[36] K. Xin, X. Zhou, H. Qian, H. Yan, T. Tao, Chlorine-age based booster chlorination optimization in water distribution network considering the uncertainty of residuals, Water Supply, 19 (2019) 796–807.
[37] M.A. Al-Zahrani, Optimizing dosage and location of chlorine injection in water supply networks, Arabian J. Sci. Eng., 41 (2016) 4207–4215.
[38] W. Kurek, M.A. Brdys, Optimised allocation of chlorination stations by multi-objective genetic optimisation for quality control in drinking water distribution systems, IFAC Proc. Vol., 39 (2006) 232–237.
[39] J. Rayner, T. Yates, M. Joseph, D. Lantagneet, Sustained effectiveness of automatic chlorinators installed in community-scale water distribution systems during an emergency recovery project in Haiti, J. Water Sanit. Hyg. Dev., 6 (2016) 602–612.
[40] C. Null, C.P. Stewart, A.J. Pickering, H.N. Dentz, B.F. Arnold, C.D. Arnold, J. Benjamin-Chung, T. Clasen, K.G. Dewey, L.C.H. Fernald, A.E. Hubbard, P. Kariger, A. Lin, S.P. Luby, A. Mertens, S.M. Njenga, G. Nyambane, P.K. Ram, J.M. Colford Jret, Effects of water quality, sanitation, handwashing, and nutritional interventions on diarrhoea and child growth in rural Kenya: a cluster-randomised controlled trial, LANCET Global Health, 6 (2018) 316–329.
[41] A.J. Pickering, Y. Crider, S. Sultana, J. Swarthout, F.Gb. Goddard, S.A. Islam, S. Sen, R. Ayyagari, S.P. Luby, Effect of in-line drinking water chlorination at the point of collection on child diarrhoea in urban Bangladesh: a double-blind, cluster-randomised controlled trial, LANCET Global Health, 7 (2019) 1247–1256.
[42] V.G. Tzatchkov, A.A. Aldama, F.I. Arreguin, Advection-dispersion-reaction modeling in water distribution networks, J. Water Resour. Plann. Manage., 128 (2002) 334–342.
[43] U. Simunič, P. Pipp, M. Dular, D. Stopar, The limitations of hydrodynamic removal of biofilms from the dead-ends in a model drinking water distribution system, Water Res., 178 (2020) 115838, doi: 10.1016/j.watres.2020.115838.
[44] J.W. Costerton, Bacterial biofilms: a common cause of persistent infections, Science, 284 (1999) 1318–1322.
[45] T.-F.C. Mah, G.A. O'Toole, Mechanisms of biofilm resistance to antimicrobial agents, Trends Microbiol., 9 (2001) 34–39.

[46] P.S. Stewart, Antimicrobial tolerance in biofilms, Microbiol. Spec., 3 (2015), doi: 10.1128/microbiolspec.mb-0010–2014.
[47] D. Kowalski, B. Kowalska, K. Boryczko, Water Circulation System in Dead End Pipes of the Water Supply Network, Patent Application P 439278, Urząd Patentowy RP, 2021 (in Polish).
[48] D. Kowalski, B. Kowalska, K. Boryczko, Valve Connection System, Patent Application P439280, Urząd Patentowy RP, 2021 (in Polish).
[49] D. Kowalski, B. Kowalska, K. Boryczko, Water Supply Tee, Patent Application P439279, Urząd Patentowy RP, 2021 (in Polish).
[50] E. Hołota, B. Kowalska, D. Kowalski, Localization method for water quality monitoring points using chlorine concentration measurements in real water network, Desal. Water Treat., 199 (2020) 227–233.
[51] N.B. Hallam, J.R. West, C.F. Forster, J.C. Powell, I. Spencer, The decay of chlorine associated with the pipe wall in water distribution systems, Water Res., 36 (2002) 3479–3488.