SOME ASPECTS REGARING CHLORINE DECAY IN WATER DISTRIBUTION NETWORKS

LIANA IOANA VUŢĂ[1], GABRIELA ELENA DUMITRAN[2]

ABSTRACT. – A major objective of drinking water treatment is to provide microbiologically safe drinking water. The combination of conventional drinking water treatment and disinfection has proved to be one of the major public health advances in modern times. The quality of drinking water delivered to the customer's tap is influenced by a number of processes; namely water treatment, disinfection and changes during transport of treated water via the distribution system. All natural waters and even treated drinking water exerts disinfectant demand due to the reactions with NOM and other constituents in water. Therefore, the applied disinfectant dose must be sufficient to meet the inherent demand in the treated water, to provide sufficient protection against microbial infection. Thus, controlling free residual chlorine properly is definitely important to ensure meeting regulatory requirements and satisfying customer needs.

This paper presents the main aspects regarding chlorine decay in drinking-water distribution networks and, also a free chlorine decay simulation with EPANET2 on Ramnicu Valcea water distribution system.

Keywords: drinking water quality, chlorine decay, distribution system, Epanet.

1. INTRODUCTION

Water distribution system makes water available to the consumer in proper quantity and pressure. Tap water should not contain microorganisms, parasites or substances that might represent a potential hazard for human health and it must meet the minimal requirements stipulated in regulations concerning the quality parameters of potable water (microbiological and chemical indicators).

The quality of water delivered to the customers depends on its initial chemical and physical composition, the proper choice of purification technology, technical condition of water storage tanks and the pipe network as well as hydraulic conditions and exploitation manner of the water distribution system. Thus, water distribution systems act as large-scale chemical and biological reactors and sometimes, due to improper design or operation, can greatly modify the quality of water (e.g. long retention times which lead to water aging, reduced disinfectant residual and formation of disinfection by-products, bacterial growth, appearance of cooper and lead, taste and odor problems and so on).

[1] University "Politehnica" of Bucharest, Power Engineering Faculty, 060042 Bucharest, Romania, e-mail: l_vuta@yahoo.com, tel: 0744535933

[2] University "Politehnica" of Bucharest, Power Engineering Faculty, 060042 Bucharest, Romania, e-mail: dumitran@hydrop.pub.ro, tel: 0741146060

Preserving the water quality throughout the distribution system is, therefore, one of the most challenging technological issues for suppliers.

Many water utilities use chlorine residual to inactivate potential pathogenic organisms and preserve water quality during distribution. In 1976, it was discovered that disinfections by-products (DBPs) were produced during the disinfection process (Marhaba and Washington 1998). Chlorine reacts with natural organic compounds found in water (humic and fulvic acids) and form a wide range of undesired halogenated organic compounds, including trihalomethanes (THMs), haloacetic acids (HAA), chlorophenols, chloral hydrate and haloacetonitriles (Gallard and von Gunten 2002). The concern of DBPs formed during disinfection processes is based on the evidence that they have some adverse health effects: cancer, reproductive disorders, liver and kidney damage, birth defects and possibly miscarriage (Arora et al. 1997).

Thus, controlling the residual chlorine concentration in drinking water is a very important aspect, since the decrease of chlorine concentration below the minimal level may cause secondary development of microorganisms and excessive chlorine concentration may cause formation of dangerous disinfection by-products.

2. MECHANISM OF CHLORINE DECAY

Chlorine decay in distribution system is generally considered to consist of two components. One component is associated with decay in the bulk phase of the water, and the other with the wall demand.

Chlorine demand and DBPs formation are influenced by treatment conditions and by the constituents in the raw and treated water. The demand due to inorganic compounds is smaller than the one associated with the reaction between chlorine and natural organic matter (NOM).

Among the factors that influence the demand of chlorine and the formation of DBPs can be mentioned:

- Chlorine dose: high chlorine concentration lead to increased DBPs leves;
- Reaction time: long reaction times results in high chlorine demand and increased DBPs leves;
- pH: an increase in the pH lead to increase in THMs formation but to decrease in HAA; pH modification has a neglijable effects on chlorine demand;
- Temperature: high temperature lead to greater chlorine demand and higher levels of DBPs.

In order to be able to estimate correctly the residual concentration in water distribution systems, all the factors that influence the chlorine demand must be identified.

3. MODELLING APPROACH

Chlorine propagation inside the water distribution system may be studied with the use of mathematical models comprehensively describing the variable hydraulic conditions and reflecting individual factors influencing the disinfectant decay. Simulation of residual chlorine concentration in selected water supply network nodes makes gathering the knowledge about transported water quality possible and helps in considering the network segments/parts in which water quality deterioration occurs.

One of the available software for water distribution network modelling is Epanet. Epanet allow the hydraulic studies of water distribution systems and also the movement and fate of drinking water constituents within distribution systems.

Decay simulation conducted within EPANET takes into consideration the phenomena of chlorine reaction with chemical species at bulk fluid and with pipe walls.

The reactions occurring in the bulk flow can be modelled with n-th order kinetics, where the instantaneous rate of reaction (R in mass/volume/time) is assumed to be concentration-dependent according to:

$$R=K_b \cdot C^n \qquad (1)$$

Where *Kb* = bulk reaction rate coefficient, *C* = reactant concentration (mass/volume), and *n* = reaction order.

The decay of free residual chlorine because of reaction occurring in the bulk water is generally assumed in the literature (Munvalli and Kumar, 2006; Haestad, et al., 2001) to be a first order reaction.

In practice, bulk decay coefficients can be determined by running a bottle test on the water entering the distribution system.

The contribution of wall reactions is introduced into the software through another constant K_w , whose meaning is more complex. The rate of water quality reactions occurring at or near the pipe wall can be considered to be dependent on the concentration in the bulk flow by using an expression of the form:

$$R=(A/V)K_w \cdot C^n \qquad (2)$$

Where K_w = wall reaction rate coefficient and *(A/V)* = the surface area per unit volume within a pipe (equal to 4 divided by the pipe diameter).

There is currently no established method for directly determining the kinetics of chlorine decay due to pipe wall reactions and calibration against field data must be used instead. Still, the literature indicate that pipe diameter and pipe material are the categories most likely to impact wall coefficient values in a calibration process (Munvalli and Kumar, 2006; Haestad, et al., 2001; Michael Hudkins, et al., 2010).

To assure the correct use of the water quality simulator, incorporated in the EPANET, a model calibration process must be done, determining the correct values to K_b and K_w coefficients. In most cases, model calibration is conducted *a posteriori*, altering parameter values in order to obtain, in the model, values that match real ones. Still, values reported in the literature, for similar condition regarding the distribution system structure can be used in order to determine the residual chlorine concentration at the consumers.

4. CASE STUDY: RAMNICU VALCEA WATER DISTRIBUTION SYSTEM

The Ramnicu Valcea network is a gravity fed system from 4 reservoirs, and the distribution to consumers (about 120,000 inhabitants) is provided through metal pipes network, with sizes ranging from 80 to 600 mm. The network layout is presented in figure 1, and figure 2 presents the base demands at consumers.

For the daily flow variation, three different regimes are considered: domestic, commercial and industrial consumers. The flow patterns are presented in Figures 3. For all pipes, the equivalent pipe roughness is set to 0.2 mm and Darcy – Weisbach formula is used as a headloss equation.

Under these assumptions, the hydraulic behaviour of the network was investigated, using Epanet v2. From the hydraulic point of view, the network does not present any problems: water in sufficient quantity and at adequate pressure is delivered to all consumers. The minimum available pressure is recorded in junction 5 and is above 9 m.

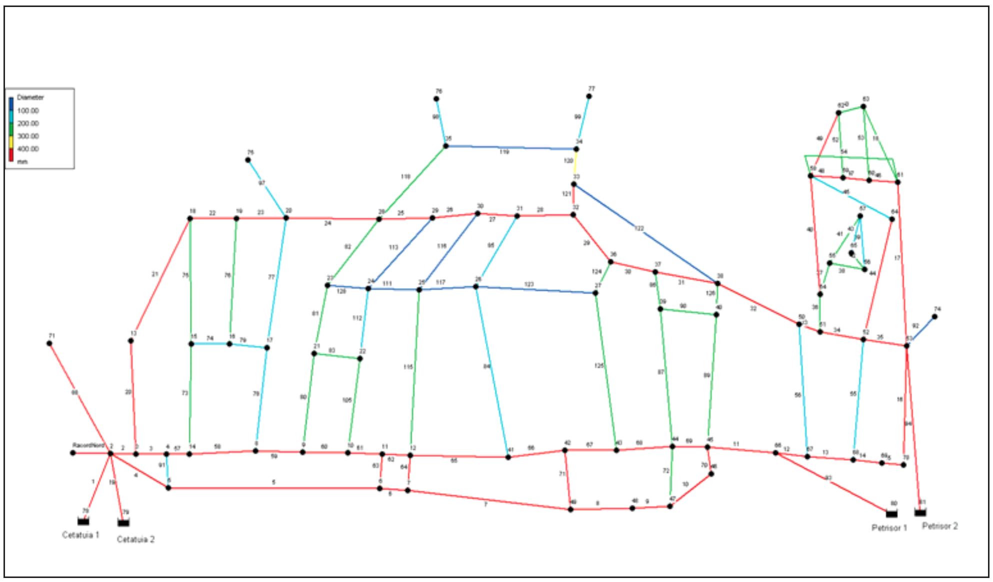


Figure 1. ***Ramnicu Valcea water distribution system layout***

Regarding the residual chlorine concentration in Ramnicu Valcea network nodes, previous investigations considered only the bulk flow reaction (Rotaru 2006; Vuta 2008).

In this paper, two hypotheses are considered for modelling chlorine decay: the first one considering only the chlorine reaction in the bulk flow and the second, considering also the pipe wall reaction. The values for k_b and k_w used (-0.1 h^{-1} and -0.17 h^{-1} respectively) have been chosen around the ones reported in the literature (according with the pipe material, diameters and age/roughness) (Castro et al. 2003; Nagatani et al. 2008; Hudkins et al. 2010).

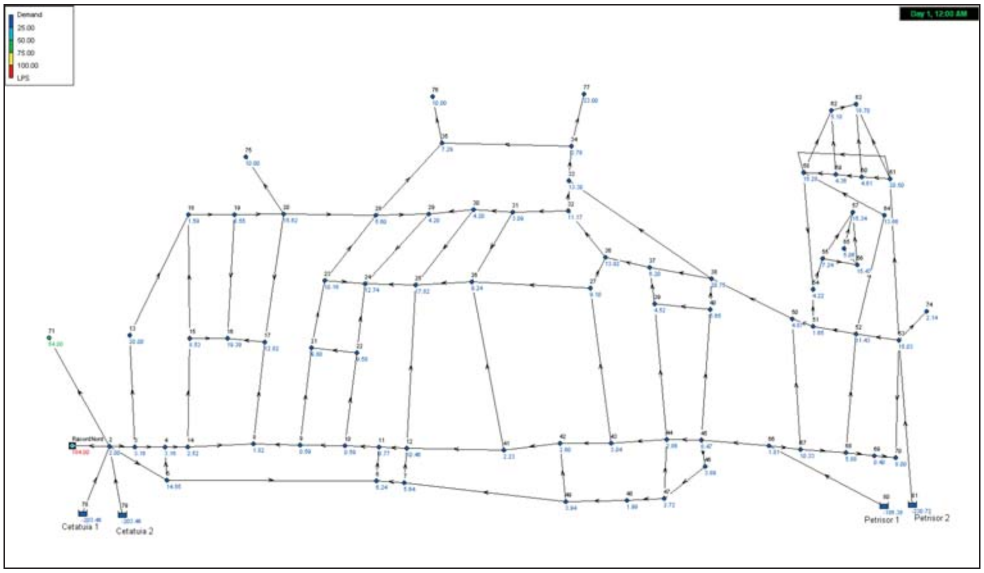
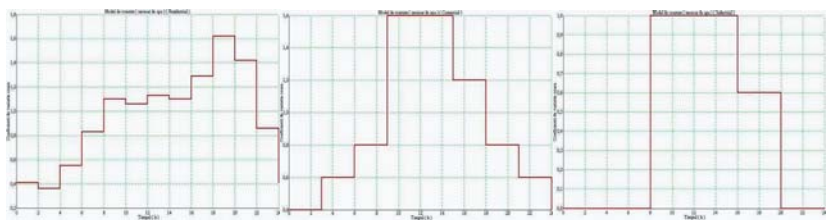


Figure 2. ***Base demands for Ramnicu Valcea water distribution system***



Figures 3. ***Flow patterns for domestic, commercial and industrial consumers***

When considering only the bulk flow reaction and a first-order decay reaction, few nodes experienced low levels of residual chlorine concentration during low period consumption (between 2.00 and 7.00 am): 18, 29, 31, 75, 76. 75 and 76 are industrial consumers, 31 is commercial and 18 and 29 are domestic. The low residual chlorine concentration find in those nodes is related with high travel time of water from reservoirs, as it can be seen in figure 4 and figure 5.

Figure 4. ***Chlorine concentration in networks nodes, k_b = -0.1 h^{-1}, k_w = 0***

Figure 5. ***Water age in networks nodes***

Differences in residual chlorine concentration are expected to appear when considering also pipe wall reaction. In this case, beside the bulk reaction described by a first-order decay reaction, a zero-order reaction at the pipes wall is considered. As a result, large area of the network presents very low residual chlorine concentration, presented in figure 6. The correlation between high water age and low chlorine concentration is still evident.

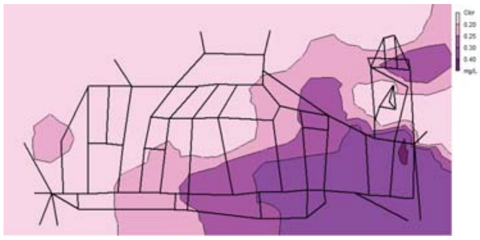


Figure 6. ***Chlorine concentration in networks nodes, k_b = -0.1 h^{-1}, k_w = -0.17 h^{-1}***

In this case, the residual chlorine concentration drops below 0.1mg/l in some nodes in the network. Figure 7 presents the values obtained for node 18 in the two hypotheses. As it was expected, introduction of the pipe wall reaction lead to high chlorine demand, making the system unsecure if the residual chlorine concentration is very low (for some nodes in the network, during the low demand period, residual chlorine concentration drop below 0.1 mg/l). In the theoretical case presented in this article, the chlorine demand increased only by 30%, but, according to the literature, the wall demand can represent up to 80% from the total disinfectant.

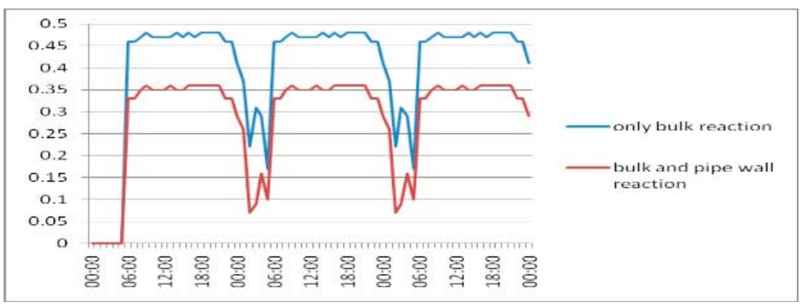


Figure 7. ***Differences between residual chlorine concentrations for node 18***

6. CONCLUSION

Controlling the residual chlorine concentration in drinking water is a very important aspect, since the decrease of chlorine concentration below the minimal level may cause secondary development of microorganisms and excessive chlorine concentration may cause formation of dangerous disinfection by-products. Mathematical modelling of chlorine decay along the water supply system is a problem whose solution is not yet absolutely mastered.

Still, hydraulic/water quality models can be used by drinking water utilities in order to efficiently plan, operate, and expand their potable water systems. But, in applying water quality models to actual water distribution system it is critical that a well-calibrated hydraulic model to be used along with site-specific reaction rate data.

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