Environmental Engineering and Management Journal *November/December 2008, Vol.7, No.6, 737-741*
http://omicron.ch.tuiasi.ro/EEMJ/

"Gheorghe Asachi" Technical University of Iasi, Romania

MODELLING CHLORINE DECAY IN DRINKING WATER MAINS

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Abstract

Drinking water treatment plays an important role in maintaining public health. Chlorine is the most often disinfectant used for microbiological protection of water. Required residual chlorine concentration must be in treated water when it leaves treatment plant, to comply with the regulations. The chlorine residual must be 0.5 mg/L at the entrance into the distribution system and 0.25 mg/l at consumers, according to the law. Any less and there is no guarantee that the water has adequate quality. The major problem that occurs as water flows between treatment plant and the consumer is water quality deterioration because of decreasing of residual chlorine concentration, especially for long residence times. This can be lead to high microbiological concentration in water downstream and it is necessary additional treatment with chlorine. This study presents a theoretical model based on dispersion equation, which was validated with experimental measurements in drinking water mains that supply Ramnicu-Valcea town, Romania.

Key words: drinking water treatment, disinfection, chlorine decay, dispersion equation

1. Introduction

Disinfection is the last safety barrier on the way to render sanitary quality to drinking water. Chlorine is the most used disinfectant for this purpose, providing high degree of sanitation at a relatively low cost. The major drawback is formation of disinfection by-products because of chlorine reaction with natural organic matter from water. Destruction of harmful microorganisms by chlorine is mainly related to contact time, concentration of chlorine and water quality. Successful chlorination requires that amount of chlorine added corresponds with chlorine demand tests to achieve disinfection and oxidation. A little more amount of chlorine than is required is added, to be sure that is sufficient. This will lead to free chlorine residual that can be measured. However, chlorine must not be added in amounts that are wasteful and create unnecessarily operational costs. There are many researches to predict chlorine demand, (Chen and Jensen, 2001; Haas et al., 2002; Yu and Cheng, 2003).

A number of researches have been developed to modeling chlorine decay in drinking water distribution system: (Islam et al. ,1997), (Clark and Sivaganesan, 2002; Ucak and Ozdemir, 2004; Leeuwen et al, 2004; Jivan, 2005). A review of several models for predicting the decay of disinfectants and the formation of disinfecting by-products have been presented by Clark et al. (2001). These models are mostly based on first-order decay, second order decay, power-law decay (nth order) and exponential decay assumption or reacting balance equation. Some authors divided the chlorine decay into two phases: an initial consumption phase and a slower second phase.

In this paper it is used dispersion equation to model chlorine decay, with a first-order decay term for chlorine consumption with different values along the pipe, correlated with flowrate. A customized program was developed in FlexPDE for numerically integration of equation. The results were compared with experimental data from mains that supply Ramnicu - Valcea town.

The water distribution system for Ramnicu – Valcea area is composed of: 1) raw water pipe (8574 m length and 1200 mm diameter) that brings water from Bradisor Artificial Lake on Lotru river to

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hydroelectric power plant Valea lui Stan (Stan's Valley); 3) Drinking Water Treatment Plant (DWTP) located in Valea lui Stan village; 3) treated water distribution pipe to Ramnicu - Valcea (1200 mm diameter, 12 mm thickness and 36 615 m length, made of carbon steel).

Water flows by gravity in distribution systems, because of the difference of ground elevation (DWTP - 350.5 m, Ramnicu-Valcea - 312 m), leading to great energy savings. However, the system includes 3 pumping stations for increasing water supplying pressure. DWTP supplies water in 6 municipalities in Ramnicu Valcea area. Average production is 1600 l/s. Water is treated initially in mixing tank with addition of chemicals (aluminum sulphate, polymers, chlorine and lime) and after that with sedimentation, filtration, final chlorination and storage. There are 2 storage tanks in DWTP, each of 975 m^3, laying out under the filters. After years of work, in distribution pipe occurred deposits of 15…25mm height. In 2004 the distribution pipe was cleaned using COLBACH patented technology, initially used in oil industry, based on helicoidally brushes on a cylinder.

2. Mathematical model

Theoretical study of chlorine decay considers dispersion and consumption of chlorine in water. General unsteady dispersion equation of chlorine in water is:

$$\frac{\partial \overline{C}}{\partial t}+\frac{\partial}{\partial x}(\overline{u}\overline{C})+\frac{\partial}{\partial y}(\overline{v}\overline{C})+\frac{\partial}{\partial z}(\overline{w}\overline{C})= \frac{\partial}{\partial x}\left(\varepsilon_x\frac{\partial \overline{C}}{\partial x}\right)+\frac{\partial}{\partial y}\left(\varepsilon_y\frac{\partial \overline{C}}{\partial y}\right)+\frac{\partial}{\partial z}\left(\varepsilon_z\frac{\partial \overline{C}}{\partial z}\right)+ D_m\left(\frac{\partial^2 \overline{C}}{\partial x^2}+\frac{\partial^2 \overline{C}}{\partial y^2}+\frac{\partial^2 \overline{C}}{\partial z^2}\right) + S(x,y,z,t) \qquad (1)$$

where S(x,y,z,t) is the source or consumption of chlorine.

The following assumptions are made in order to simplify this equation:
- unidirectional flow on Ox axis direction, v = w = 0
- there is molecular diffusion on longitudinal axis direction Ox and it is negligible on the others axis
- axial symmetric flow
- dispersion on transversal direction and longitudinal direction have the same intensity, so that

$$\frac{\partial C}{\partial x}\approx\frac{\partial C}{\partial y},\ \text{but}\ \frac{\partial C}{\partial z}=0$$

The dispersion equation becomes

$$\frac{\partial \overline{C}}{\partial t}+\frac{\partial}{\partial x}(\overline{u}\overline{C})=\frac{\partial}{\partial x}\left(\varepsilon_x\frac{\partial \overline{C}}{\partial x}\right)+\frac{\partial}{\partial y}\left(\varepsilon_y\frac{\partial \overline{C}}{\partial y}\right) + D_m\frac{\partial^2 \overline{C}}{\partial x^2}+S(x,y,z,t) \qquad (2)$$

This equation should be numerically integrated for determining chlorine concentration variation along longitudinal axis of the pipe. In order to simplify it, additional hypotheses are considered:

a) permanent flow regime; thus, axial component of velocity, u, is constant along the pipe
b) transversal and vertical dispersion are negligible against axial dispersion
c) molecular diffusion effect is negligible against turbulent dispersion

Eq. (2) becomes

$$\frac{\partial \overline{C}}{\partial t}+\frac{\partial}{\partial x}(\overline{u}\overline{C})=\frac{\partial}{\partial x}\left(\varepsilon_x\frac{\partial \overline{C}}{\partial x}\right)+S(x,y,z,t) \qquad (3)$$

The last right term of equation takes into account chlorine concentration decay because of consumption reactions. It is considered first-order decay term for chlorine consumption

$$\frac{\partial \overline{C}}{\partial t}+\frac{\partial}{\partial x}(\overline{u}\overline{C})=\frac{\partial}{\partial x}\left(\varepsilon_x\frac{\partial \overline{C}}{\partial x}\right)-kC \qquad (4)$$

3. Numerically integration

For numerically integration of Eq. (4) a customized program was written using FlexPDE software (version 2.21b), (Robescu et al., 2004). Distribution pipe is presented in fig. 1: AB = 1.2 m (diameter of the pipe), BD = 5846 m (distance between Water Treatment Plant of Valea lui Stan and Brezoi), DF = 20500 m (distance between Brezoi and Pausa) and FH = 19800 m (distance between Pausa and Ramnicu Valcea). Because the ratio length/diameter is too big and therefore is very difficult to compute and visualize results, the distribution pipe is divided in sections of 300 m or 350 m length. Final results for chlorine distribution in previous section are used as initial conditions for the next section.

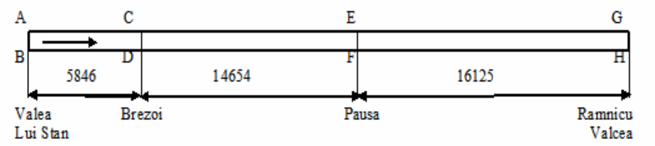

Fig.1 Distribution pipe

The boundaries conditions for a certain section (Fig.2) are Dirichlet for MP (value of residual chlorine concentration at pipe inlet) and Neumann for MN and PQ (flux of chlorine is zero).

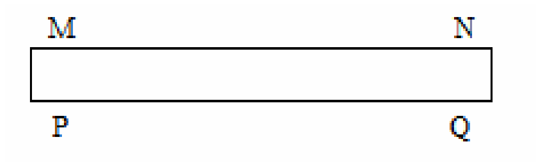

Fig.2 Boundaries conditions for a certain longitudinal part of the pipe, 300 or 350 m length

The constants in equation are considered D_m = 0.01 m^2/s and $\varepsilon_x = \varepsilon_y$ = 0.01 m^2ngth /s. For decay rate there are different values in the literature. Clark et al (2001) indicate k = 0.55 d^{-1} = $0.63\cdot10^{-5}$ s^{-1}, resulting from the measurements realized for Cherry Hill/Brushy Plains and Barsan (2005) presents a summary of decay rates found in the literature noticed that the range is 0.1 – 0.5 h^{-1} = (2.77 – 13.88) 10^{-5} s^{-1}. In this paper different values for decay rate is taking into account: k = $2\cdot10^{-5}$ s^{-1} in the first section (Drink Water Treatment Plant – Brezoi), k = $25\cdot10^{-5}$ s^{-1} in the second section (Brezoi – Pausa) and k = $5\cdot10^{-5}$ s^{-1} in the third section (Pausa – Ramnicu Valcea). These different values for rate of flow are considered because of the flowrate variations between DWTP and Ramnicu Valcea: u = 0.65 m/s for the first section, u = 0.64 m/s for the second section and u = 0.52 m/s for the third section.

These values result from the measurements, which were done between July 4th 2005 and July 22nd 2005, regarding flowrates and pressures in water mains. The main reason for rate of flow decreasing is the decreasing of flowrate due to supplying with water of Brezoi (15 L/s) and Pausa (130 L/s).

Initial chlorine concentration, at the exit from Drinking Water Treatment Plant is considered 1.14 mg/L, taking into account of a medium value from those resulting from measurements.

Figs. 3 and 4 presented results for chlorine distribution in pipe, 300 m upstream Brezoi, respectively Pausa. Theoretical results from FlexPDE are processed in Matlab R2007,for a better view of chlorine distribution for entire length of the pipe, and are presented in Fig.5.

One can observe that the residual chlorine concentrations are in the limits imposed by regulations for Brezoi and Pausa (Fig. 3), but for Ramnicu Valcea and the village close to it, Bujoreni (25.464 km), are below of these limits. Thus, an additional chlorination has to do in Pausa so that the chlorine residual in Ramnicu Valcea to be above limits imposed by regulations.

4. Experimental research

The simulation results were validated with real-experimental data. Experimental measurements had in view chlorine residual concentration in water in some important points: at the exit of Drinking Water Treatment Plant Valea lui Stan, at 5846 m from DWTP where is the bifurcation for water supply of Brezoi, at 20500 m from DWTP where is the bifurcation for water supply of Pausa and at 36615 m from DWTP where is the water supply for Ramnicu Valcea city. The measurements were done in August and September 2005. The experimental results are presented in Fig. 6, together with numerical results.

The residual chlorine concentration at the exit of water treatment plant during experiments is in the range 1 - 1.25 mg/L. This concentration decrease along the distribution pipe, but for Brezoi and Pausa is above the regulation limit. The situation is different for Ramnicu Valcea where the residual chlorine concentration is in the range 0.05 - 0.3 mg/l, below the regulation limits.

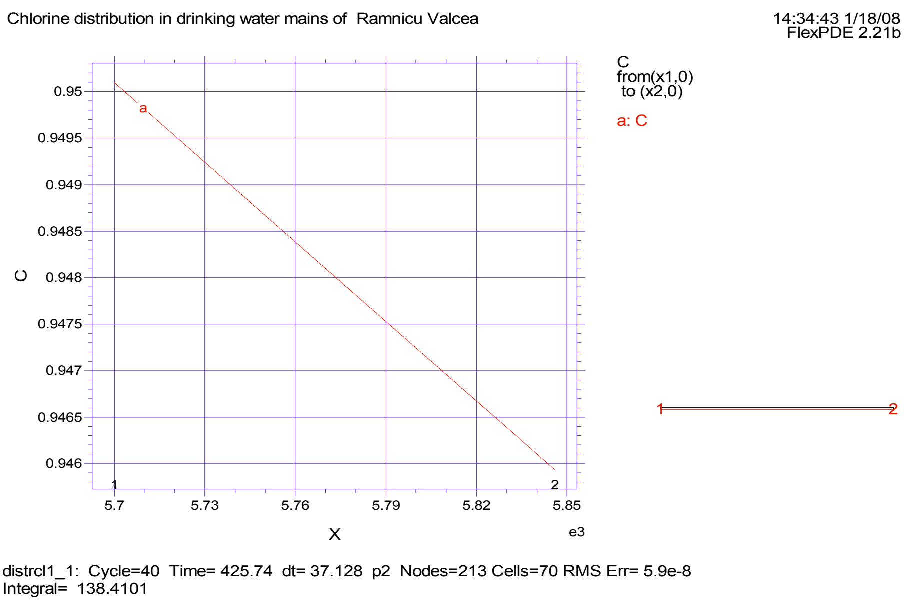

Fig.3. Chlorine distribution in pipe, 300 m upstream Brezoi

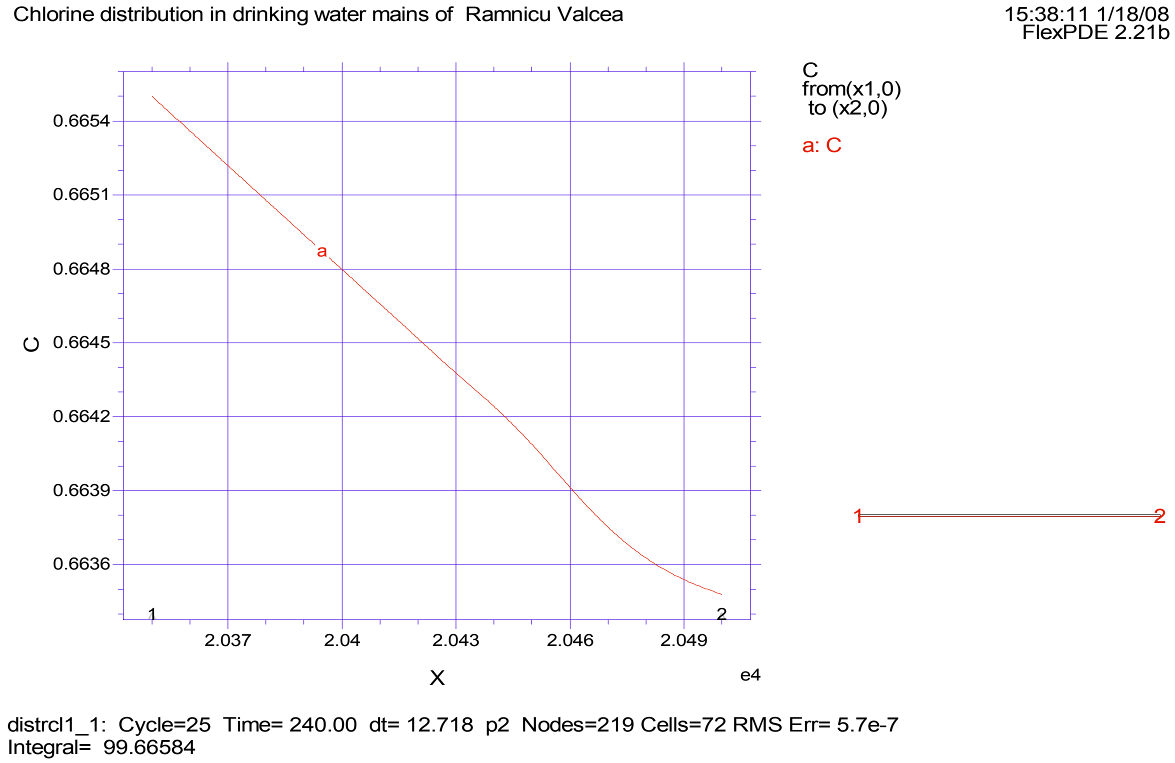

Fig.4. Chlorine distribution in pipe, 300 m upstream Pausa

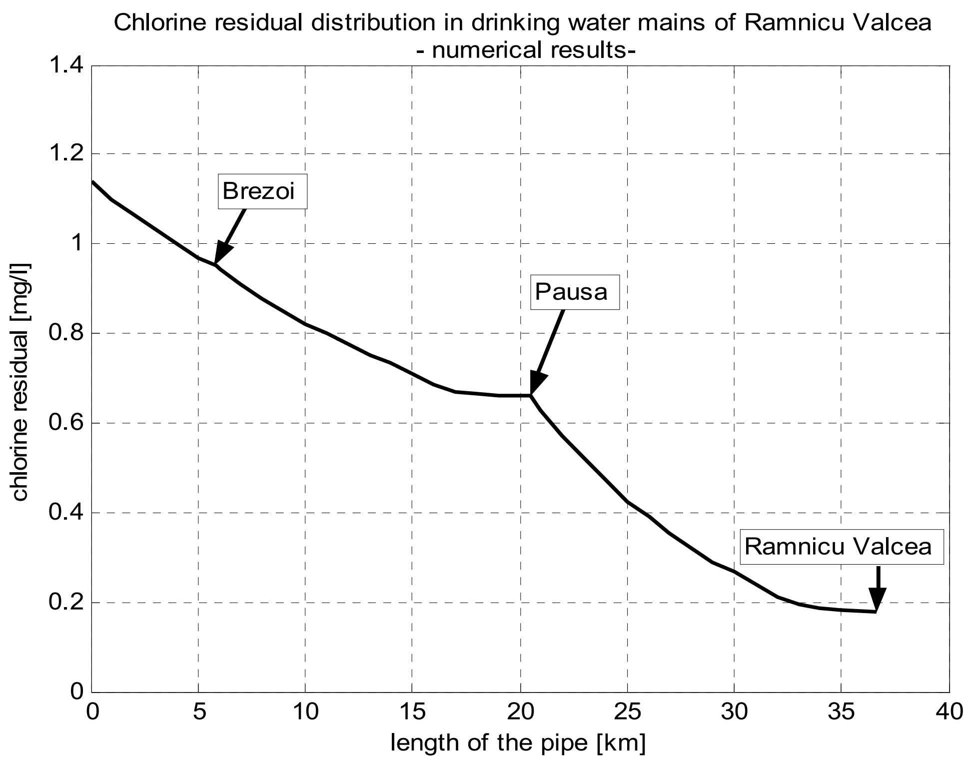

Fig. 5. Theoretical results for chlorine residual distribution in drinking water mains of Ramnicu Valcea area

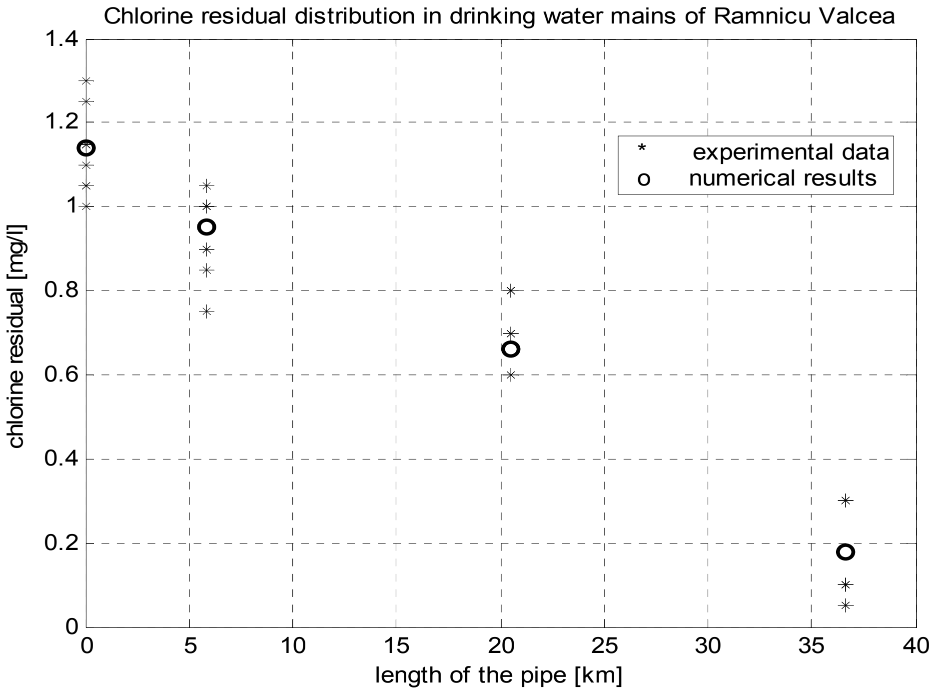

Fig. 6. Experimental and theoretical results for chlorine concentration in drinking water mains

Theoretical results are close to experimental ones. Differences may result because the mathematical model doesn't take into account different aspects related to biochemical reactions that occurs in the pipe and which are difficult to model.

5. Conclusions

Mathematical model presented in the paper predicts pretty well chlorine concentration in water mains and can be used. Initial data introduced in the program can be easily modified taking into account a given situation and the results are immediately obtained. Thus, the points where additional chlorination is needed are identified.

Abbreviations and notations

C - chlorine concentration in water [mg/L];
x,y,z - coordinates (x – distance along the pipe) [m];
t - time [s];
u, v, w - average flow velocity components [m/s];
ε_x, ε_y, ε_z - longitudinal, transversal, respectively vertical dispersion coefficients [m^2/s];
D_m diffusion constant [m^2/s] ;
k - first – order reaction rate decay coefficient [s^{-1}].

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