Modelling Flow Processes in Urban Distribution Networks

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This paper outlined the terms of residence times and their effects on the quality of drinking water distributed through urban networks of populated centers. Residence times longer than seven days for buried pipes and two days for the above ground pipes may encourage the development of biochemical ecosystems in pipes sectors of low and very low speed flow, with adverse consequences on water quality distributed to consumers. These shortcomings caused by the reduction of residual chlorine below the limit allowed by the technical arrangements can be eliminated by opening external hydrants weekly or mounting on the urban distribution networks of public fountains with continuous or intermittent activity in order to ensure hygiene and public health. The case study was conducted on the distribution network of Timişoara using EPANET program in which the hydraulic parameters (flow, diameter, speed, and head loss) are correlated with periods of stagnation of water (residence) on the sections of pipe and with residual chlorine doses allowed in each point of consumption. Distribution analysis of water flow rates through the network pipes pointed out that in almost all cases they were from 0.3 to 0.9 m/s and the residual chlorine in drinking water has been at least 0.5 mg/L.

Keywords: distribution network, flow rate, biological ecosystem, residence, residual chlorine

Distribution systems are groups of buildings and plants which provide the necessary water pressure and quality requirements demanded by consumers. Quantitative and qualitative requirements are crucial elements for the environmental comfort in inhabited areas [1, 9, 10, 16, 17].

Degradation of water quality in distribution systems is determined by the formation of sediment deposits on the pipe sections with reduced flow rates, the development of biological ecosystems due to favorable environmental conditions (organic substrate, temperature and residence times above the permissible limits), the transfer of some microelements from the structure of related materials, transport conditions, accidental contamination caused by damage or pipes fractures the, overcoming of the residence time and reducing under the permissible limits of residual chlorine in the distribution network sectors [2, 3, 4, 11].

Microbiological ecosystems which are formed in distribution networks have as the main source of development, the energy of the organic carbon existing in organic matter dissolved in distributed water.

Bacteria growing in water and on the inside walls of pipes of urban distribution networks area in the form of bacterial films, although not dangerous to humans can determine, by direct or indirect forms, quantitative changes of distributed drinking water, aspect highlighted through an unpleasant taste and even the appearance of small livings.

Pipes of a distribution network consist of the main pipes (arteries), service pipes and connections.

Flow rates of water through the pipes of urban distribution networks are determined by fluctuations of water consumption during the day or low water consumption over large periods of time. Typically, these speeds are between 0.3 m/s and 1.4 m/s. There are also situations where, on certain sections, speeds are reduced so much that even get water to stagnate for longer periods of time.

Plastic pipes (PVC, PE-HD) may influence biological stability of water through the effect of manufacturing additive used and by the transfer of biodegradable microelements in drinking water from these pipes [2, 3, 6, 7].

Reduced flow rates below the minimum allowable flow (0.3 m/s), favours the formation of sediments and various microbiological ecosystems, thereby contributing to the reduction of residual chlorine well below the permissible limits of technical standards (0.5 mg/L), with negative effects on water quality from distribution systems.

Accidental contamination of water distribution systems is determined by: pipes fractures, micro cracks and leaky joints of pipes, when the working pressure drops below atmospheric pressure, interventions that take place on the distribution networks; overcome of the stationing times of water in pipes, by favoring the development of bacterial biofilms, with decisive effects on the quality of drinking water.

The stationing / residence period of water in distribution system pipes may be considered, by analogy with underground reservoirs and water towers, of 7 days for underground pipes and of 2 days for ground pipes [12].

Exceeding the permissible residence times of water in distribution networks pipes, favours development of some specific microbiological ecosystems with detrimental effects on hygiene and health of consumers.

Table 1 shows the minimum rates established depending on allowed residence time and pipes length (junctions, connections, secondary arterials and pipes) [12].

Low flow rates, determine the chlorine consumption increase, reflected on the cost of treated water, and especially by the probability of forming of organo chlorinated compounds in section of pipes with excess of chlorine.
Theoretical considerations on the evolution of chlorine in urban distribution networks

Chlorine is a chemical disinfectant with permanent action, which brought to water distribution networks, reacts with mineral and organic compounds, as well as with the bacterial microorganisms presented on the inner surface of pipes.

Speed of response to chlorine consumption is a value temperature dependent, on the chlorine concentration, on the compounds that react with chlorine as well as on chlorine nature (HClO or Cl2O), evidenced by a relationship form as:

\[ V = \frac{dC}{dt} = K \cdot C \]  

The solution of differential equation (1) is a function of the form:

\[ C = C_0 \cdot e^{-Kt} \left( t = \frac{l}{v} \right) \]  

in which:

- \( C \) is the concentration of free chlorine at time \( t \);
- \( C_0 \) – initial concentration of chlorine into the water distribution network;
- \( K \) – Kinetic constant is a value dependent on water temperature, on the compounds that react with chlorine and the chlorine nature used in the disinfection process;
- \( t \) – reaction time;
- \( l \) – section length \( ij \);
- \( v \) – water speed in section \( ij \).

For modeling of chlorine concentration \( C \) in distribution networks pipes have been considered the following assumptions: the regime of movement of water in pipes is permanent; water flow is the piston type without axial dispersion; mixture at nodes is perfect; movement of chlorine in network respects the law of conservation of mass. Chlorine concentration at downstream (\( C_j \)) of the section, is expressed as figure 1, depending on the concentration of the upstream end (\( C_i \)), with which water crosses the section \( \cdot i-j \).

Through the by-pass from the point "i" dose of chlorine \( C_i \) is introduced and \( P_i \) is harvested for studying the reaction kinetics of chlorine consumption \( (C_i) \) with which water crosses the section "i-j".

Through the by-pass from the point "j", \( P_j \) is harvested to study the reaction kinetics of chlorine consumption \( C_j \) with which water crosses the section "i-j".

The difference in chlorine consumption (\( \Delta C \)) measured as the difference between \( P_i \) and \( P_j \) samples, represents the chlorine used on the section of pipe "i-j".

Through a proposed method it is determined the kinetic constant \( K \) which emphasizes the consumption of chlorine in the distribution network nodes section (fig. 3).

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Tube types</th>
<th>L (m)</th>
<th>V (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>t = 7 days</td>
</tr>
<tr>
<td>1</td>
<td>Tubes between/ on branches</td>
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<td>0.0198</td>
</tr>
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<td></td>
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<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>600</td>
<td>0.9920</td>
</tr>
</tbody>
</table>

Table 1

**Fig. 1.** Consumption of chlorine in section of pipes

**Fig. 2.** Chlorine concentration in junction node of sections of pipes

\[ C_j = \sum q_i \cdot C_i \sum q_o 
\]

Equation (3) was accepted by [5, 13, 1], to simulate the free chlorine concentration in distribution networks, depending on distribution time [2, 5, 13].

Kinetic constant \( K \) of equation (2) can be determined by the method proposed in [14].

In the first method, the constant \( K \) is determined on sections of the distribution network in accordance with the scheme shown in figure 3 [1, 2].

Through the by-pass from the point "i" dose of chlorine \( C_i \) is introduced and \( P_i \) is harvested for studying the reaction kinetics of chlorine consumption \( (C_i) \) with which water crosses the section "i-j".

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**Fig. 3.** Kinetic constant calculation scheme K
Simulation algorithm of chlorine evolution through distribution networks, for stationary currents or with very low speeds, in connections or branched pipes, shows a substantial reduction of residual chlorine down to zero [12].

The value of flow rates in the pipes networks conditions the stationary time of water in pipes, and distribution networks.

Table 1 shows standing times of water-course in the junctions, connections, secondary arterials and pipes, for the case of the underground and ground pipes [10], [12].

Hydraulic modelling of the distribution networks. Case study - Timisoara

Hydraulic modelling of water supply network in Timisoara city with 350,000 inhabitants, was made with EPANET program [18]. The program allows the determination of flow and rates for each pipe, the water pressure in each node, the water level in reservoirs, water residence time in the network and the residual chlorine concentration in different parts of the distribution network [8], [15].

The distribution network consisted of 11,294 sections of pipe with diameters between 50 mm and 1,600 mm having length of 606,423 m, including 15,764 m for branches respectively, a total of 10,113 nodes of which 2400 branches.

Timisoara city distribution network is supplied from three sources (Plant No.1, Plants No.2 and Plant No.5) each having specific operating regimes of water consumption on the heath of the village.

Plant no. 1 operates in three different pumping schemes: pump \( P_1 \), with operating program between the hours 0-6 in throttled regime \( (Q = 976-1044 \text{ mc/h and } H_p = 19 \text{ m CA}) \); pump \( P_2 \) with operating program between the hours 0-6 and 22-24 in throttled regime \( (Q = 907-1087 \text{ mc/h and } H_p = 25 \text{ m CA}) \), pump \( P_3 \), the hours 10-22 in throttled regime \( (Q = 2340-2592 \text{ mc/h and } H_p = 28 \text{ m CA}) \).

For plant no. 2 water distribution is achieved by using a single pump equipped with variable speed, with two pressure regimes: night regime \( (Q = 2250-2646 \text{ mc/h and } H_p = 19 \text{ m CA}) \), between hours 0-6 and 22-24; day regime \( (Q = 2948-4734 \text{ mc/h and } H_p = 28 \text{ m CA}) \) between hours 6-22 [11].

Plant no. 5 operates with a single pump, in throttled regime \( (Q = 660 \text{ mc/h and } H_p = 23 \text{ m CA}) \) between hours 20-22.

For a more accurate assessment of system functioning were taken into account the losses of water through the use of two types of simulation:

Option 1. Considering the concentration of losses in nodes in the vicinity of water plants, to be proportional to flow pumped by each pump in hand, allowed the evaluation of the system as being without network lossless, issues that gave information on ideal operating conditions of the system. In this case we have obtained the most adverse operating conditions, with the lowest rates possible on pipes, which led to the maximum possible detention time, having as a consequence, the deterioration of the quality of drinking water.

Option 2. Considers the losser distribution proportional with flows consumed by each user, resulting in a situation where the pump flow in the network is considered as consumed flow at the points of consumption or on the network.

By comparing the two versions simultaneously can be established for each node, pipe or consumption area, the afferent losses.

This loss must be linked, it was compared with the real ones obtained by direct measurements.

Water quality modeling were introduced in each reservoir chlorine doses identical to those applied by each plant individually, the program allowing the simulation chlorine consumption on the network in a period of time fixed in advance. The operating time of modeling was chosen as 68 h considered to be representative. [10, 11, 18].

To simulate the evolution of water quality in the distribution network in Timisoara were chosen following variants: chlorine dosage only at plants no.1 and no.5, the variant that allows graphical or tabular view of the influence of underground water on the water from network, chlorine dosage only at plant no. 2, variant which allowed graphic or tabular view of the influence of surface water on water from network; chlorine dosage in both sources of water.

It is known that drinking water distribution network serves as a reactor, continuously fed by the intimate side of the water and water-material interface, the many physical and chemical reactions (corrosion, chlorine consumption by the reaction of chlorine with natural organic matter from the water mass, leading to secondary products of the processes of disinfection, flocculation, sedimentation of particles, etc.) and biological reactions with biomass proliferation. Real phenomena in the network are generally poorly understood and difficult to manage. So, researchers in the field are constantly concerned about the quantification and clarification of reactions that occur in the water mass and the phenomenon of biofilm development, representing major research targets in multidisciplinary research in many research centers in the country and abroad.

To simulate the evolution of water quality in the network, data entered in the program are those recommended by the literature in terms of consumption of chlorine in the network. Thus, it was introduced in the program Overall coefficient of mass reaction or Chlorine Reduction “in block” (Kb), representing the reduction, due to the action of chlorine in the water mass and Global reaction coefficient to the wall or Reducing “the wall” (Kw ) as being caused by the action of biofilms formed on the pipes walls. During distribution of water through a piping system, residual chlorine used to protect water quality must be maintained, to ensure that water distributed via the system does not degrade (connections, pipes without continuity, prolonged storage or in other circumstances unknown) that may cause self pollution of drinking water.

The analysis of distribution rates of water in network revealed that they mostly fall between 0.3 and 0.9 m/s.

There were however found, leakage rates below the permissible limit as follows: 2089 pipe sections with speeds of 0.2 to 0.1 m/s; 3601 pipe sections with speeds from 0.1 to 0.05 m/s, the 3598 pipe sections with speeds from 0.05 to 0.01 m/s, 960 pipe sections with speeds of 0.01 to 0.001 m/s; 356 pipe sections with speeds below 0.001 m/s. Conditions of service pressures were situated between 8 and 22.5 mCA.

Surface water, produced and pumped by the plant no. 2 in the distribution network has as influence limit the perimeter from the north of the city, the south meets tapes of influence 1 and 2.

Tape 1 shows that surface water is mixed with underground water (free chlorine is between 0.6 and 0.3 mg/L) having the approximate limit the northern perimeter of the city.

Tape 2 shows that surface water is mixed with underground water (free chlorine is between 0.3 and 0.01 mg/L) specific in the area of southern part of Timisoara.
Underground water produced and pumped by the plant no. 1 in distribution network having as limit the perimeter of the city, located in the South, and in North meet the tapes of influence 3 and 4.

Tape 3 shows that water from network is provided from underground water source (free chlorine is between 0.5 and 0.3 mg/L) with the approximate limits of the city southern perimeter.

Tape 4 shows the effect of mixing underground water with surface water (free chlorine is between 0.3 and 0.01 m/L) similar to tape 2.

Plant no. 5, having a program running very low, about 2 h/day (hours 20-22), makes its influence to be felt in the small area, in the city western perimeter. In this area the maximum residual chlorine concentration is 0.4 mg/L and minimum values approaching 0 to 0.05 mg/L.

Distribution of residual chlorine concentration, speeds and pressures size, within the distribution system of Timisoara city, after 68 h of function were simulated with EPANET program.

Table 2 shows the residual chlorine concentration for the five characteristic areas, highlighting the residual chlorine, compared with the residence time of water in the distribution pipes of the hearth of Timisoara city.

Analyzing the distribution of water rates in the distribution network, it is noted that in almost all cases these are between 0.3-0.9 m/s. It was also noted that speeds decrease on some sections well below the permissible limits as follows: in section 2089 rate is 0.2 - 0.1 m/s; on the section 3061 rate is between 0.1 - 0.05 m/s; on the section 3598 rate is between 0.05 - 0.01 m/s; on the section 1128 rate is between 0.01 m/s; on the section 960 i rate is between 0.01- 0.001 m/s; on the section 356 rate is 0.2 - 0.1 m/s; on the section 771 rate is below 0.001 m/s. Regime of work in the city, located in the South, and in North meet the admitted limits permitted by the technical standards, performing of new connections and revision of the existing ones.

Technical maintenance of distribution networks requires providing the following operations: inspection and preventive overhaul, planned routine repairs and cleaning and washing operations, preparation for operation in winter.

Conclusions

This paper analyzed the effects of low and very low flow rates of residual chlorine in urban water distribution networks.

The negative effects of low water rates and low pressures were awarded in the case study conducted with the program EPANET modeling water distribution system of Timisoara, Romania. The case study points out that, portions of decreasing the flow rate and water stagnation for more than seven days, residual chlorine falls below the limits imposed by Romanian standards (0.5 m/L). These conclusions lead to the application of appropriate technical measures to prevent and stop the phenomena that may endanger water quality. For a safe disinfection, residual chlorine in drinking water must be at least 0.3 mg/L. Chlorine process is easy to apply, but must be carefully controlled, because if the dose increases above the limit of 0.5 mg/L organo chlorinated may occur with negative effects on the health of consumers.

Stagnation / stationing longer favours the development of biochemical processes which manifest themselves on the health of consumers. Stagnation / stationing longer favours the development of biochemical processes which manifest themselves through a degradation of drinking water quality due to the reduction of residual chlorine concentration.

Starting from the consideration that the sanitary rules do not allow stagnation of drinking water in underground pipes and reservoirs more than seven days, we could establish a minimum rate in the water pipes, so that free residual chlorine at the end of the network to be at least 0.25 mg/L [3, 4, 7, 16].

Minimum flow rate calculated from the condition that the pipe section between two consecutive connections (L = 12-15 m), should not to exceed stationing time by more than 7 days and the flow rate assured of 0.025 m/s (2.16 m/day) is equivalent to the apparent flow rate of underground water through a small grain sand layer.
Existence in the distribution pipes of some water currents with speeds higher than 0.025 mm/s, ensures minimum residual chlorine concentration, necessary for water quality safety of the consumers [3, 6, 16].

References
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