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Hydrodynamic Modeling of a Surface Water Treatment Pilot Plant

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***Abstract*—**A mathematical model for the hydrodynamics of a surface water treatment pilot plant was developed and validated by the determination of the residence time distribution (RTD) for the main equipments of the unit. The well known models of ideal/real mixing, ideal displacement (plug flow) and (one-dimensional axial) dispersion model were combined in order to identify the structure that gives the best fitting of the experimental data for each equipment of the pilot plant. RTD experimental results have shown that pilot plant hydrodynamics can be quite well approximated by a combination of simple mathematical models, structure which is suitable for engineering applications. Validated hydrodynamic models will be further used in the evaluation and selection of the most suitable coagulation-flocculation reagents, optimum operating conditions (injection point, reaction times, etc.), in order to improve the quality of the drinking water.

***Keywords*—**drinking water, hydrodynamic modeling, pilot plant, residence time distribution, surface water.

I. INTRODUCTION

SURFACE water is used all over the world as a resource for drinking water. Depending on the quality of the source, there are different methods of purifying the raw water. Such methods consist of physical processes like filtration and sedimentation, biological processes like slow sand filters or activated sludge, chemical processes such as coagulation, flocculation, chlorination, etc.

In drinking water treatment, product water quality, operational costs, environmental impact (water spills in treatment and distribution, use of chemical products, production of sludge and waste material) are some of the criteria applied for the evaluation of the process effectiveness. By using modeling in combination with on-line monitoring and real-time process control, the treatment effectiveness can be improved, the optimization and control of process parameters resulting in a better and more stable water quality, better use of the installed infrastructure, lower treatment costs and reduction of environmental emissions [1].

An optimal operation of a water treatment plant requires, as first step, the understanding of the flow behavior along the treatment facility. An effective method to diagnose flow characteristics within a wide range of flow systems is the residence time distribution (RTD). In such study, a known tracer distribution (impulse, step, step-counter-step signals, etc.) is introduced into the inlet of the system and the tracer concentration at the system outlet is registered and analyzed in order to identify flow models for each equipment [2]. RTD analysis can reveal flow distribution characteristics such as transient times, short-circuiting, re-circulation zones, dead zones etc.

In this paper, an experimental procedure was used in order to determine the residence time distribution (RTD) of water flow through a pilot plant treatment chain, from the entry point of the raw water to the treated water outlet. The equipment models have been validated by experiments and the simulation results agreed well with experimental data.

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II. EXPERIMENTAL

A. Pilot Plant Description

In Timişoara (Romania) two thirds of the drinking water comes from surface sources (Bega River) and the rest of the water is ensured by ground sources. The regional operating company of the public water services is Aquatim S.A [3].

In order to be able to set-up further improvements of the treatment technologies in place (coagulation-flocculation reagents, optimum operating conditions, etc.), a pilot plant was built in the years '80. During 2000-2002, the plant was modernized in order to be able to operate in a wide range of operating parameters and to fully comply with actual treatment technologies. In fact, the unit reproduces the processes used to purify raw water from the Bega River at 1:34 scale, unit average treating capacity being around 145 (m^3/h).The process flow diagram of the pilot plant is shown in fig. 1: water coming in from the Bega River is firstly screened, this process being followed by prechlorination. Coagulation reagents are added in the pipe that leads into the mixing chamber and the mix of water and coagulants goes into the reaction chamber where the coagulation-flocculation process is taking place. When the water flows into the longitudinal settling tank, the flocks settle out from the water and, finally, are removed. Next, the water is passed through filters which remove particles too small to settle out in the settling tank. In the final step, chlorine is added and then the water is directly discharged into the sewerage network.The residence time distribution (RTD) of the liquid was measured using the pulse (step-counter-step) or step tracer injection methods, dynamic behavior of the pilot plant being monitored for different raw water flow rates.

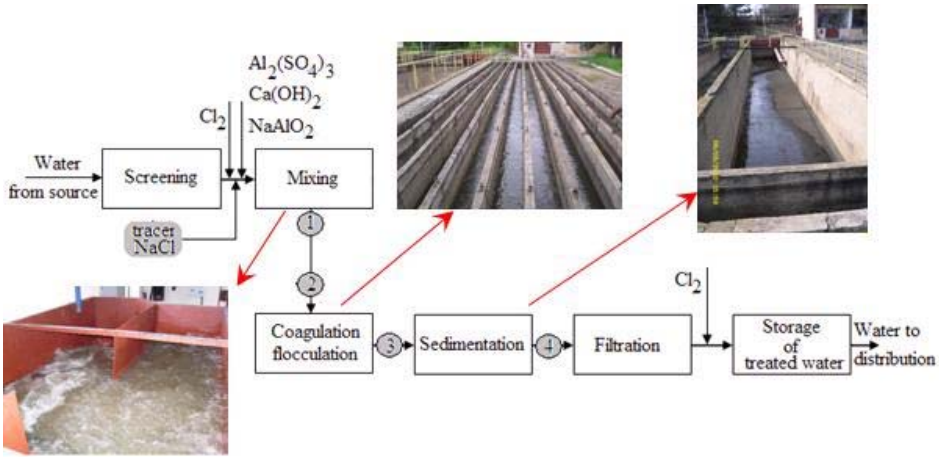

Fig. 1 Process flow diagram of water treatment pilot plant

As a chemical tracer, a brine solution (NaCl) was used, tracer concentration being measured by water conductivity. The solution was injected into the feed stream entering the mixing chamber, in the same point where coagulation reagents are usually added. The tracer response was monitored as a function of time, by the measurement of the electrical conductivity in the following points: 1 - output of the mixing chamber; 2 – input to the reaction chamber; 3 – output of the reaction chamber: 4 – output of the settling tank. All experiments were performed at atmospheric pressure and environmental temperature.

For attaining high level of reliability, each experiment has been repeated three times and average results were considered.

B. Hydrodynamic Models Description

Flow behavior modeling based on the measurement and interpretation of the residence time distributions (RTD) experiments are important aspects of chemical reaction engineering [4]. The residence time distribution of a chemical unit, like a chemical reactor, is a probability distribution function that describes the amount of time a fluid element has spent inside the equipment. RTD applications range from the characterization of flowing systems, to the evaluation of flow patterns for developing system models. The flow behavior through a drinking water treatment plant is one of the most important parameters in terms of the unit's effectiveness [5].

In the development of the pilot plant dynamic model, the natural shape of the equipments as well as the preliminary results of RTD experiments have been taken into account for the selection of models structure for each equipment. Finally, two hydrodynamic models or a combination of these models have been used for the characterization of all equipments:

- the dispersion model (plug flow with axial dispersion) which has been used for the reaction chamber and, as a particular case, for the pipe linking mixing chamber to reaction chamber (practically, close to the plug flow behavior);
- Cholette-Cloutier (CC) model. This real mixing model was used for the mixing chamber (two CC in series) and for the settling tank (five CC in series).

Dispersion model (one-dimensional plug flow with axial dispersion model) is one of the models used to describe non-ideal flow in tubular like equipments (reactors, columns, etc.). For this model, the equation describing the evolution of the concentration of ''*A''* species along *z* axis and over time has the form:

$$(H/w)\cdot(\partial C_A/\partial t)=(1/Pe)\cdot\left(\partial^2 C_A/\partial z^2\right)-(\partial C_A/\partial z)+(H/w)\cdot r_A \quad (1)$$

Where: t is the time (s), C_A is the concentration of ''*A''* species in (kmol/m^3), H is the height or total length of the equipment in (m), w is the fluid velocity ($w = F_v / S$) in (m/s), S is the cross-sectional area of the unit in (m^2), F_v is the volumetric flow rate in (m^3/s), r_A is the production or consumption of ''*A''* species per unit of volume and time in (kmol/m^3*s), Pe is the Peclet ratio, dimensionless and z is the dimensionless axial coordinate ($z= h/H$), where h is the axial coordinate in (m).

In (1), Peclet ratio (Peclet number), a dimensionless ratio, is a measure of axial mixing (ratio of transported stream by convection and stream caused by axial dispersion):

$$Pe = (w \cdot L)/D_{AX} \quad (2)$$

Where: D_{AX} is the axial dispersion coefficient in (m^2/s) and L is the feature size ($L=H$) in (m).

In the case of reaction chamber, the boundary conditions associated with (1) are the well known Danckwerts boundary conditions for the closed to dispersion case (assuming plug flow behavior for the pipe entering the reaction chamber):

- inlet condition:

$$C_{Ain} = C_A(0^+,t) - [(1/Pe)\cdot(\partial C_A/\partial z)]_{z=0^+} \quad (3)$$

- outlet condition (continuity of composition):

$$(\partial c_A/\partial z)_{z=1} = 0 \quad (4)$$

In (3), C_{Ain} is the concentration of ''*A''* (kmol/m^3) at the reactor inlet.

If ''*A''* is a chemical tracer, the chemical reaction doesn't take place and therefore, in (1), the last term on the right side is zero:

$$(H/w)\cdot(\partial C_A(t)/\partial t)=(1/Pe)\cdot(\partial^2 C_A(t)/\partial z^2)-(\partial C_A(t)/\partial z) \quad (5)$$

The partial differential equation (5) is solved by a finite difference algorithm (partial derivatives are written as quotients of differences) with explicit integration over time. At each of the two boundaries, a hypothetical out-of-area cell has been added in order to fulfill the boundary conditions in the discrete system [6].

''*Cholette-Cloutier'' model* (fig. 2): in the modeling of real mixing equipment, we can take into account ''bypass'' routes, respectively areas where the fluid doesn't penetrate (the so-called dead zones) or areas where the fluid is stationary. Cholette-Cloutier model takes into account a stationary zone, an exchange of substance with the mainstream on the basis of the difference of the concentrations taking, however, place.

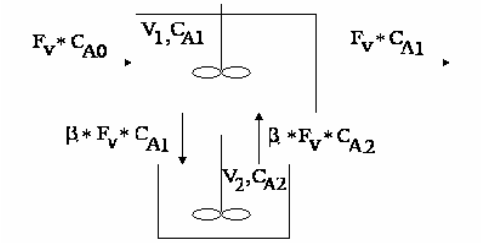

Fig. 2 Chollette-Cloutier model: real mixing model containing steady areas

Cholette-Cloutier model has two parameters:

- fraction ''β'', accounting for the stream to and from the steady area;
- fraction ''φ'', accounting for the fraction of the stationary volume compared with the system volume.

Both volumes V_1 and V_2 from fig. 2 are treated as well mixed reactors, the stream which is changed between them being a fraction ''β'' of the supply flow. The equations describing Cholette-Cloutier model are (6) to (8) (in case of a tracer, $r_A=0$):

$$V_1\cdot(dC_{A1}/dt)=F_V\cdot(C_{A0}-C_{A1})+\beta\cdot F_V\cdot(C_{A2}-C_{A1})+r_{A1}\cdot V_1 \quad (6)$$

$$V_2\cdot(dC_{A2}/dt)=\beta\cdot F_V\cdot(C_{A2}-C_{A1})+r_{A,2}\cdot V_2 \quad (7)$$

$$V_1=(1-\varphi)\cdot V; \qquad V_2=\varphi\cdot V \quad (8)$$

Where: V, V_1 and V_2, in (m^3), are the volume of the unit and the volumes of each zone of CC model, respectively.

III. Results and Discussion

A. Experimental Set-Up and Procedure

The general arrangement of the pilot plant is shown in fig. 1. Preliminary tests have been done in order to evaluate the modifications of equipments parameters (like liquid level) versus raw water flow rate passing through the pilot plant in the limits of 70 (m^3/h) to 180 (m^3/h). Tracer dosing is realized by using a peristaltic pump at constant flow rate of 0.04 (m^3/h). Two types of experiments were carried out:

- pulse signal (in fact, step-counter step signal): the tracer has been injected, usually for 40 seconds, in the same point were the coagulation reagents are injected;
- step signal: in this case, tracer was injected as long as to obtain a new steady state in the settling tank (up to 10 hours).

The first type of experiments has been valorized in the evaluation of mixing chamber hydrodynamic behavior, step signal being used for reaction chamber and settling tank hydrodynamic parameters estimation. It is to be noted that, given the geometric dimensions of the equipments (average liquid volumes: mixing chamber 1.6 m^3, reaction chamber 55 m^3, settling tank 290 m^3), in the case of pulse signal, the tracer concentration versus time profile in the last two equipments is very flat, making the evaluation of model parameters very difficult. However, special experiments have been done by tracer injection at the reaction chamber inlet, these experiments allowing a better estimation of number CC models in series in the case of settling tank. A problem for all long time experiments was the modification in time of the conductivity of raw water.The hydrodynamic parameters of all equipments have been estimated by minimizing the sum of square deviations of models predicted values towards the experimental values. Finally, optimal values of models parameters obtained for different flow rates were expressed, usually in linear form, in function of raw water flow rate.

B. Mixing Chamber

The mixing chamber is divided in two compartments (fig. 1): quieting chamber and the baffles chamber. As mentioned before, the hydrodynamic model has been built up by using Cholette-Cloutier models in series (one CC for each compartment). Two typical RTD experiments together with the optimal values resulted from least square method are shown in fig. 3: for simplicity, model parameters, the fractions ''β'' and ''φ'' have been taken as identical in both compartments of the mixing chamber.

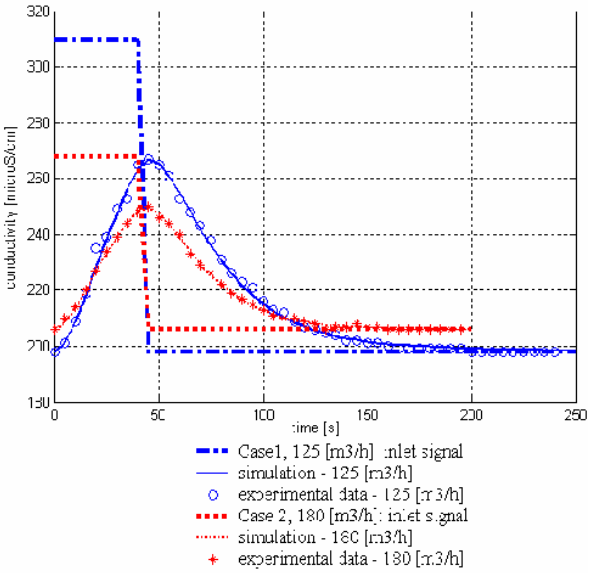

Fig. 3 Typical experimental results for the mixing chamber: Optimal values of the model parameters:

Case 1, flow rate 125 (m^3/h): φ=0.12; β=0.049
Case 2, flow rate 180 (m^3/h): φ=0.075; β=0.0081

Because of its long length (44 m), the pipe between mixing and reaction chamber has been modeled separately as (one dimensional axial) dispersion model. Results for two flow rates are shown in fig. 4. Output signal of the mixing chamber, as resulted by using the optimal values of mixing chamber model parameters (expressed as functions of raw water flow rate), are also shown in fig. 4.

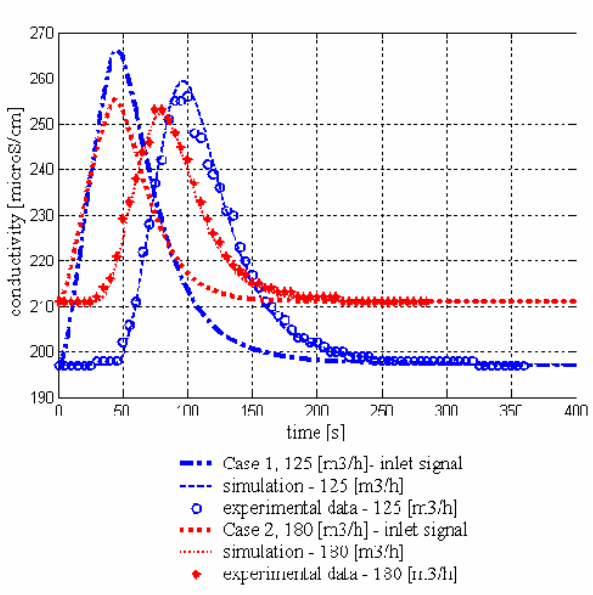

Fig. 4 RTD results for the input to reaction chamber (pipe outlet). Optimal values of the Peclet number:
Case 1, 125 (m^3/h): *Pe*=9200 and for Case 2, 180 (m^3/h): *Pe*=9000

Finally, for the pipe behavior, taking into account all the results for the Peclet number, an average value of around 8700 has been used in the generation of the inlet signal for the reaction chamber. At such high values, in the design case, plug flow behavior can be assumed.

C. Reaction Chamber and Settling Tank

The hydrodynamic modeling of the reaction chamber was done again by an axial dispersion model while the settling tank was modeled by CC models in series. A similar approach for the sedimentation process, but using a different combination of simple models, has been done by Lopez et al. [7]. A typical RTD experiment together with the optimal values of models parameters is shown in fig. 5.

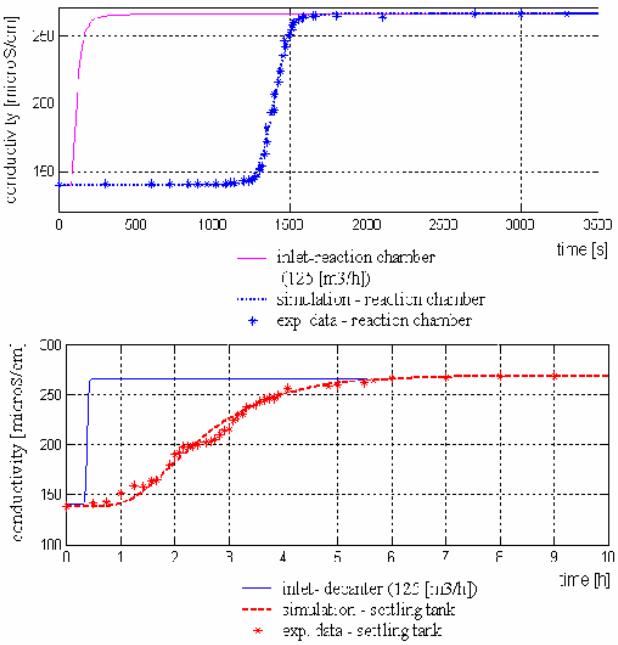

Fig. 5 RTD results for the reaction chamber and settling tank at 125 (m^3/h). Optimal values of models parameters:
- Reaction chamber: *Pe*=780;
- Settling tank: 5 CC models in series, φ=0.2; β=0.15

Regarding models parameters, in the case of reaction chamber, Peclet number optimal values resulted from RTD experiments were again expressed (in linear form) as function of flow rate passing the unit. High values of the Peclet number obtained in the investigated flow rate range have shown that the behavior of reaction chamber is close to plug flow. For the settling tank, after reviewing all experimental data, in the investigated flow rate range, constant values for model parameters have been assumed as best option in the modeling.

As we mentioned above, for both equipments, for each RTD experiment, the generation of the input signals has been done by using the optimal values of the model parameters (expressed in function of raw water flow rate) obtained for the unit placed in front of the investigated unit (pipe for reaction chamber, reaction chamber for the settling tank).

D. Models Validation

In order to check models predictions versus plant data, a new set of experiments has been carried out for the evaluation of the models accuracy. Fig. 6 and 7 are showing models predictions versus experimental data for all four equipments taken into consideration for a water flow rate of around 145 (m^3/h).

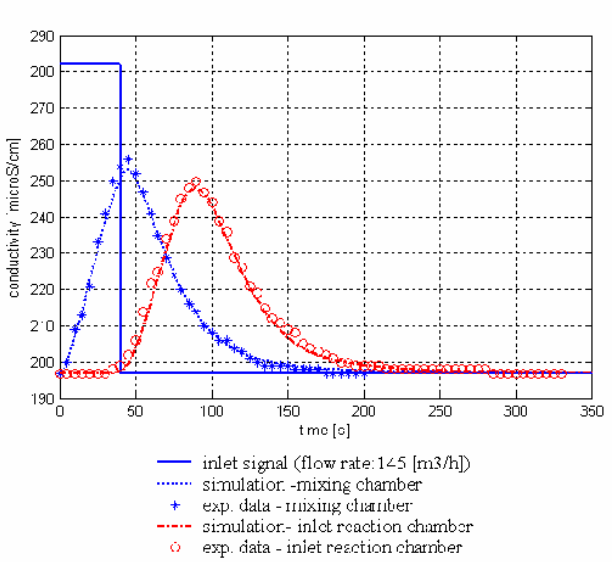

Fig. 6 Mixing chamber and pipe to reaction chamber: experimental results versus models predictions at 145 (m^3/h)

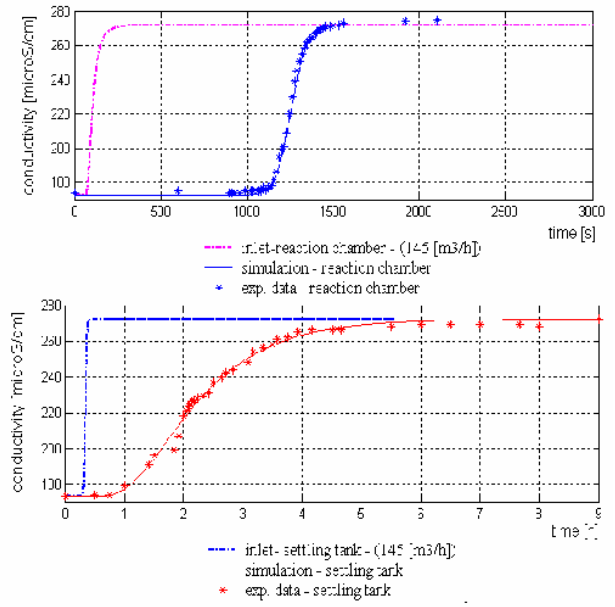

Fig. 7 Reaction chamber and settling tank: experimental results versus validated models predictions at 145 (m^3/h)

As revealed by the fig. 6 and 7, models predictions of the pilot plant behavior is quite accurate. Experiments made outside the model parameters estimation initial domain: 120(m^3/h)–180(m^3/h) have shown also a good agreement between models predictions and RTD results.

IV. Conclusion

Residence time distribution experiments have been carried out for the development of the hydrodynamic models of a surface water treatment pilot plant equipments. The well known models of real mixing (Cholette-Cloutier) and axial dispersion were combined in order to identify models structure that gives the best fitting of the experimental data for each unit. RTD experimental results have shown that pilot plant hydrodynamics can be quite well approximated by a combination of simple mathematical models, such structure being suitable for engineering applications. Validated hydrodynamic models will be further used in the evaluation and selection of the most suitable coagulation-flocculation reagents, optimum operating conditions (injection point, reaction times , etc.), in order to improve process economics and drinking water quality.

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