Literature Review of Feedback Control for Drinking Water Purification

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Abstract

The disinfection of raw water plays an important role in environmental engineering. In this document we overview several feedback controllers proposed by different authors to purify the water contained in water distribution systems. Several techniques to purify the water and the sensors needed as part of the whole system are presented to provide an overview of the components and processes encountered in water treatment plants.

1 Literature Review

Purification of drinking water is a very important problem in environmental engineering. Purification of drinking water is typically achieved via adding a disinfectant. Chlorine is the most common disinfectant used in drinking water purification systems because it is inexpensive and destroys a large number of pathogens. The purification of drinking water involves several stages of treatment of the raw water for the removal of suspended solids, color, and bacteria before entering the distribution network. Clarification, disinfection, pH adjustment, filtration and taste and odor removal are part of the stages of treatment. The quality of drinking water is altered by the use of nitrogen-based fertilizers commonly used in agriculture or products of domestic use. Denitrification of drinking water is needed in this case to reduce the concentrations of nitrites and nitrates present in the raw water. However, in this document we emphasize the controller's role in the chlorination process since this is the most common method used for the purification of drinking water.

Stricter drinking water quality standards demand improvement of control systems for water treatment. The regulation of chlorination in drinking water systems is based on open-loop, manual control; however, several closed-loop controllers have been proposed. The application of feedback control in drinking water purification systems has been delayed due to the lack of sensors for measuring chlorine concentration in a reliable fashion. Although chlorine concentration sensors have been used in large drinking water systems, these sensors are typically used for monitoring purposes.

In this document, we review some techniques used for purifying raw water, and the control strategies proposed so far for trying to supply drinking water in a reliable manner. This control problem is very complex due to the variable quality of raw water, the seasonal changes that temperature and pH have on disinfection capabilities, the transport delays associated with the transport time of water from one point to another, and the multiple-input, multiple-output nature of the problem (i.e., multiple number of chlorine sources and multiple points of water consumption through several different pipe paths). There are two approaches that are described in this document: The first one covers the application of feedback control for the disinfection of clarified water in a single point of a drinking water plant. The second approach deals with distributed control for the purification of raw water in multiple locations of a drinking water distribution system.

The efficient operation of a water plant depends upon the success of the clarification stage [1]. In [1] a feedback control scheme is implemented using color and turbidity sensors and variable speed pumps. The sensors are used to determine the current characteristics (i.e., color and turbidity) of the raw water and the pumps are used to dose a coagulant into the raw water, which achieves clarification of the water. A third measurement, a conductivity sensor, has been considered in [1] to suppress errors obtained from the color sensor (i.e., color sensor measurements are considerable higher than laboratory results) when the turbidity of the water is high. An on-line neural network is being evaluated to estimate the color of the water based on color, turbidity and conductivity sensor measurements. An instrumentation/actuation scheme is presented in [2] for monitoring and controlling water treatment. In [2] the authors emphasize the benefits of the implementation of a distributed control system over a centralized scheme. In [3] the authors describe the use of an optimum dosing rate of coagulant for a water purification system. Raw water contains a large amount of impurities that are removed by filtering, sedimentation and flocculating, and centrifugal separation. The impurities are removed by a coagulant dose, which must change according to the changes in the quality of the raw water inflow in water purification system. The coagulant dosing rate is determined based on jar-test results or a reference table. However, the time it takes to examine the sample at laboratories, the lack of availability of laboratory staff, and the reference tables just based on temperatures and turbidity of the raw water are all factors that result in considerable delays in taking appropriate correction actions by adjusting the coagulant dose to the raw water. In [3] a fuzzy model is used to determine the amount of coagulant dosing rate needed in normal conditions, whereas a neural network model is used for the same purpose, but for very large changes in the raw water quality. Five input variables (i.e., turbidity, temperature, alkalinity, pH and ΔpH of the raw water) are used for the models. A threshold in the turbidity of the raw water is used to determine the current condition of the raw water. If the current turbidity value is below that threshold, then the condition of the raw water is considered normal and the fuzzy model computes the coagulant dosing rate. If the turbidity value is above the threshold, then the neural network model sets the coagulant dosing rate. The coagulant dosing rate computed by the models is the set-point of a PID controller used in the water purification system.

The effluent turbidity control of a deep bed rapid sand filter run by a direct filtration method is described in [4]. The operation of this filter depends on the physical and chemical properties of raw water, flow rate, bed depth, grain size of the media, and the type of coagulant used. Direct filtration differs from conventional filtration by eliminating the flocculation and sedimentation stages, resulting in cost savings and plant size reduction. In [4] a combination of a fuzzy controller and an integral one is used to regulate the alum dose pumped into the filter. An expert system for a water purification system that performs supervisory control of water quantity, and automatic filter basin control, is developed in [5]. The sand bed filters can be in four possible states: waiting for filtering, filtering, waiting for scouring, and scouring. The filter basins in a water purification systems are usually divided into groups connected in parallel. On-line data are gathered from distributed control systems throughout the water purification system. In [5] filter basin control is based on control of filter scouring basin and control of the number of filter basins in operation. Filter scouring occurs when the water flow falls below a preset minimum value. The number of filters in operation is controlled to match the plant processing flow to total filtering flow. A different approach is presented in [6] where the proposed chlorination control system for water treatment is a double cascade PI loop for controlling the hypochlorite dosed in the system by means of free chlorine measurements taken at two sample points of the disinfection system.

Denitrification of drinking water has been proposed in several studies. In [7] SISO and MIMO robust variable structure controls for fixed bed bioreactors are developed. A SISO variable structure control is used to control the total concentration of nitrates and nitrites by changing either the inlet flow rate or the ethanol concentration. A MIMO variable structure control is needed to optimally regulate the ethanol concentration of drinking water. In [8] drinkable water is also treated by a fixed bed bioreactor. A multi-input/multi-output sliding control law of a distributed parameter biofilter is designed to improve the quality of the water in order to control the harmful component concentration at the outlet of the bioreactor and to optimize the addition of carbon source.

Modeling and control design have been addressed for drinking water distribution systems in several papers. Water supplies (i.e., tanks or reservoirs) in water distribution systems are typically treated to kill bacteria. The problem with this treatment is that chlorine decays exponentially in water, and the transport delay of water through pipes causes the chlorinated water to stay in the system for some time. The control challenge for this particular case is to design a strategy that doses the chlorine at treatment stations in order to keep the chlorine residual amount in the distribution system within pre-established concentration values. In [9] an input-output model is presented to relate chlorine supply concentrations at treatment stations to chlorine concentrations at specific nodes within a drinkable water distribution system. The model in [9] is decomposed into two parts: The first one is an algorithm that determines the time the water spends in a particular pipe and finds the node in which the water entered the pipe. The second part is an algorithm that finds when and where the chlorine was introduced into the system. In [10] the authors use the same model developed in [9] but measured data gathered from real systems are used to calibrate the model off-line. The authors claim that closed-loop controllers are not implemented yet in water distribution systems because control algorithms are not available and chlorine sensors were not accepted by that time [10]. An adaptive controller is considered for water distribution systems with periodic variation of parameter uncertainty due to varying consumer demands [11]. An approximation of the input-output model is considered in [11] as a periodic time-varying, discrete time linear model with uncertain or unknown coefficients. A design approach based on parameter estimation and adaptive control techniques is introduced in [12]. Several guidelines for selection of actuators and sensor locations are provided in this paper.

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