Osmaniye Korkut Ata University

Feedback control over the chlorine disinfection process at a wastewater treatment plant using a Smith Predictor, a Method of Characteristics and Odometric Transformation

Feridun DEMIR[a,b,*], Spyros A. SVORONOS[b]

[a]*Department of Chemical Engineering, Osmaniye Korkut Ata University, Osmaniye 80000, Turkey*

[b]*Department of Chemical Engineering, University of Florida, Gainesville, Florida 32611-6005, USA*

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Outline

Process description

- The Kanapaha Water Reclamation Facility (KWRF)
- Chlorination reactions

Process control objectives

Process control challenges

- Large and variable dead-time
- Disturbances
- Dynamic model for a disinfection

Approach -I-

- Cascade/Ratio control

Approach-II-

- The Smith predictor (Dead-time compensator)
- Odometric transformation
- Method of characteristics

Open loop simulation results

Closed loop simulation results

Process description

- An advanced wastewater treatment plant in Gainesville, Florida, and uses chlorine for disinfection

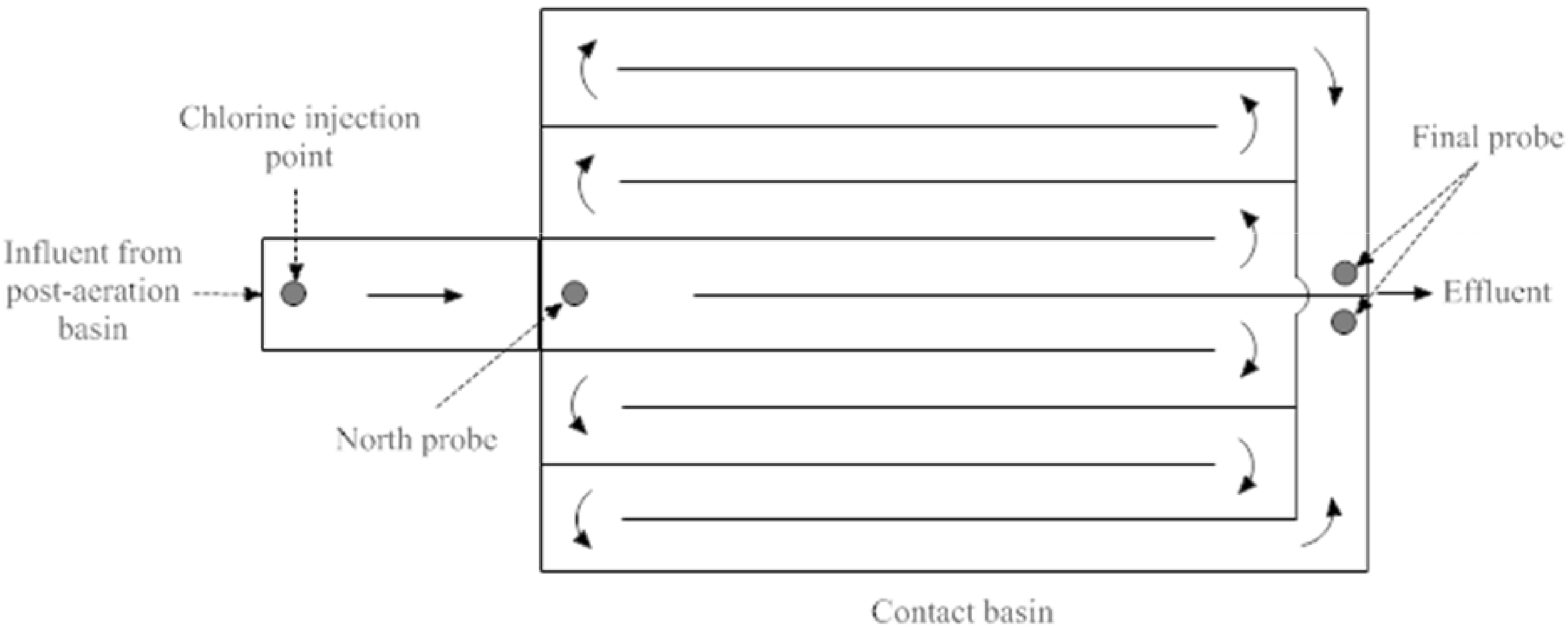
- Treats the wastewater to the standards for drinking water, and most of the water effluent is used for irrigation, reuse, and injection into groundwater.

- Current allowable capacity of 14.9 million gallons per day.

- Performs the disinfection process in two chlorine contact basins that are open to the atmosphere

Process description

A schematic representation of the disinfection process



Sampling points for the chlorine measurements

Chlorination reactions

- Modeled based on the breakpoint chlorination by Morris and Isaac (1983) for a wastewater

Reaction	Forward-rate constant	Reverse-rate constant
$NH_3 + HOCl \leftrightarrow NH_2Cl + H_2O$	$6.6\times10^8 \exp\left(-\frac{1510}{T}\right)$	$1.38\times10^8 \exp\left(-\frac{8800}{T}\right)$
$NH_2Cl + HOCl \leftrightarrow NHCl_2 + H_2O$	$3\times10^5 \exp\left(-\frac{2010}{T}\right)$	$7.6\times10^{-7}\left(\frac{L}{mol\cdot s}\right)$
$NHCl_2 + HOCl \leftrightarrow NCl_3 + H_2O$	$2\times10^5 \exp\left(-\frac{3420}{T}\right)$	$5.1\times10^3 \exp\left(-\frac{5530}{T}\right)$
$2NH_2Cl \leftrightarrow NHCl_2 + NH_3$	$80\exp\left(-\frac{2160}{T}\right)$	$24.0\left(\frac{L}{mol\cdot s}\right)$

- Reaction rates are in units of L/mol-s, concentrations are in mol/L and the temperature is room temperature (25°C).

Chlorination reactions

- Proposed reaction rate expressions for the reactions

$$r_{HOCL} = -k_1[NH_3][HOCl] + k_2[NH_2Cl] - k_3[NH_2Cl][HOCl] + k_4[NHCl_2]$$
$$-k_5[NHCl_2][HOCl] + k_6[NCl_3] - k_{Disinfection}[HOCl]$$

$$r_{NH_3} = -k_1[NH_3][HOCl] + k_2[NH_2Cl] + k_7[NH_2Cl]^2 - k_8[NHCl_2][NH_3]$$

$$r_{NH_2Cl} = k_1[NH_3][HOCl] - k_2[NH_2Cl] - k_3[NH_2Cl][HOCl] + k_4[NHCl_2] - k_7[NH_2Cl]^2$$
$$+k_8[NHCl_2][NH_3]$$

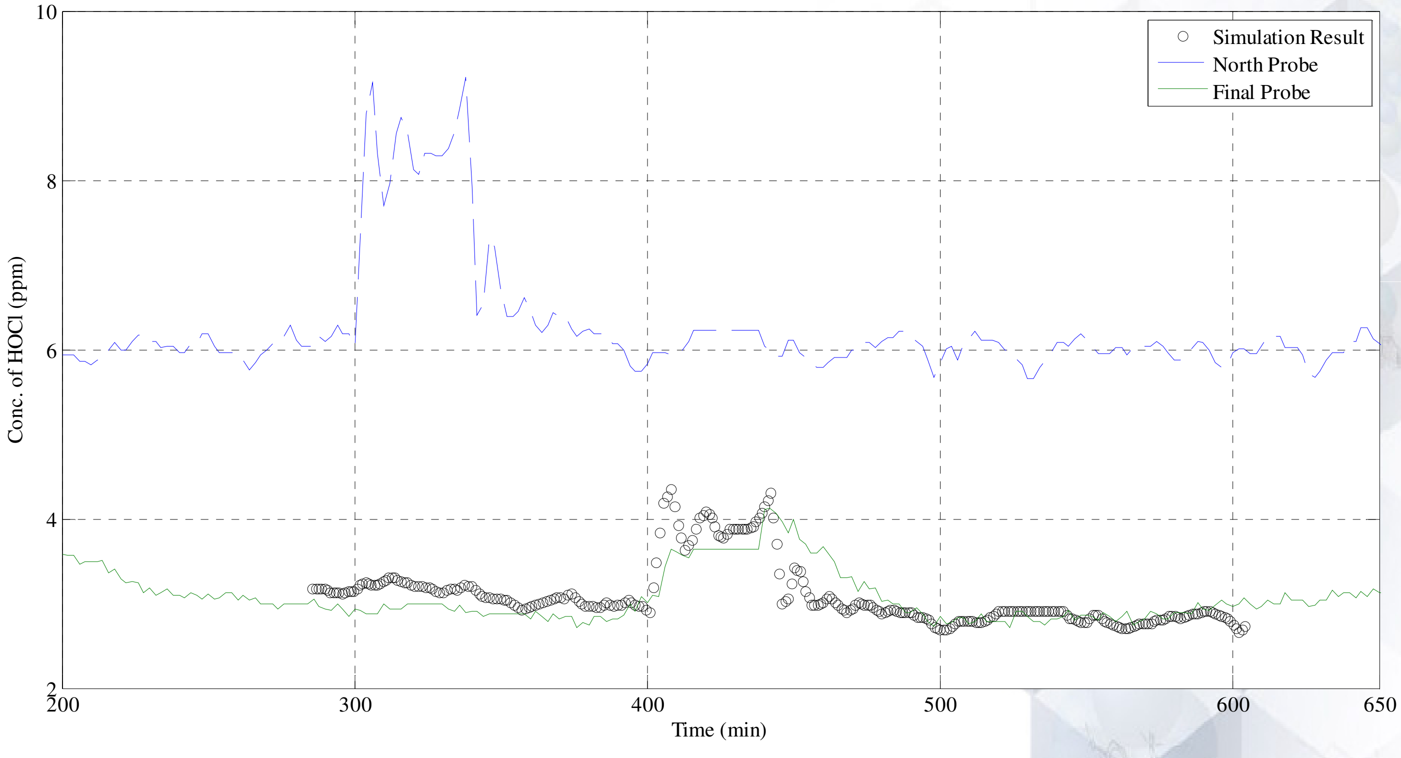
$$r_{NHCl_2} = k_3[NH_2Cl][HOCl] - k_4[NHCl_2] - k_5[NHCl_2][HOCl] + k_6[NCl_3] + k_7[NH_2Cl]^2$$
$$-k_8[NHCl_2][NH_3]$$

$$r_{NCl_3} = k_5[NHCl_2][HOCl] - k_6[NCl_3]$$

- The term $k_{Disinfection}[HOCl]$ represents the chlorine consumed during the disinfection

Chlorination reactions

- A first-order kinetic model is able to describe the chlorine disinfection in the ammonia-free part of wastewater



- The reaction rate constant, $k_{Disinfection}[HOCl]$, was estimated to be 0.0073 h^{-1}

Process control objectives

- Develop a process control strategy and design an appropriate feedback controller for the disinfection process
- Overcome the large and variable transportation lags
- Produce an effluent that meets required environmental regulations at the end of the contact basin
- Avoid the formation of organic compounds known as trihalomethanes
- Add an appropriate amount of chlorine into the influent

Process control challenges

- Significant changes of flow rate
- Quality of wastewater
- Complex reactions of chlorine residuals with ammonia in wastewater and dynamic behavior
- Biological processes (the complexity of the physical and biochemical phenomena)
- Large and variable dead-time
- Lack of adequate sensors and actuators
- Difficulty to design an appropriate process control system
  - Feed forward-feedback control
  - Linearized and optimal control, Nonlinear multiobjective model-predictive control
  - Fuzzy control, Optimization control
  - Adaptive and robust-adaptive control
  - Model predictive control

Process control objectives

Large and variable dead-time

- Primary control issue because the contact basin is too long (≌200 m)
- Complicates the stability analysis and the controller design
- Flow rate changes relative to daily water usage

$$\frac{Maximum\ flow\ rate}{Minimum\ flow\ rate} \approx 10 \rightarrow \frac{Maximum\ dead - time}{Minimum\ dead - time} \approx 10$$

- Changes from 1h to 2 or 3 h for the chlorine disinfection of wastewater treatment plant
- The average dead-time is 2 hours in the KWRF

Process control challenges

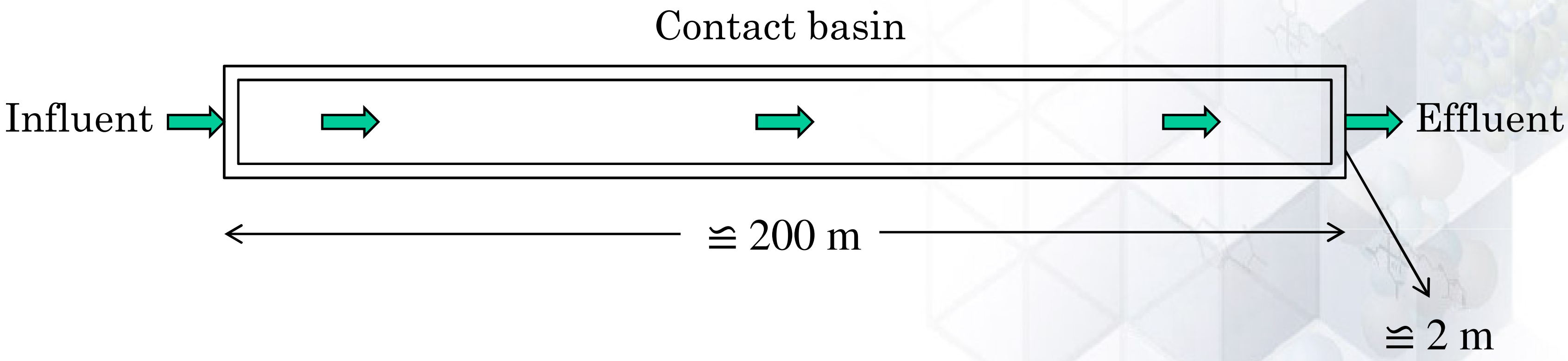
Disturbances

- Affect the output without being adjusted by the process operator or an automatic method
- Sunlight and rainfall are some disturbances in the KWRF because contact basin is open to the atmosphere
- Sunlight affects the chlorine chemistry due to UV and reduces the final chlorine content
- Rainfall reduces the chlorine concentration via dilution, affecting the chlorine levels at the end of the contact basin

Process control challenges

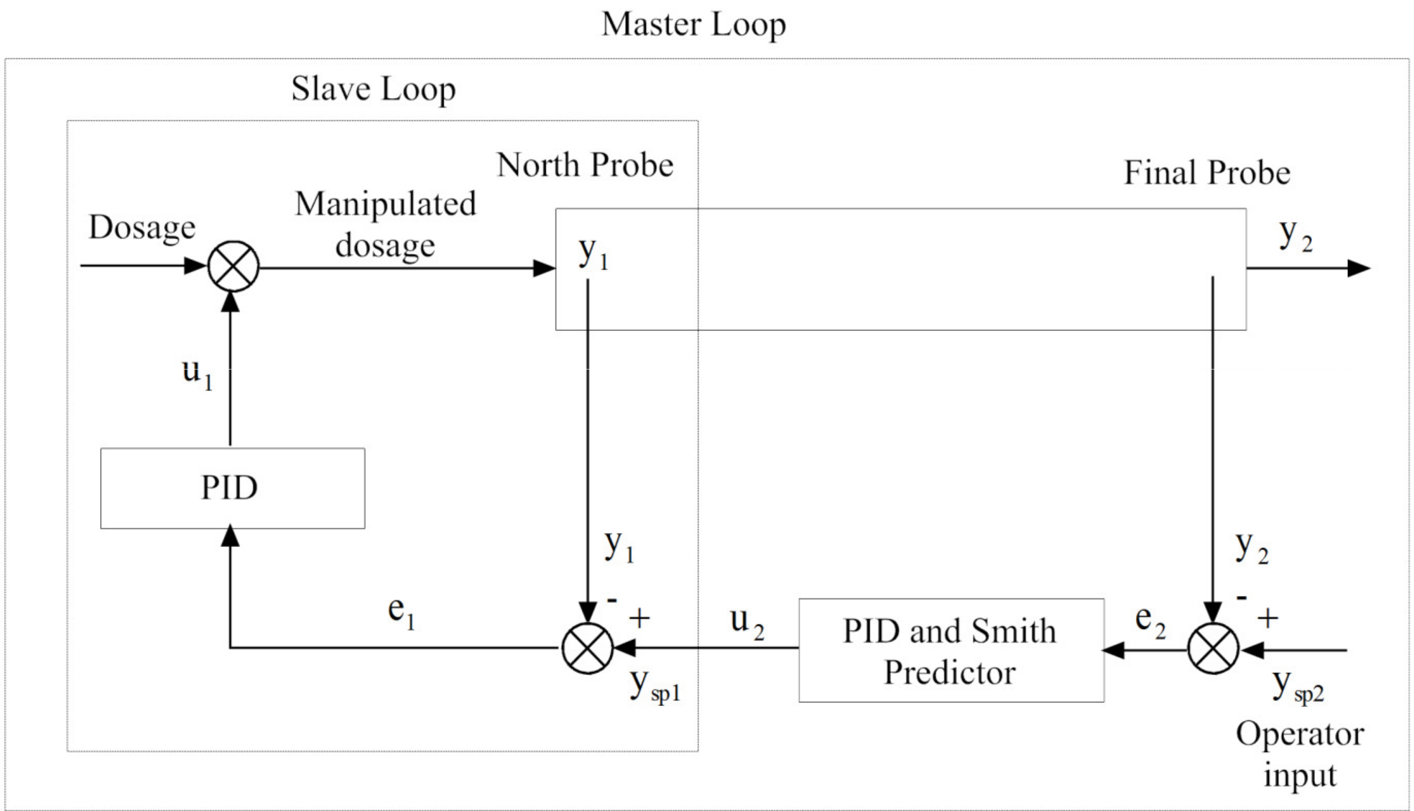
Dynamic model for a disinfection

Assumption: Plug flow reactor



Approach -I-

Cascade/Ratio control (Ratio of Cl_2 dosage to influent flow rate)

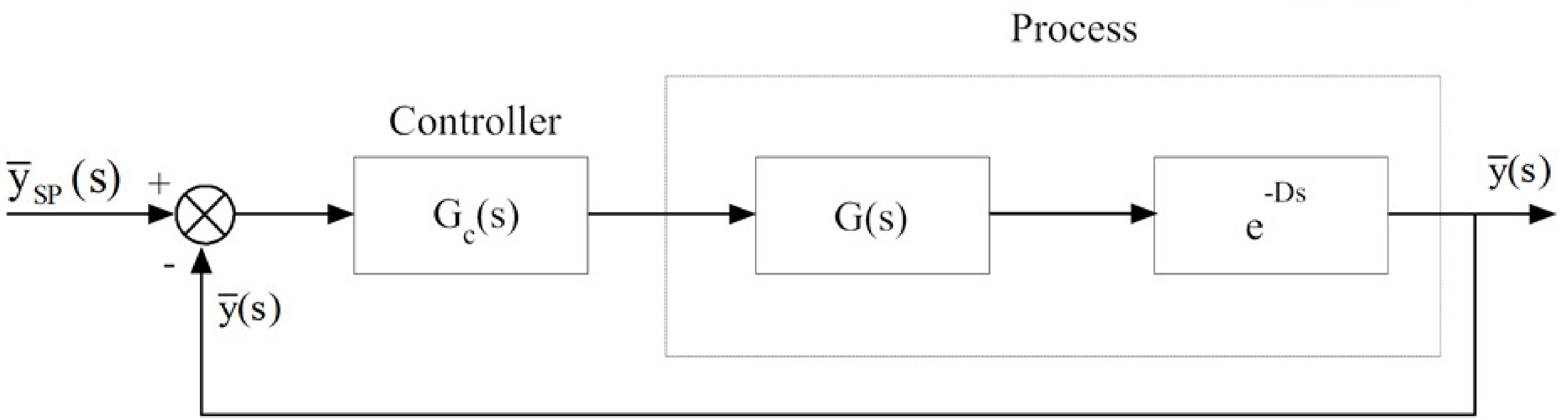


- Improve the system performance in the presence of long dead times between the control and process variables

Approach-II-

The Smith predictor (Dead-time compensator)

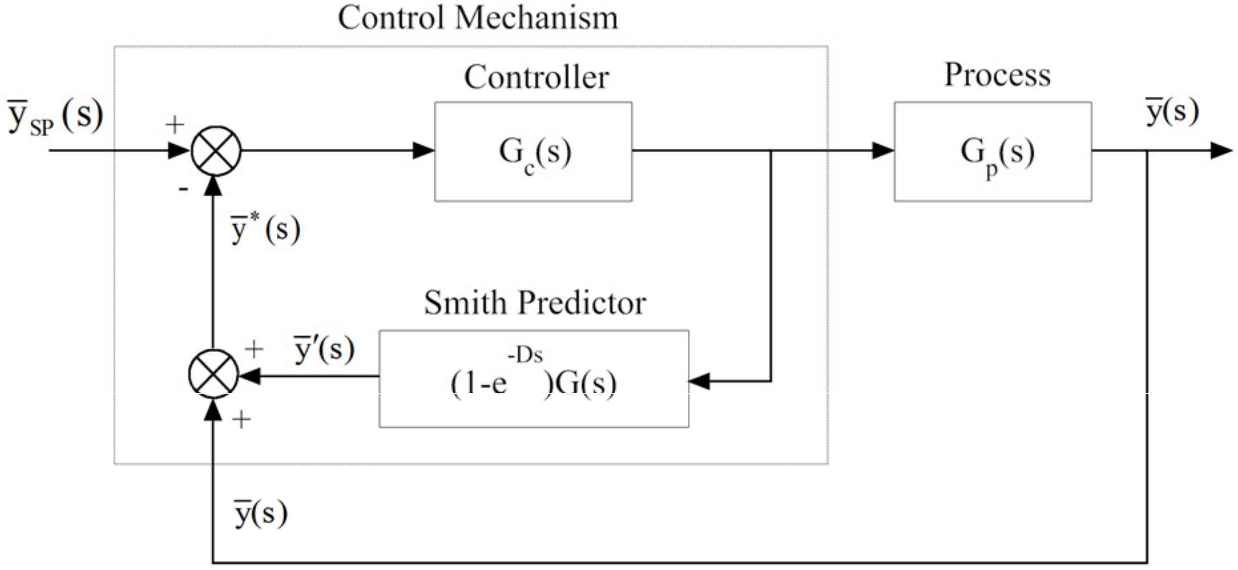
- Cancel out the dead-time and obtain a delay-free transfer function
- The Smith predictor structure used in this study was derived by George Stephanopoulos (1984)



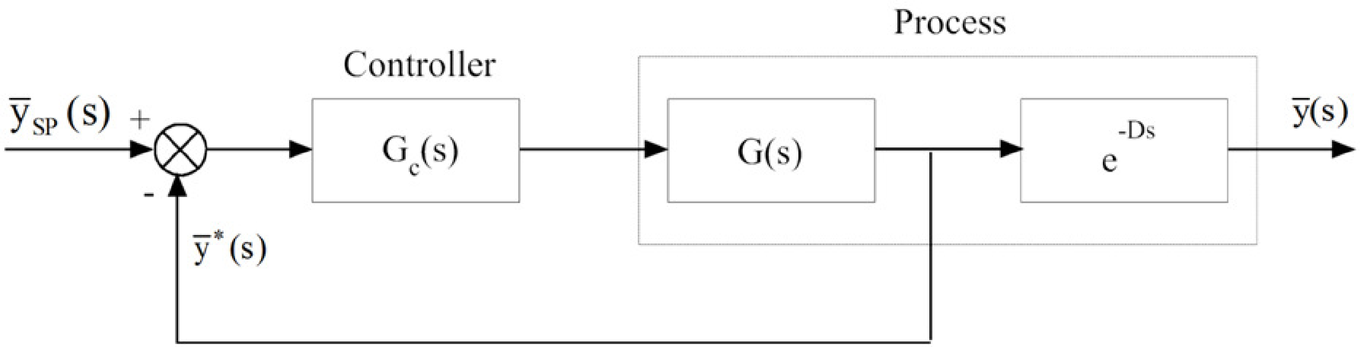
Block diagram for a feedback control

Approach-II-

- The Smith predictor structure



- Delay-free feedback block diagram



Odometric transformation

- First introduced by Svoronos and Lyberatos (1992) and Harmon et al. (1990)
- They claimed that

  "Variability in the effective time constant can be considerably reduced if one considers, instead of time, the cumulative amount of a quantity generated, consumed, or fed as the independent dynamic model variable"

Odometric variable *(β)*

$$\frac{\partial \beta}{\partial t} = v(t) \quad \rightarrow \quad \beta(t) = \int_0^t v(t)$$

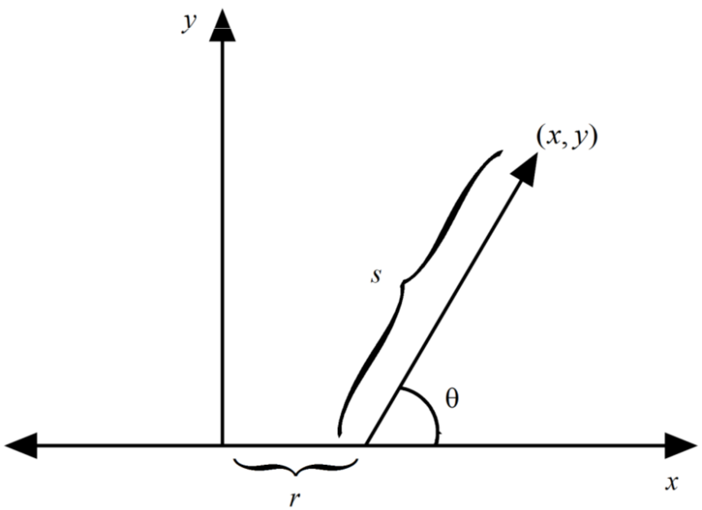
$$\frac{\partial C_i}{\partial \beta} = -\frac{\partial C_i}{\partial z} + \frac{1}{v(\beta)} r_i\left(\underline{C}(\beta, z)\right)$$

- Transforms the dynamics of the system to an equivalent constant time delay model
- Replaces time with a new odometric variable (*β*)
- (*β*) represents the displacement of flow or cumulative distance traveled by water

Method of characteristics

- Many PDEs occur when modeling the chlorine disinfection reactions
- Solves PDEs by reducing them to a set of ODEs
- General expressions of a PDE as follows (P and Q are constants)

$$P\frac{\partial z}{\partial x} + Q\frac{\partial z}{\partial y} = R(x,y)$$



$$x = r + s * \cos(\theta)$$
$$y = s * \sin(\theta)$$

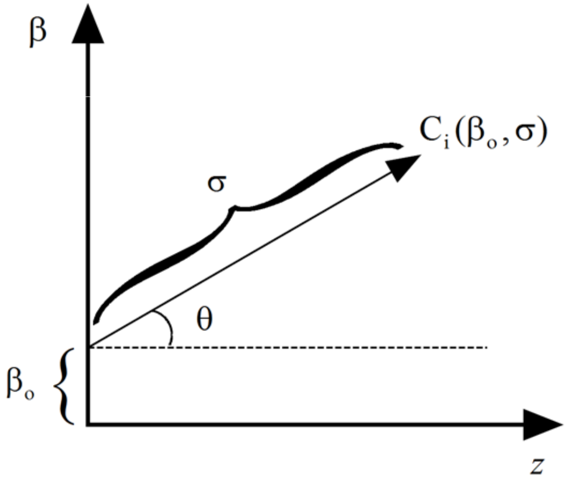
$$\theta = \tan^{-1}\left(\frac{Q}{P}\right)$$

$$z(x,y) = z(x - y\cot(\theta)) + \int_0^{y\,\mathrm{cosec}(\theta)} R(x - y\cot(\theta) + s'\cos(\theta), s'\sin(\theta))\frac{ds'}{\sqrt{P^2 + Q^2}}$$

Applying transformation techniques

- Transforms the system dynamics to a constant time delay model and ODEs

$$\frac{\partial C_i}{\partial \beta} = -\frac{\partial C_i}{\partial z} + \frac{1}{v(\beta)} r_i\left(\underline{C}(\beta, z)\right)$$

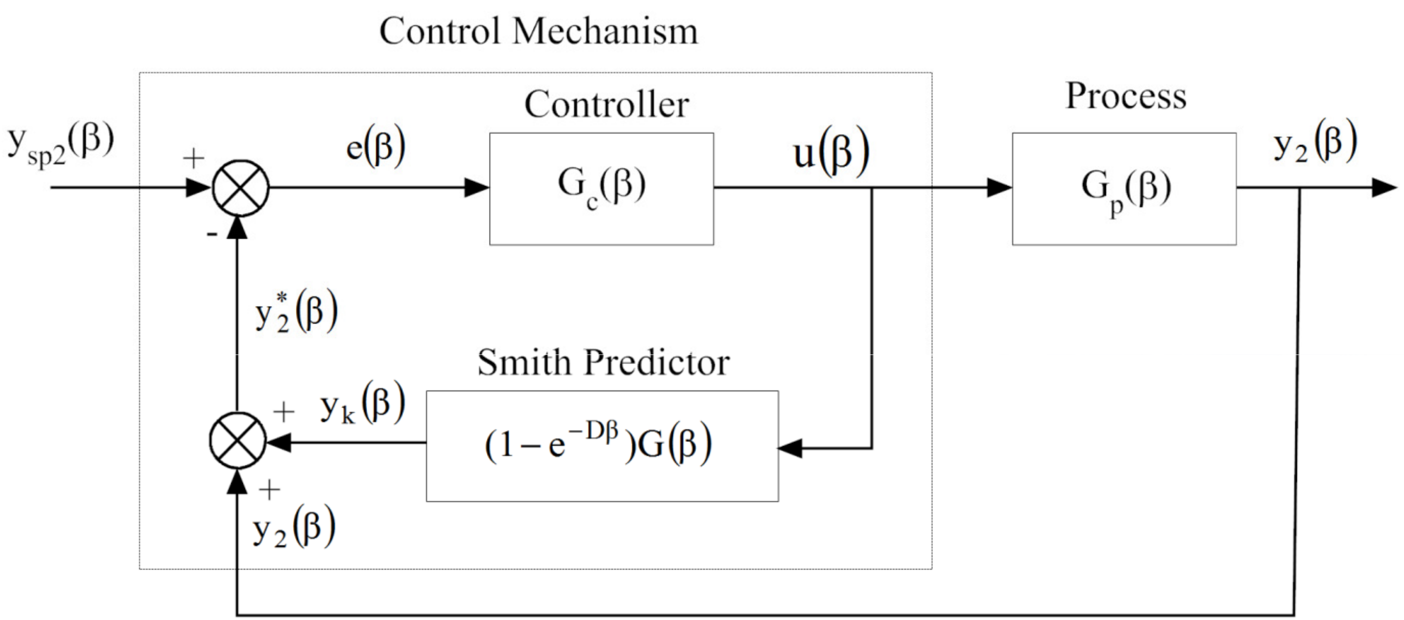


$$\beta = \beta_o + \sigma \sin(\theta)$$
$$z = \sigma \cos(\theta)$$
$$\theta = 45^o$$

$$\frac{\partial c_i\left(\beta_\circ + \frac{\sigma}{\sqrt{2}}, \frac{\sigma}{\sqrt{2}}\right)}{\partial \sigma} = \frac{1}{\sqrt{2}} \frac{1}{v\left(\beta_\circ + \frac{\sigma}{\sqrt{2}}\right)} r_i\left(\underline{c}\left(\beta_\circ + \frac{\sigma}{\sqrt{2}}, \frac{\sigma}{\sqrt{2}}\right)\right)$$

Smith predictor scheme

Smith predictor scheme for the master controller in terms of (β)



Process control equations

- Set point for the slave controller

$$u(\beta) = y_{sp1}(\beta)$$

- Discrete change in the odometric variable

$$\Delta\beta = \frac{D}{N}$$

- Signal (y_k) produced by the Smith Predictor

$$y_k(\beta) = \left(1 - \frac{\Delta\beta}{\tau}\right) y_k(\beta - \Delta\beta) + K_{gain}\left(u(\beta - \Delta\beta) - u(\beta - D - \Delta\beta)\right)\frac{\Delta\beta}{\tau}$$

$$y_2^*(\beta) = y_2(\beta) + \left(1 - \frac{\Delta\beta}{\tau}\right) y_k(\beta - \Delta\beta) + K_{gain}\left(u(\beta - \Delta\beta) - u(\beta - D - \Delta\beta)\right)\frac{\Delta\beta}{\tau}$$

- Feedback error for the master loop

$$e(\beta) = y_{sp2}(\beta) - y_2^*(\beta)$$

- Velocity form of the discrete control law for the master loop

$$u(\beta) = u(\beta - \Delta\beta) + K_c\left(\left(e(\beta) - e(\beta - \Delta\beta)\right) + \frac{\Delta\beta}{\tau_I} e(\beta) + \frac{\tau_D}{\Delta\beta}\left(e(\beta) - 2e(\beta - \Delta\beta) + e(\beta - 2\Delta\beta)\right)\right)$$

Results

Simulation

- The flow rate of the wastewater, the residence time, and the rate constant of the disinfection reactor were obtained experimentally from the KWRF
- Coded in VISUAL BASIC

Open loop simulation (apparent process parameters)

- The dynamic model solved by approximating the reactor small with N continuous-stirred-tank reactors (CSTR)
- Various time increments (Δt=0.5, 5, 10, and 20 s) were used while integrating
- The apparent process parameters, the process gain ($K\ gain$), the time constant (τ), and the delay (D) were determined from the step response data

Results

Closed-loop simulation (tuning)

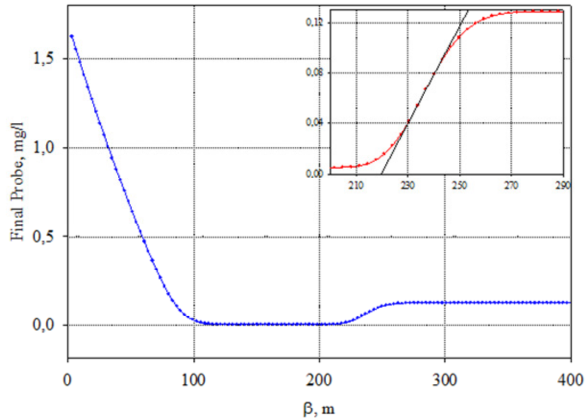
- The daily change in flow rate of wastewater was assumed to be sinusoidal
- The PID form of the master controller was used with the dead-time compensation for the tuning process
- One fixed tuning was evaluated for the different time increments, the number of reactors, and the corresponding apparent process parameters.
- The master PID controller was tuned and fixed to the following constant settings:

$K_c = 0.5$

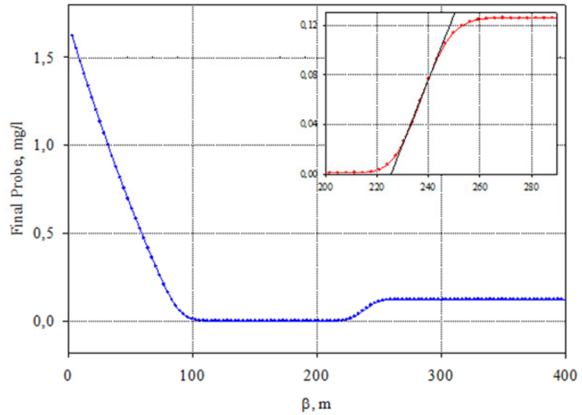
$\tau_I(\beta) = 100$ m

$\tau_D(\beta) = 0$

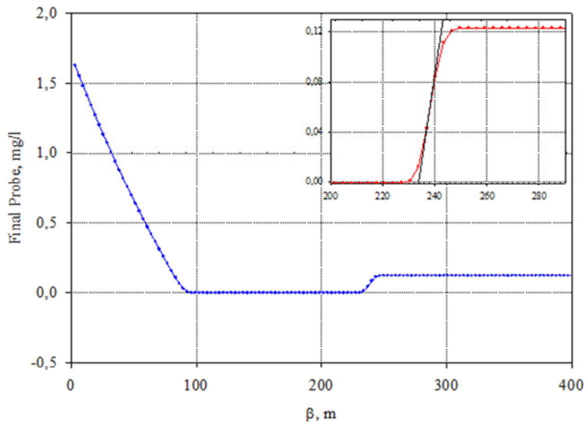
Open loop simulation results



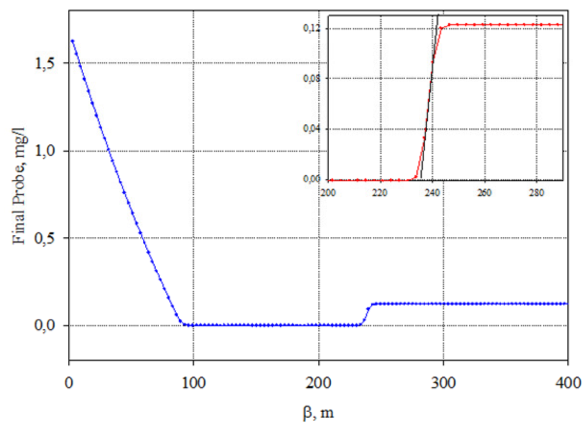
Reactor num. (N) = 50



Reactor num. (N) = 100



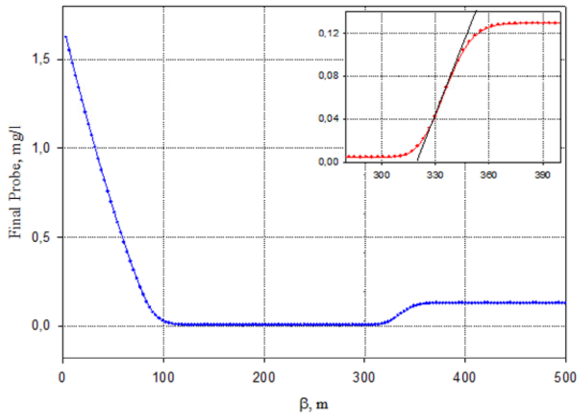
Reactor num. (N) = 500



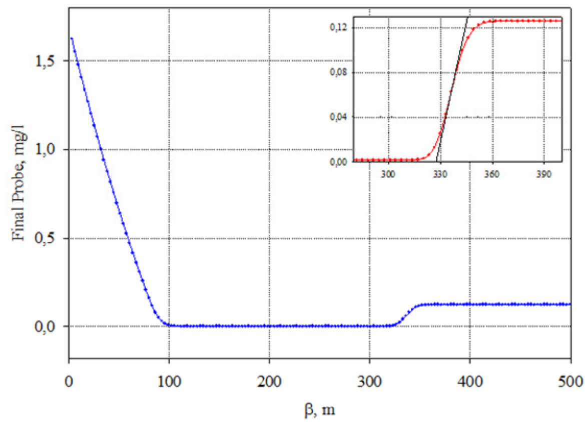
Reactor num. (N) = 1000

Open loop simulation results ($\Delta t = 0.5$)

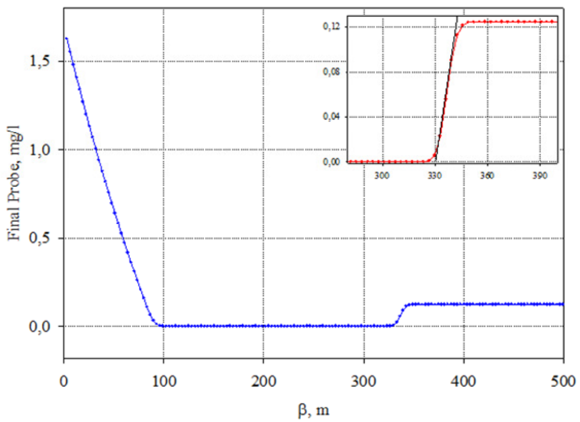
Open loop simulation results



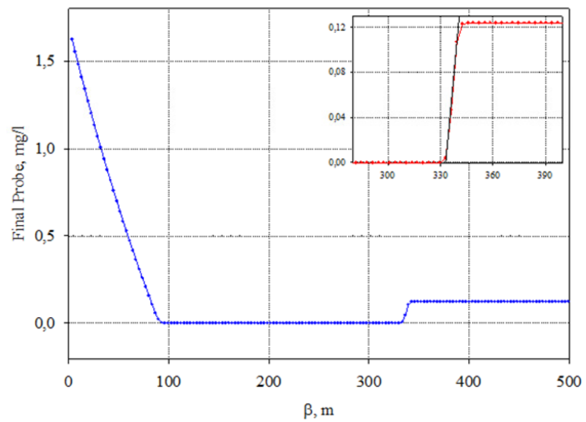
Reactor num. (N) = 50



Reactor num. (N) = 100



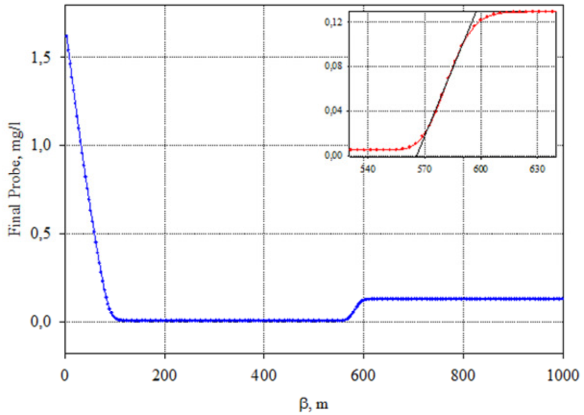
Reactor num. (N) = 200



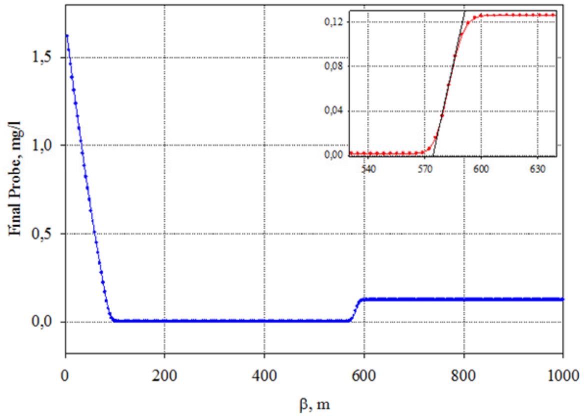
Reactor num. (N) = 300

Open loop simulation results ($\Delta t = 5$)

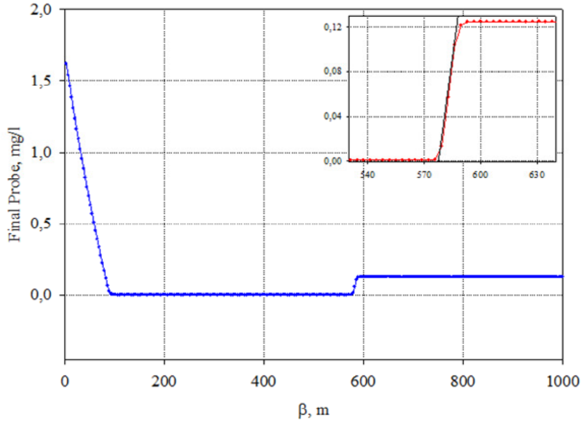
Open loop simulation results



Reactor num. (N) = 50



Reactor num. (N) = 100

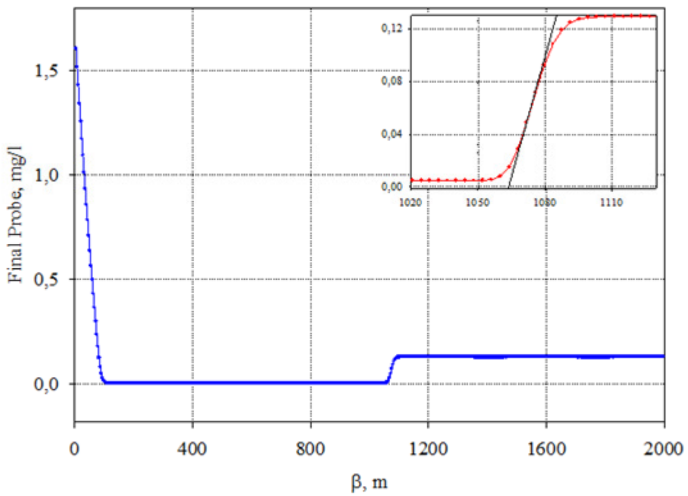


Reactor num. (N) = 150

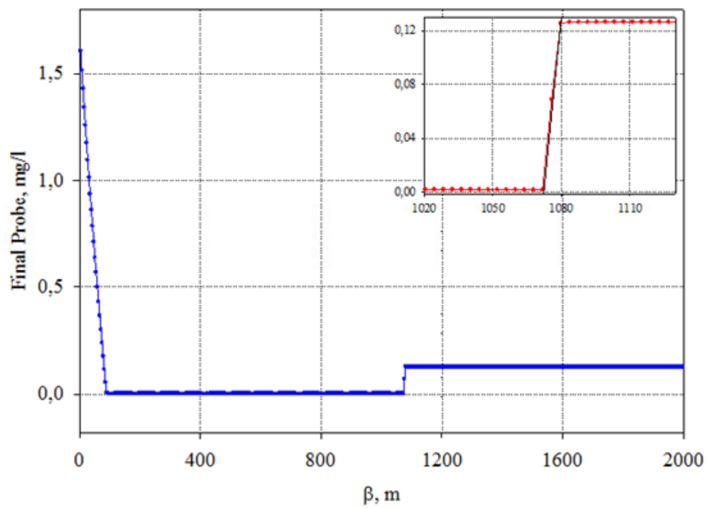
Open loop simulation results ($\Delta t = 10$)

Open loop simulation results

- The delay calculated from the open loop response is similar to the delay calculated theoretically using the odometric transformation



Reactor num. (N) = 50



Reactor num. (N) = 90

Open loop simulation results ($\Delta t = 20$)

Process parameters

- Results from the open loop simulation program (Δt = 0.5, 5, 10, 20)

Reactor Number	Process Gain, K_{gain}	τ (m)	Delay (D) (m)
50	0.061696	33	72
100	0.061366	21	80
500	0.061555	10	85
1000	0.06142	7	87

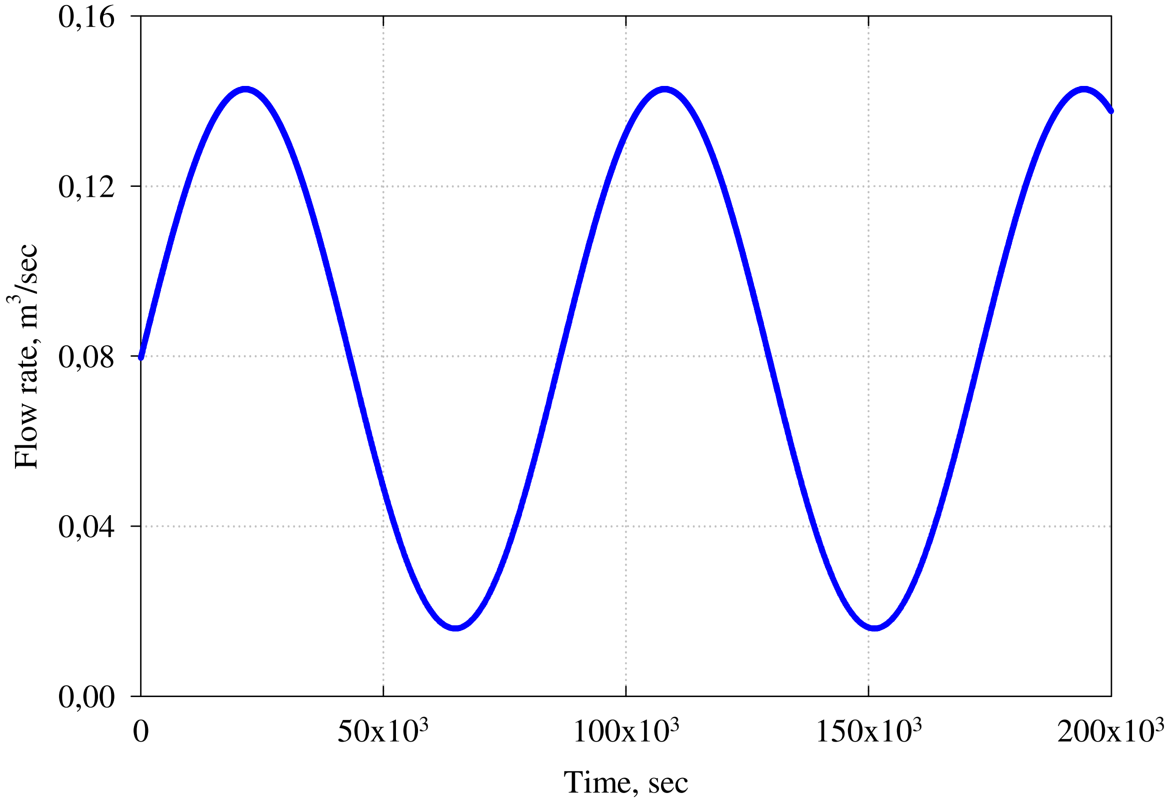
Reactor Number	Process Gain, K_{gain}	τ (m)	Delay (D) (m)
50	0.061785	32	73
100	0.062154	19	80
200	0.0622	10	85
300	0.062153	7	87

Reactor Number	Process Gain, K_{gain}	τ (m)	Delay (D) (m)
50	0.062066	29	74
100	0.062247	16	81
150	0.062231	8	86

Reactor Number	Process Gain, K_{gain}	τ (m)	Delay (D) (m)
50	0.062314	22	79
90	0.062267	7	87

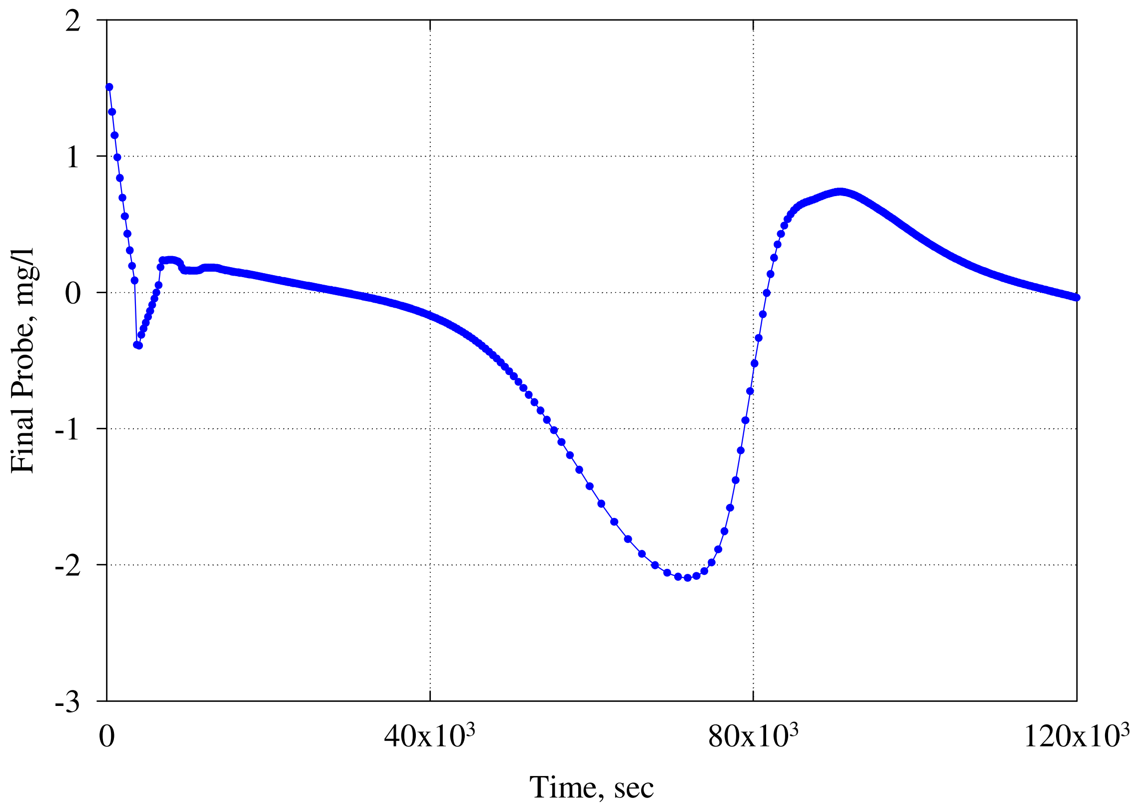
Flow rate of the wastewater

Assumed sinusoidal change in the flow rate of wastewater over time



Closed loop simulation result

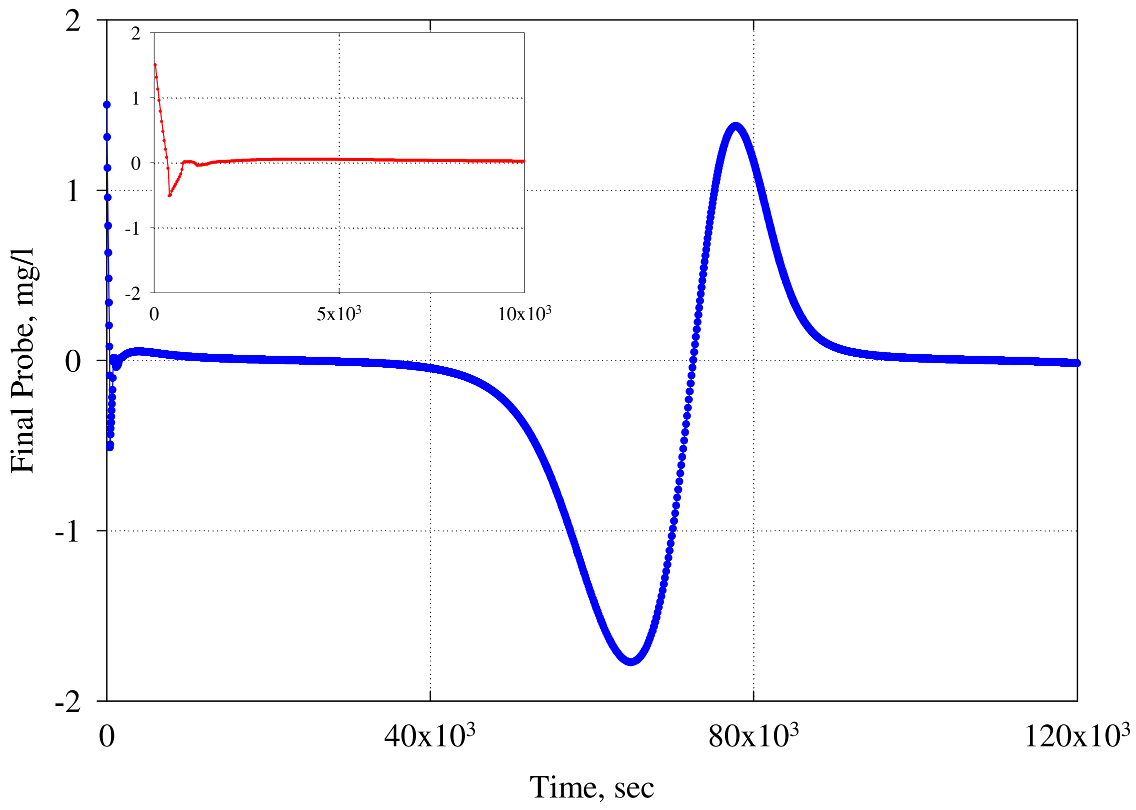
The closed loop performance is poor



$K_{gain} = 0.06155$, reactor num. = 500, $\tau = 10$, $t = 0.5$, $D = 85$.

Closed loop simulation result

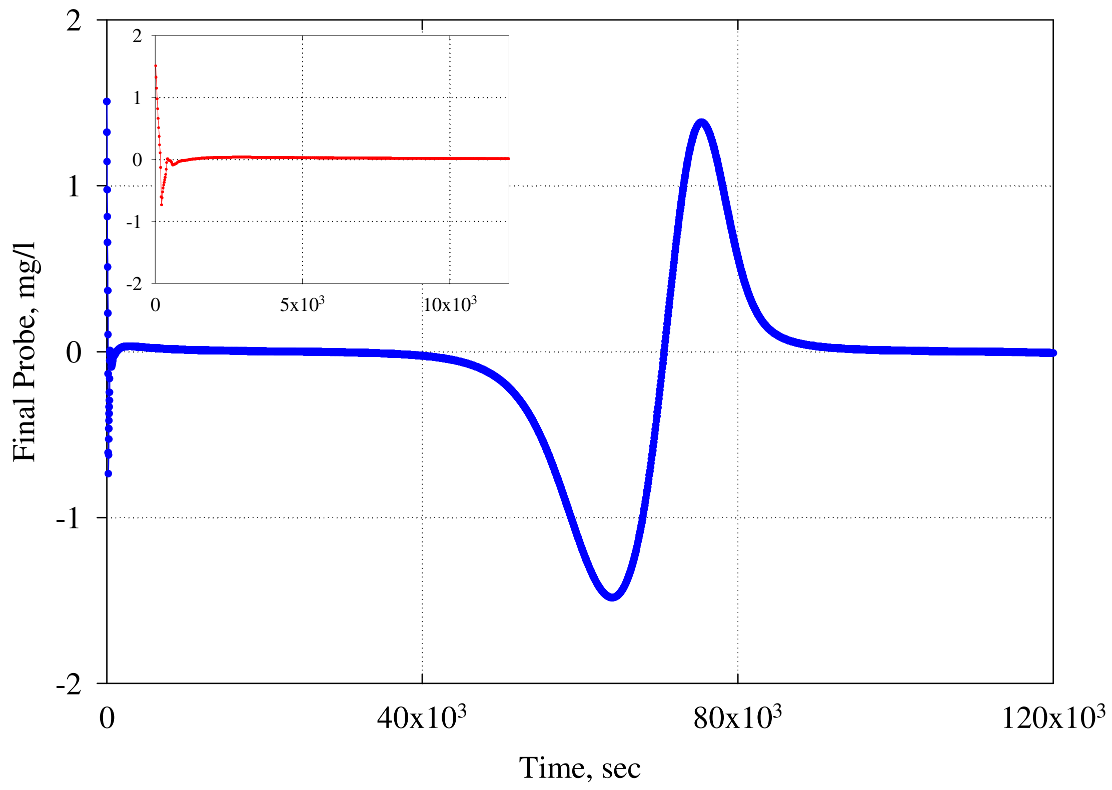
The performance is improved because the deviation values of the final probe measurements are close to zero



$K_{gain} = 0.06215$, reactor num. = 200, $\tau = 10$, $t = 5$, $D = 85$.

Closed loop simulation result

More improved control performance

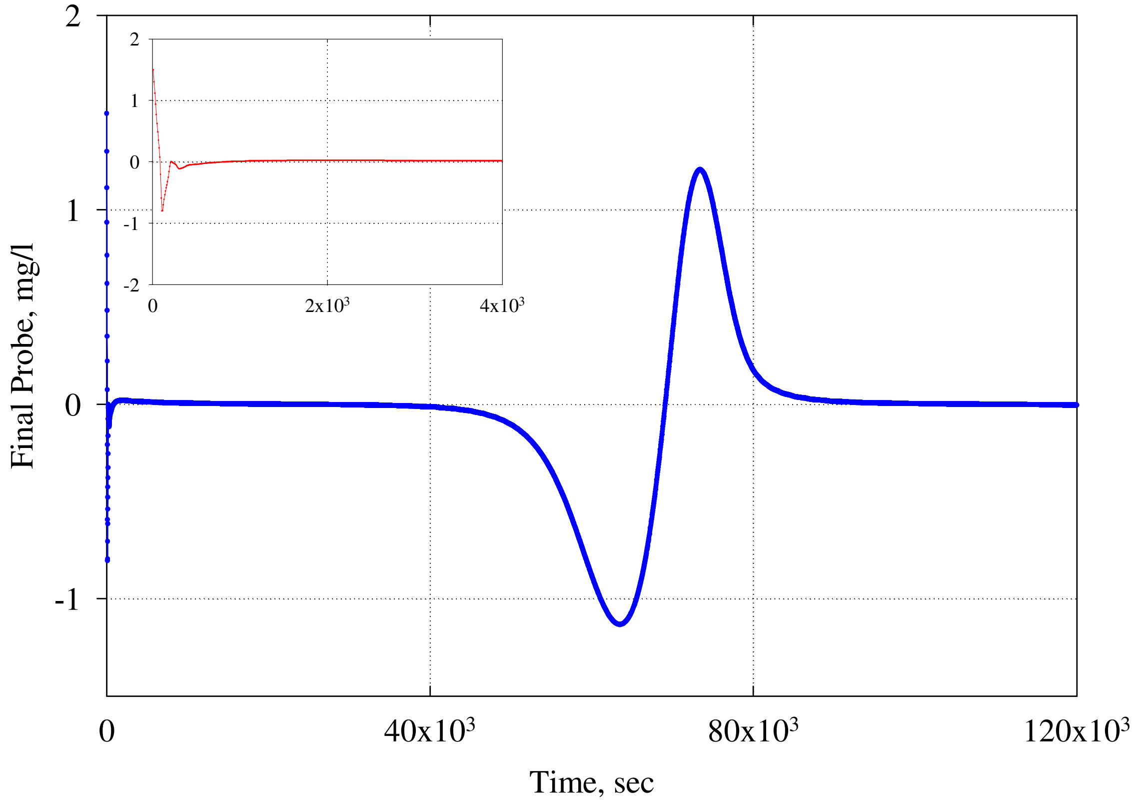


K_{gain} = 0.06225, reactor num. = 100, τ = 16, t = 10, D = 81

Closed loop simulation result

GOOD CONTROL

The deviation values of the final probe measurements is zero



K_{gain} = 0.06231, reactor num. = 50, τ = 22, t = 20, D = 79

Conclusions

- Cascade control with a dead-time compensation strategy was suitable for application with an odometric transformation
- The odometric transformation permits the design of a Smith Predictor with a constant dead-time
- The joint application of the method of characteristics and the odometric transformation successfully control the performance

Acknowledgements

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Article

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