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Real-time experimental generalized minimum variance control of operating parameters in an electrocoagulation process

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ABSTRACT

The aim of this study was to keep electrical conductivity, pH and temperature constant during electrocoagulation (EC) treatment of pulp and paper industry wastewater (PPIW) via real time generalized minimum variance (GMV) and adaptive generalized minimum variance (AGMV) controllers and to determine the effect of control action on pollutant removal and energy consumption. Uncontrolled treatment was carried out at the initial conditions of 2 mS/cm electrical conductivity, pH 8 and 20°C temperature with chemical oxygen demand (COD) removal efficiency of 34.58% and energy consumption of 128.25 kWh/kg COD. Results revealed that treatment under constant electrical conductivity, pH and temperature conditions showed an increase of 9.96% and 8.28% in COD removal and a reduction by 37.49% and 27.25% in energy consumption for multi input-multi output (MIMO) GMV and AGMV controllers respectively compared with uncontrolled treatment. Comparison of MIMO GMV and AGMV control studies implied that GMV controller gave better results than AGMV controller when controller performances, pollutant removal efficiencies and energy consumption values were evaluated together.

Keywords: Generalized minimum variance control; Advanced control strategy; Coordinated control; Electrocoagulation; Wastewater treatment

1. Introduction

The pulp and paper industry consumes large amounts of fresh water as high as 76–227 m^3 water per ton of product [1] and in parallel with this, generates significant quantities of wastewater during various stages of production including wood preparation, pulping, bleaching and papermaking [2,3]. The characteristics of wastewater may vary considerably based on the water usage amount, the type of raw materials and applied production processes [1,2,4,5]. It is reported that pulp and paper industry effluents are highly coloured and toxic, have high content of chemical oxygen demand (COD) and biological oxygen demand (BOD) including approximately 700 organic and inorganic compounds [4]. These harmful contaminants should be removed in order to reduce fresh water consumption by recycling of treated wastewater. Discharge into a receiving environment after treatment is also beneficial for human life and aquatic environment [6,7]. Many researchers have conducted studies on treatment of pulp and paper industry wastewater (PPIW). In the recent years, new technologies have been developed since consecutive mechanical and chemical and/or biological technologies do not efficiently remove recalcitrant organic materials such as lignin and its derivatives present in PPIW [8]. Electrochemical technologies have attracted considerable attention due to the effective removal of high molecular weight dissolved organic matters compared with other physicochemical treatment methods [4,9]. The efficiency of pollutant removal in an electrocoagulation (EC) process is affected by wastewater properties such as electrical conductivity and pH and operating parameters including temperature, electrolysis time, current intensity

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and electrode material. EC has theoretically the same base as the coagulation/flocculation method [10]. However, it is based on the principle that coagulant species including hydroxide precipitates are produced by electrolytic oxidation of the sacrificial anodic material, which is dissolved as ions by electric current applied through metal electrodes such as aluminum and iron [7,11]. Thus, the EC method is more advantageous than the coagulation/flocculation method in which metal salts and polyelectrolytes are used as coagulants/flocculants in terms of sludge formation [12,13]. In recent years EC was considered as a simple, efficient and economical method that can successfully treat different effluents, such as boron containing wastewater [14], municipal wastewater [15], textile wastewater [16,17], dairy wastewater [18], industrial area wastewater [19], tannery wastewater [20], heavy metal removal [21] and PPIW [9,22]. EC treatment of industrial wastewater were performed by Cheballah et al. [23] and 100% Cr and 95.95% COD removal was achieved with the energy consumption of 22.07 kWh/kg of chromium. Drouiche et al. [24,25] achieved more than 97% fluoride removal from post treated photovoltaic wastewater using aluminum electrodes. Boudjema et al. [26] reduced COD, turbidity, fecal coliforms and *Escherichia coli* by 80%, 95%, 99% and 99% of river water, respectively with 30 min EC treatment using aluminum electrodes. Previously performed studies on EC treatment mostly focused on adjusting the initial values of parameters such as pH, electrical conductivity and temperature [27–29]. When effective pollutant removal and cost reduction are considered, keeping the operational parameters constant at their optimum values by means of an advanced controller during treatment will provide safer and more economical operating conditions and contribute to increase the efficiency [30]. Few experimental studies have been carried out on real-time control in domestic, coke, sulphide containing and textile wastewater treatment [31–34].

In the present work, batch treatment of PPIW is implemented by using EC method under real-time controlled conditions of electrical conductivity, pH and temperature. Auto regressive moving average with exogenous input (ARMAX) models that identify the dynamic behaviour of operational conditions of EC process were developed to be used as process models in the control algorithms and the model parameters were determined by the recursive least squares (RLS) method. In control studies, flow rates of supporting electrolyte, acid and base solutions and cooling water valve position (on/off) which were selected as manipulated variables were calculated by the control algorithms coded in MATLAB™ and calculated controller output signals were transferred to related manipulated variables via the data acquisition device. Multi input-multi output (MIMO) control of electrical conductivity, pH and temperature were realized by applying Generalized Minimum Variance (GMV) and adaptive GMV (AGMV) controllers for constant set point values. Integral of the square of the error (ISE) and integral of the absolute value of the error (IAE) criteria [35] were utilized to evaluate controller performances both theoretically and experimentally. Real-time pH control was conducted as a coordinated control strategy with the use of simultaneous acid and base solution flow. Due to more complex algorithm of coordinated control than that of electrical conductivity and temperature, robustness of pH controller was examined by applying positive and negative step disturbances.

2. Materials and methods

2.1. System model

As a requirement of model-based computer control, it is necessary to obtain the relations between the input and output variables to generate the system model. Mass-energy balance equations and system identification are two ways of developing mathematical models. In complex systems, it is difficult to obtain a model by using mass-energy equations method which is an analytical approach, and in some cases it may be insufficient to fully define the system. System identification provides a much faster data-based technique including measured input-output relation from experimental data. Polynomial discrete time models are commonly used in system identification for monitoring and control studies [36,37]. The polynomial equation for a single input-single output system is given in the following equation including random load effects in the system output.

$$A\,y(t) = B\,u(t-1) + C\,e(t) \quad (1)$$

A and *C* are monic polynomials in the backward shift operator z^{-1}. *B* is a polynomial in the z-domain. $y(t)$, $u(t)$ and $e(t)$ are the output, input and noise of the system respectively. The roots of A and B polynomials are called the poles and zeros of the system respectively that are interpreted as the system is unstable or has non-minimum phase property if one of the poles or zeros are out of the unit circle in z plane [38]. ARMAX model of the system can be written as follows:

$$\begin{aligned} y(t) + a_1 y(t-1) + \ldots + a_{n_a} y(t-n_a) &= b_0 u(t-1) + \ldots + b_{n_b} u(t-n_b) \\ &\quad + e(t) + c_1 e(t-1) + \ldots + c_{n_c} e(t-n_c) \end{aligned} \quad (2)$$

Selection of the model and estimation of the model parameters are crucial since the performance of the control algorithm significantly depends on the fit of the system model.

2.2. Generalized minimum variance control

Minimum variance (MV) technique [39] is attained to minimize, for a given linear input-output model, the following cost function:

$$J(u,t) = \Xi\left\{\left(y(t+k) - r(t+k)\right)^2\right\} \quad (3)$$

where the control signal *u* stimulates the plant output at time $(t + k)$, *k* is the system delay, *y* indicates the output of the system, *r* is the set point and *E* denotes the expectation. It is possible to minimize this cost function at time *t* by the choice of $u(t)$ as an appropriate control output. At the next sampling interval $(t + \Delta t)$, a new difference occurs between *y* and *r* which requires *u* to get a new value. In MV control the choice of time delay is important since unsuitable values can destabilize the system. In order to eliminate the difficulties in the MV technique Clarke and Gawthrop [40,41] designed GMV method as a generalization of MV algorithm. The GMV cost function by an appropriate choice of u is given below.

$$J(u,t) = \Xi\left\{\left(y(t+k) - r(t+k)\right)^2 + \lambda\left(u(t)\right)^2\right\} \tag{4}$$

The technique generally holds the control weighting coefficient λ as small as possible in order to sustain a minimum output variance while still preserving closed loop stability. An alternative method of stabilizing the GMV control law is to modify the cost function to reach zero error in case of a non-zero set point by applying incremental controller output, $\Delta u(t)$, to the system.

$$J(u,t) = \Xi\left\{\left(y(t+k) - r(t+k)\right)^2 + \lambda\left(\Delta u(t)\right)^2\right\} \tag{5}$$

The positive λ value simply prevents control signal saturation. GMV cost function can also be represented by the following equation.

$$J(u,t) = \Xi\left\{\phi^2(t+k)\right\} \tag{6}$$

The GMV control uses the following pseudo system output, $\varphi(t + k)$, to minimize the cost function expressed by Eq. (7).

$$\phi(t+k) = Py(t+k) + Qu(t) - Rr(t) \tag{7}$$

where P and R are the filtering actions of system output and set point. Pseudo system output includes a feed-forward polynomial Q. Feed-forward term helps avoiding the problems about the removal of output noise before signal transmission.

$\varphi(t + k)$ is a generalized system output with two sections, one of which can be made zero by u. This is the best estimate of $\varphi(t + k)$ obtained up to time t which is defined as the predicted output.

$$\phi\left(t+k|_t\right) = \frac{1}{C}\left[(BE+QC)u(t) + Gy(t) - CRr(t) + Ed\right] \tag{8}$$

The second section is a function of $e(t+1)$, $e(t+2)$, …, $e(t+k)$ as a noise source and cannot be influenced by the control action $u(t)$.

$$Ee(t+k) = \phi(t+k) + \phi\left(t+k|_t\right) \tag{9}$$

The cost function is minimized by setting equal to zero and this gives the GMV control law.

$$Fu(t) + Gy(t) - Hr(t) + Ed = 0 \tag{10}$$

where

$$F = BE + QC \tag{11}$$

$$H = CR \tag{12}$$

Hence:

$$u(t) = \frac{Hr(t) - Gy(t) - Ed}{F} \tag{13}$$

Application of GMV algorithm consists of following steps [36,42-44].

1) Application of a suitable input change to the system as a forcing function to obtain the system output (electrical conductivity, temperature or pH).
2) Estimation of controller parameters F, G, H from Eq. (10) by implementing the system output data in RLS algorithm.
3) Employment of Eq. (13) to evaluate the control signal in every sampling time by using the minimized Eq. (4).
4) Application of the control signal as supporting electrolyte flow rate, cooling water valve position, acid or base flow rates to the system.
5) Return to step 3.

2.3. Experimental system

All the experiments throughout the present study were performed in a 2 L plexiglass rectangular reactor and six monopolar parallel connected aluminum electrodes having dimensions of 60 mm × 60 mm × 3 mm were placed in the reactor with a gap of 1 cm between each electrode. Two different DC power supplies (MAY 11-PS Constant Current Power Supply and SUNLINE PS 305 D) operating at 0–2 A were used to perform the studies under constant current conditions. Supporting electrolyte (0.04 M NaCl), acid (0.1 M HCl) and base (0.1 M NaOH) solutions were fed to the reactor via peristaltic pumps (Longer Pump LEAD-2). A heating-cooling water circulator (Hoefer RCB 20-PLUS) with an on-off control valve were used to keep temperature constant at a desired value in the reactor and to pass cooling water through the jacket surrounding the reactor. A stirrer (MTOPS MS3020) operating at a range of 150–2000 rpm was utilized. Electrical conductivity, pH and temperature values were monitored on-line during wastewater treatment with the aid of meters (Mettler-Toledo M200 Easy). To avoid signal noise caused by electrical current during treatment, measurements were performed in a separate compartment inside the reactor where sample flow was realized through a peristaltic pump (ASPEN Standard Pump). Experimental set-up is given in Fig. 1a.

2.4. Dynamic and control studies

The wastewater samples used in the study were obtained from a pulp and craft paper plant located in Turkey. Samples were stored in containers at 4°C. The characterization of PPIW is given in Table 1.

To control electrical conductivity, pH and temperature at their desired values during EC process, experimental studies were conducted to model the variations in these parameters. Dynamic studies were implemented by applying a step change of 4.4 ml/min to supporting electrolyte flow rate for electrical conductivity, a pulse change of 5 ml/

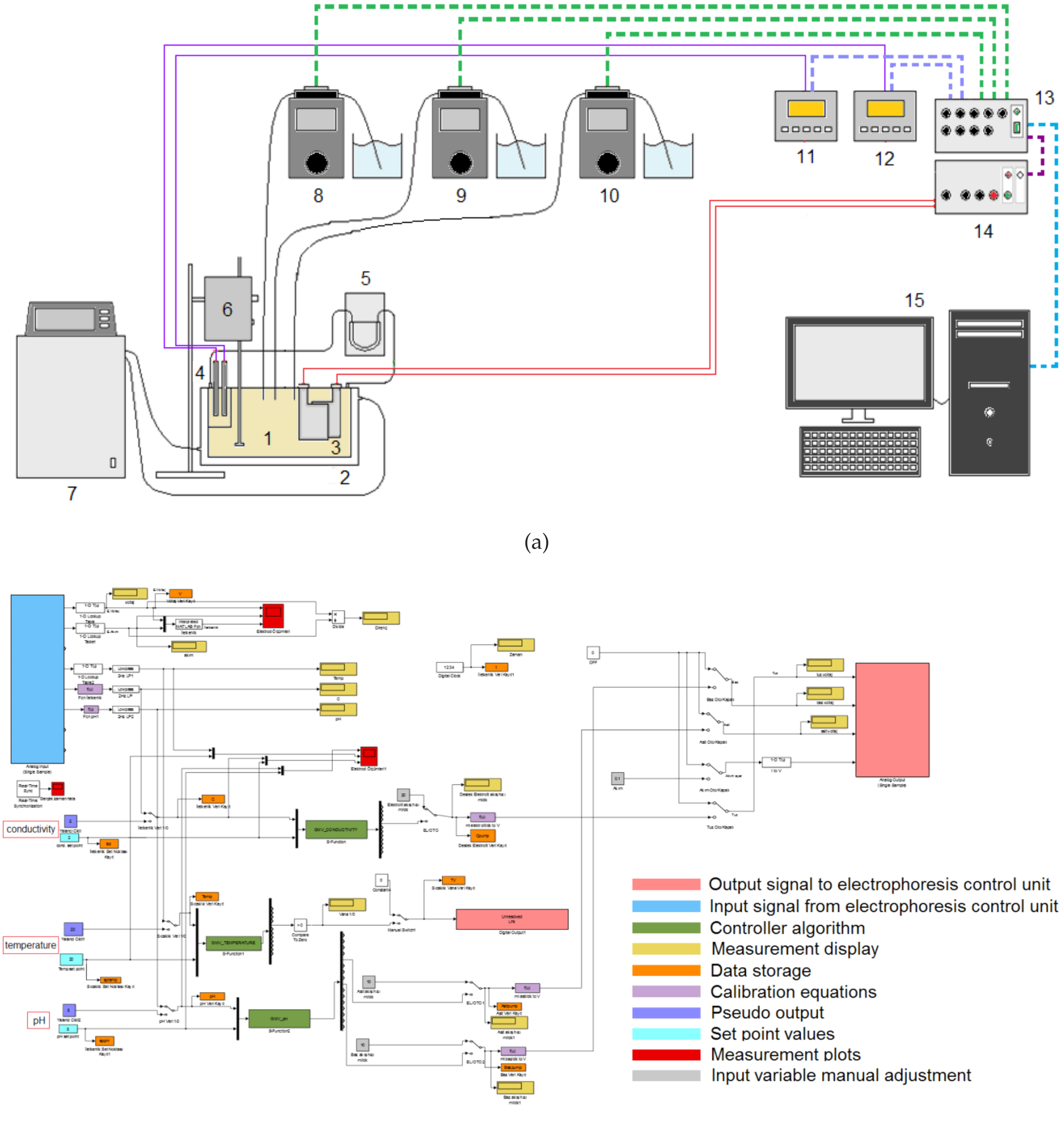


Fig. 1. (a) Experimental set-up (1: EC reactor, 2: EC reactor heating/cooling jacket, 3: electrodes, 4: pH meter, conductivity meter, thermocouple, 5: sample circulation pump, 6: stirrer, 7: water circulator, 8: acid pump, 9: base pump, 10: supporting electrolyte pump, 11: pH and temperature display, 12: conductivity display, 13: control unit, 14: power supply, 15: computer). (b) Real-time MATLAB™ /Simulink model.

min to acid and a step change of 5 ml/min to base solution flow rates for pH and a step change to cooling water flow from 0 L/min to 12 L/min for temperature [22].

EC treatment of PPIW under uncontrolled conditions was performed to compare the results with the studies under constant electrical conductivity, pH and temperature conditions. Uncontrolled treatment was carried out with the initial conditions of 2 mS/cm electrical conductivity and pH 8 which are close to natural value of the wastewater and 20°C temperature for 45 min.

Experimental control studies were carried out for electrical conductivity, pH and temperature using GMV and AGMV algorithm which was coded in MATLAB™. In order to avoid any load effect during optimum λ determination studies, one parameter was controlled by GMV controller while the other two parameters were controlled by a conventional controller. On-line signals from the meters were passed through the transducer in the process control unit (MAY 11-ESA Electrophoresis Control Unit) and transferred towards controller, designed in MATLAB™/Simulink. To

Table 1
Characterization of PPIW

Parameter	Sedimentation Status	Value
pH	After	5.82±0.05
Electrical conductivity (mS/cm)	After	2.10±0.1
Color (Pt-Co)	Before	1549±1
	After	722±1
COD (mg/L)	Before	1045±20
	After	413±20
	Dissolved	114.93±20
Turbidity (NTU)	Before	99±1
	After	49±1
Total suspended solids (mg/L)	Before	86.71±5
	After	44.25±5

adjust input variables and keep controlled variables constant at their set points, signals calculated by the controller were transferred to related manipulated variable through the converter. Multi-purpose real-time MATLAB/Simulink model which was designed to perform EC and control experiments and monitor the variations of input and output variables in the electrochemical reactor is shown in Fig. 1b.

ISE and IAE values were utilized to evaluate GMV controllers' performances. Control studies were performed at 1 A constant current, 600 rpm stirring speed conditions and temperature of the cooling water passing through the jacket around the reactor was adjusted to 12.5°C. The desired values of controlled variables were 2 mS/cm, 8 and 20°C for electrical conductivity, pH and temperature, respectively. The values of electrical conductivity and pH were adjusted using saturated NaCl solution at 20°C, 0.5 M HCl and 0.5 M NaOH solutions before each run. Supporting electrolyte flow rate, acid-base solutions flow rates and cooling water valve position (on/off) were selected as manipulated variables for electrical conductivity, pH and temperature control, respectively. In each run 1 L of PPIW was fed to the reactor. All experimental studies were carried out under 1 A constant current and 600 rpm stirring speed. At the end of 45 min of treatment, 250 ml sample was taken to settle at 4°C for 3 h to perform COD, color, turbidity and total suspended solids (TSS) analyses according to the standard methods SM 5220 D, SM 2120 C, SM 2130 B and SM 2540 D respectively [45]. COD and color were measured at 600 nm and 456 nm wavelengths respectively by using a spectrophotometer (PG Instruments T60V). Turbidity was determined by using a turbidity meter (Aqualytic AL250T-IR). TSS were filtered with a 1.2 µm glass-fiber filter and dried at 105°C in an oven (Memmert UN55). The sedimentation conditions were chosen by considering SM 5220 D of which maximum sample holding time is 28 days at 4°C [45]. The energy consumption per kg of COD removed was calculated by placing the voltage-time data stored during the operation in Eq. (14). This equation is well known and recommended for wastewater treatment as an assessment [7,22].

$$Energy\,consumption\left(\frac{kWh}{kg\,COD}\right)=\frac{I\,V_m\,t}{\left([COD]_0-[COD]_t\right)V_E} \quad (14)$$

where I is the applied constant current intensity in A, V_m is the unweighted arithmetic mean potential difference applied in V, t is the duration of treatment in h, $[COD]_0$ and $[COD]_t$ are the initial and final COD values of the wastewater in g/L and V_E is the volume of the wastewater in L. According to the equation, as current intensity, mean potential difference, duration of treatment and volume of treated wastewater are constants, high COD removal efficiency is desired for lower energy consumption. The primary reason for the difference among the energy consumption values obtained from Eq. (14) is that the denominator represents the difference of the initial and final COD measurements of the wastewater. Such differences are highly sensitive to slight variations in the values being measured. At this point, error checking must be executed carefully by considering these two COD values substituted into the Eq. (14). Therefore the removal efficiency calculations in the cases studied were made on the basis of sedimented wastewater characteristics, except for the COD removal and energy consumption which were based on dissolved wastewater characteristics.

3. Results and discussion

3.1. Dynamic analysis results

The data obtained from dynamic analyses were used separately in the recursive least squares algorithm coded in MATLAB™ and ARMAX model parameters were obtained. ISE values were computed to determine the compatibility of the model with experimental data. A second order polynomial was found sufficient to represent the plant dynamics [46]. Identity matrix multiplier and forgetting factor were taken initially as 1000 and 0.99 respectively. ARMAX models of the three processes are shown in Table 2. ISE values are found close to zero which indicates good fit between experimental and predicted data. Since the closed-loop control performance of the system depends on compatibility of the actual process with the model [47], obtained ARMAX models are suitable for use in control algorithms.

3.2. Uncontrolled treatment

The variations of the parameters in uncontrolled treatment are given in Fig. 2. According to the obtained data, it was observed that electrical conductivity decreased from 2 mS/cm to 1.87 mS/cm, pH and temperature increased from 8 to 9.05 and from 20°C to 25.3°C respectively. COD, color, turbidity and TSS removal efficiencies were obtained as 34.58%, 96.56%, 99.23%, and 96.43% respectively. Energy consumptions were calculated as 128.25 kWh/kg COD and 59.58 kWh/kg COD when constant current power supplies MAY 11-PS and SUNLINE PS 305 D were used, respectively.

When Cl^- ions are present, electrical conductivity reduction during EC process was attributed to $Cl_2(g)$ that liberated from anode [9]. If its solubility in water is exceeded locally at the electrode surface, then Cl_2 bubbles may form [48]. Cl_2 formation in the water indicates indirect oxidation of pollutants via active chlorine formation. As seen from the

Table 2
ARMAX models for electrical conductivity, pH and temperature processes

System output ($y(t)$)	System input ($u(t)$)	ARMAX Model	ISE
Electrical conductivity	Supporting electrolyte flow rate	$y(t)+0.783y(t-1)+0.072y(t-2)=0.01152u(t-1)$	0.0013
pH	Acid solution flow rate	$y(t)+0.8297y(t-1)-0.03538y(t-2)=0.0000293u(t-1)$	0.0009
	Base solution flow rate	$y(t)-0.9367y(t-1)+0.0367y(t-2)=0.0002312u(t-1)$	
Temperature	Cooling water flow rate	$y(t)-0.6424y(t-1)+0.1y(t-2)=0.03325u(t-1)$	0.0019

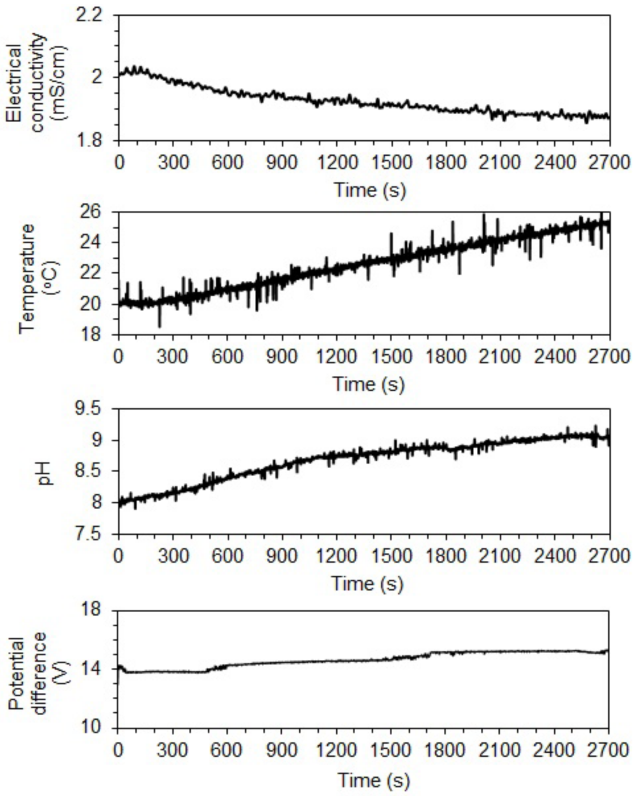


Fig. 2. Variation of electrical conductivity, pH and temperature with time under uncontrolled EC treatment.

figure, an increase in potential difference was observed after the first 10 min due to the decrease in electrical conductivity. Depending on this increase, it is expected that energy consumption will be higher than that of the constant electrical conductivity condition. The increase of pH from 8 to 9.05 indicates a rise in the amount of soluble Al species formed, which cause removal efficiency decrease [49]. Therefore it is necessary to keep pH constant to provide insoluble amorphous $Al(OH)_3$ "sweep flocs" formation which have large surface areas beneficial for a rapid adsorption of soluble organic compounds and trapping of colloidal particles [11]. As can be seen from the figure, another parameter that should be taken into account is the temperature of the wastewater given to the receiving environment since it affects the quality [50].

3.3. GMV control studies

The application of GMV algorithms for electrical conductivity, pH and temperature were realized to maintain these parameters at their desired values during EC treatment of PPIW. Controller performances were compared by means of ISE and IAE values.

Firstly, GMV control studies of electrical conductivity were implemented with constant set point profiles. The set point of electrical conductivity was set to 2.37 mS/cm. Several trials were carried out to determine the optimal value of the control weighting parameter, λ, which provides the best set point tracking. The results are given in Figs. 3a, b.

As can be seen from Figs. 3a, b, optimal value of λ was determined as 0.00005 for electrical conductivity control by considering minimum ISE and IAE. The results of this study are shown in Fig. 3c along with the manipulated variable actions. From this figure, it can be observed that electrical conductivity was satisfactorily kept at the set point.

Constant set point was realized for pH control at the value of 8. The results that were obtained after several trials of λ values for pH control are presented in Figs. 4a, b. Since pH control in this study was applied as a coordinated control strategy, λ values were examined for both acid and base solution flow rates.

It can be seen from Figs. 4a, b that an optimal λ value of 0.0000001 has the lowest ISE and IAE. This study is shown in Fig. 4c with the time variation of manipulated variables. The oscillatory response of pH has a maximum deviation of ±0.2 from the set point, implying a satisfactory control. Oncel et al. [51] noted that the optimum pH for maximum Al precipitation was 8 and that higher pH values caused a reduction in EC efficiency, depending on the formation of soluble species. Suitably, the present study showed that the control action prevented the pH increase due to the nature of the process, also reduced the amount of soluble species, which increased pollutant removal.

GMV control was also implemented for temperature at constant set point of 20°C. Experimental studies were performed with two different λ values and the results are given in Figs. 5a, b. Optimal λ was selected as 0.00001 based on minimum performance criteria. Fig. 5c presents the variations of temperature and cooling water valve position with time for λ = 0.00001.

After determining the optimum parameters for each controller, single input-single output (SISO) control studies were carried out to investigate the effect of process control on each controlled variable in terms of control performance,

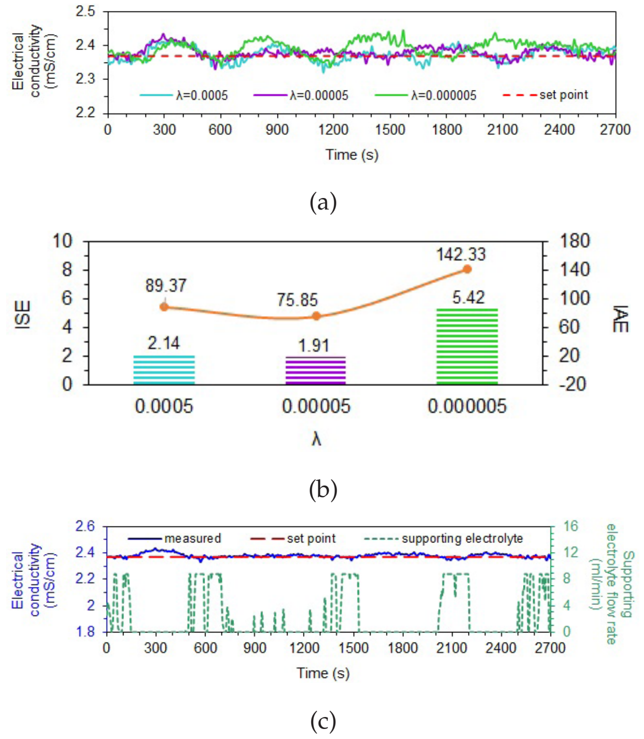


Fig. 3. (a) Effect of λ on electrical conductivity controller performance; (b) Performance comparison for λ values; (c) GMV control of electrical conductivity (λ = 0.0005).

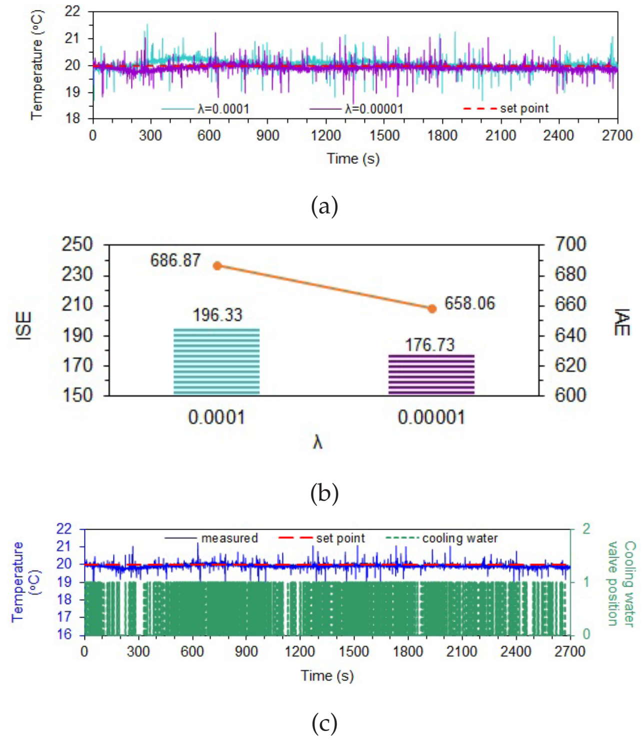


Fig. 5. (a) Effect of λ on temperature controller performance; (b) Performance comparison for λ values; (c) GMV control of temperature (λ = 0.00001).

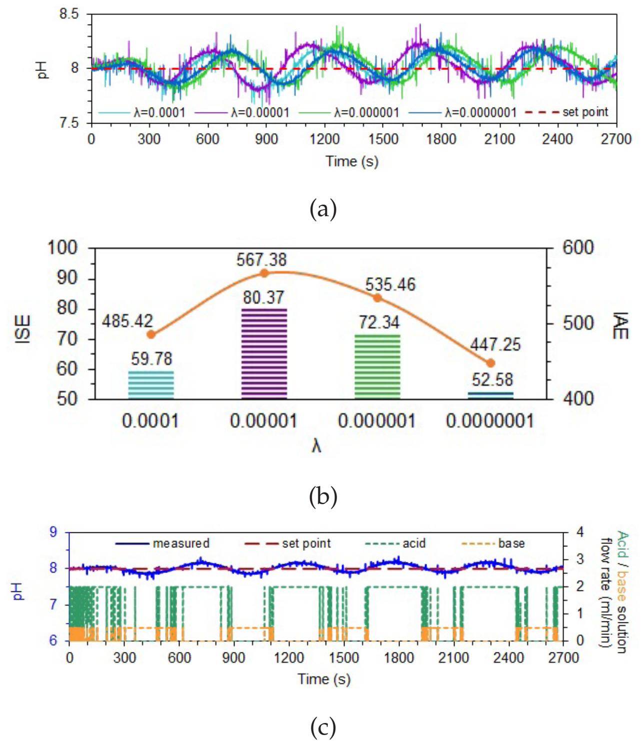


Fig. 4. (a) Effect of λ on pH controller performance; (b) Performance comparison for λ values; (c) GMV control of pH (λ = 0.0000001).

pollutant removal and energy consumption. No additional control action has been performed to prevent the load effect. Only the parameter being controlled was kept constant at the desired value, while the other parameters were time-varying. Variations of controlled and manipulated variables with time are demonstrated in Figs. 6 a–c. ISE and IAE values are given in Table 3.

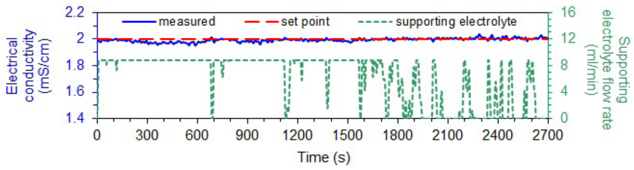
In SISO GMV electrical conductivity control study, a temperature increase of 3.6°C was observed whereas pH increased from 8 to 9.05, which was consistent with uncontrolled treatment study as well. In this study, lower temperature increase compared to the uncontrolled treatment study indicated that mean potential difference requirement was reduced as a result of Ohm's law of resistance due to electrical conductivity control which also reduced the amount of heat generated.

During SISO GMV pH control study, temperature increased from 20°C to 24.8°C and electrical conductivity reduced from 2 mS/cm to 1.95 mS/cm. As seen, pH control reduced the electrical conductivity drop directly and temperature rise indirectly compared to the uncontrolled treatment.

In SISO GMV temperature control study, a pH increase of 1.18 units and an electrical conductivity drop of 0.18 mS/cm were observed consistently with uncontrolled treatment. As a result, temperature control has limited effect on pH and electrical conductivity variations.

3.4. AGMV control studies

AGMV control approach, which is known as a combination of online parameter estimation and GMV, was also



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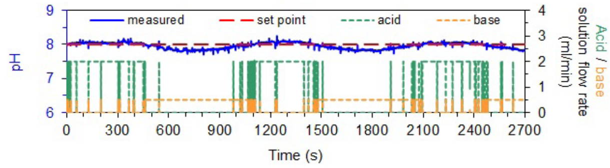

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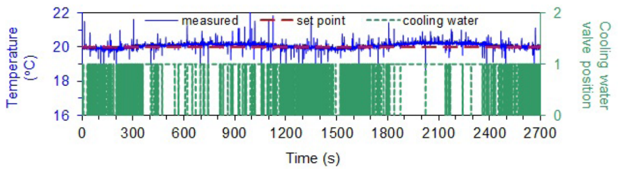


(c)

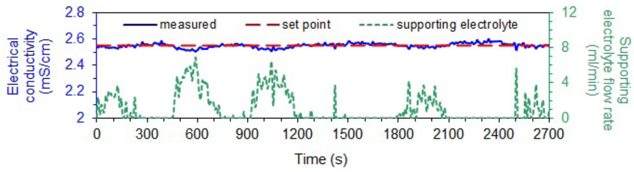
Fig. 6. SISO GMV control of (a) electrical conductivity (λ = 0.0005) (b) pH (λ = 0.0000001) (c) temperature (λ = 0.00001).

Table 3
Performance criteria for controllers

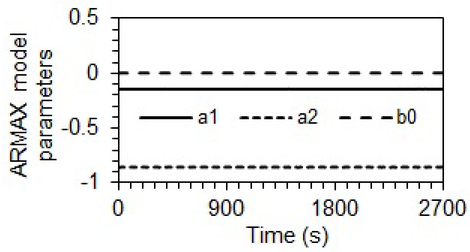
Control method	Controlled variable	Controller	ISE	IAE
SISO	Electrical conductivity	GMV	1.24	61.86
	pH	GMV	52.84	441.73
	Temperature	GMV	316.51	857.23
MIMO	Electrical conductivity	GMV	0.80	52.24
		AGMV	7.33	165.55
	pH	GMV	32.69	358.97
		AGMV	167.89	777.17
	Temperature	GMV	308.50	805.54
Servo	pH	GMV	388.33	1.72×10^3
	pH	AGMV	836.89	2.48×10^3

performed for PPIW treatment with EC to examine the effects of this control method on performance criteria, pollutant removal and energy consumption. In AGMV control, at each time step, model parameters were calculated and controller parameters were updated depending on these calculated parameters [52].

In AGMV electrical conductivity control study, set point was selected as 2.55 mS/cm and initial values of controller parameters P, Q, R were chosen as 5, 1, 5 respectively. ISE and IAE values were calculated as 1.53 and 72.57 respectively. These results show that control performances of GMV and AGMV electrical conductivity controllers are very similar. Time variations of controlled and manipulated variables, model and controller parameters are shown in Figs. 7a–c.



(a)



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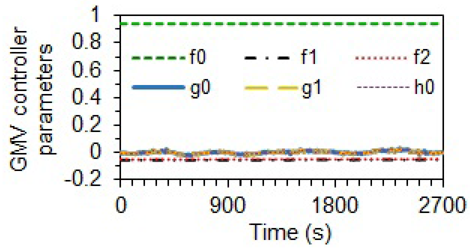


(c)

Fig. 7. (a) AGMV control of electrical conductivity (P = 5, Q = 1, R = 5); Time variations of (b) model parameters (c) controller parameters.

The effect of controller parameters on coordinated AGMV pH control is given in Figs. 8a, b. Since pH control in this study was applied as a coordinated control, P, Q, R values were examined for both acid and base solution flow rates and symbolized by adding capital initials to the end. According to the performance criteria values, optimum P, Q, R were selected respectively as 2, 1, 2 and 2, 0.8, 2 for acid and base flow rates. In this study pH showed an oscillatory response having a maximum deviation of +0.2 from the set point. The ISE and IAE values of the AGMV pH controller were calculated as 64.3 and 533.12, respectively, indicating that the control performance was moderate. The results of the study which was performed by using optimum parameters are given in Fig. 8c with the time variations of manipulated and controlled variables and ARMAX model and controller parameters for acid and base solution flow rates (Figs. 8d–g).

3.5. Comparison of controller performances

A MIMO control study was executed with optimum GMV controller parameters in order to evaluate the effect of control action on pollutant removal and energy consumption. Set point of electrical conductivity,

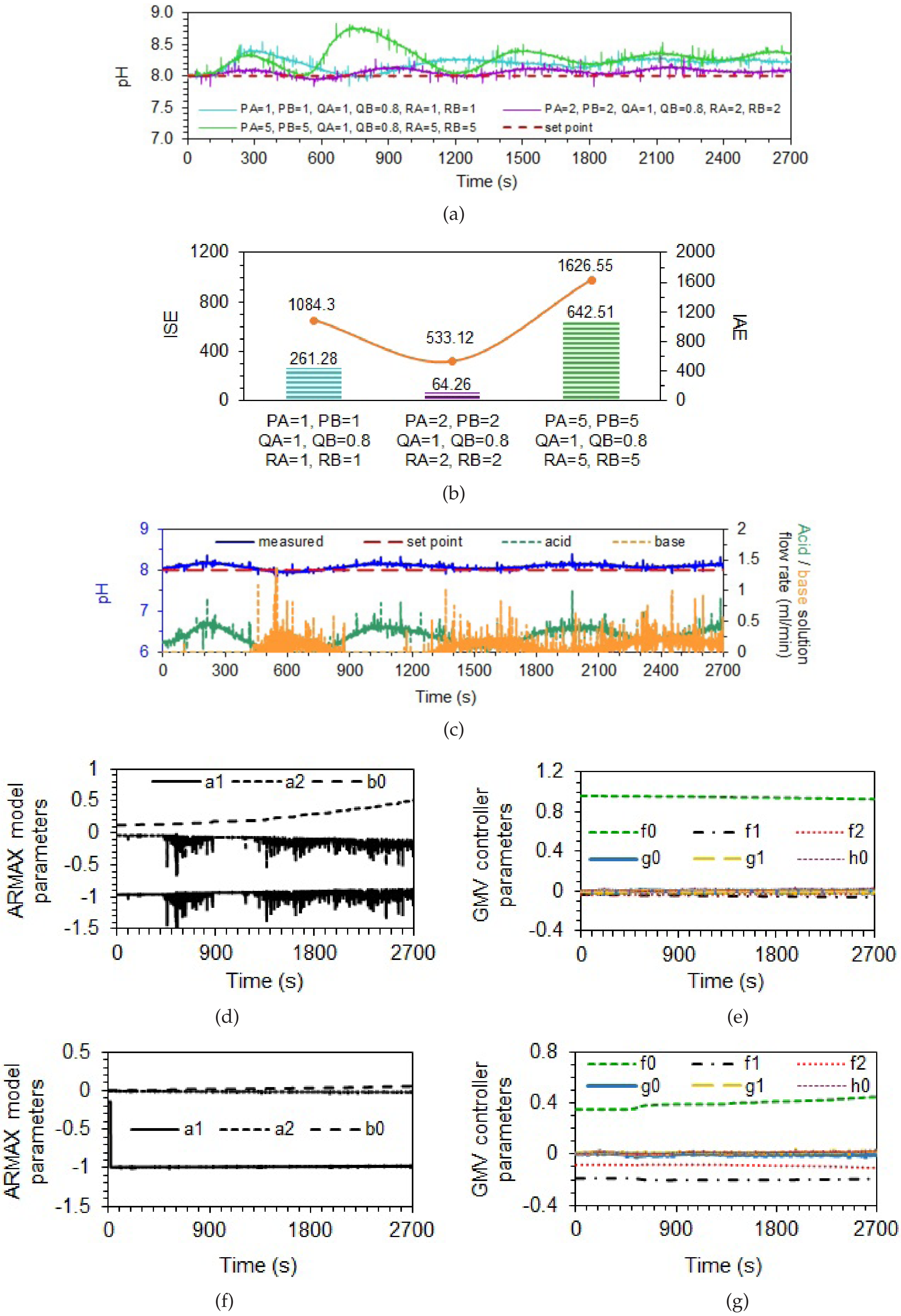


Fig. 8. (a) Effect of P, Q, R on pH controller performance; (b) Performance comparison for P, Q, R values; (c) Coordinated AGMV control of pH ($P_A = 2$, $Q_A = 1$, $R_A = 2$, $P_B = 2$, $Q_B = 0.8$, $R_B = 2$); Time variations of (d) model parameters (e) controller parameters for acid solution flow rate; Time variations of (f) model parameters (g) controller parameters for base solution flow rate.

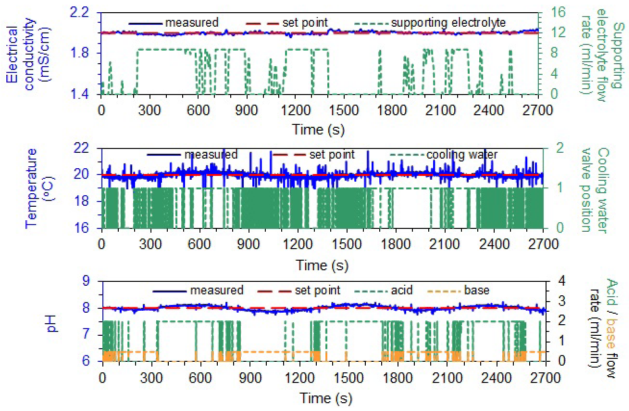
pH and temperature were selected as 2 mS/cm, 8 and 20°C respectively. ISE values of this study are given in Table 3 and variation of controlled and manipulated variables and potential difference with time are presented in Fig. 9a.

MIMO AGMV control study was performed to evaluate the performance of the electrical conductivity and pH controllers and to determine the effect of process control on treatment efficiency. Set point of electrical conductivity and pH were selected as 2 mS/cm and 8 respectively. In this study temperature was controlled by GMV controller in order to avoid the effects of any load in the process. Since the manipulated variable is switched on and off, it was considered that designing AGMV controller for the temperature parameter is unnecessary. Controlled and manipulated variable behavior were shown in Fig. 9b and performance evaluation is given in Table 3.

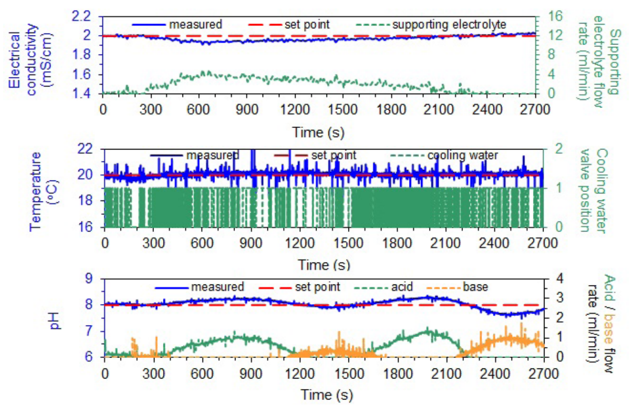
MIMO and SISO GMV electrical conductivity, pH and temperature control results showed that MIMO control of these parameters has a positive effect on individual electrical conductivity and pH controller performances whereas the absolute relative percent changes in ISE and IAE values for an on-off temperature controller is quite insignificant with 2.6% and 6.4% respectively. Results show that MIMO GMV control strategy increased performances of electrical conductivity and pH controllers by 58% and 37% in terms of ISE, 30% and 37% in terms of IAE compared with SISO GMV control strategy, respectively.

A study on random set point trajectories were carried out to evaluate GMV and AGMV coordinated pH controller performances during EC and to examine the robustness of the controllers. 0.5 unit magnitude of positive and negative step changes were applied to pH set point for 4 times during 135 min of treatment. Figs. 10a, b display the variation of pH, set point and manipulated variables with time and performance evaluation results are represented in Table 3. While the results show that both GMV and AGMV controllers successfully control the system, it should be noted that the GMV controller operates with much higher performance and can be used for set point manipulations during process operation.

Controller performances were also compared in terms of pollutant removal and energy consumption. According to the results given in Table 4, MIMO GMV control of the three parameters enhanced COD removal as approximately 5.5% compared with both SISO GMV electrical conductivity and SISO GMV temperature controllers. In addition, the COD removal performance of the MIMO GMV controller is similar to that of the SISO GMV pH controller with 9.85% lower energy consumption. SISO GMV electrical conductivity control had an improving effect of 4.92% on COD removal and a reducing effect by 33.81% on energy consumption when compared with uncontrolled treatment. Similarly, SISO GMV pH control increased COD removal as 9.12% and reduced energy consumption by 30.66% in comparison to treatment without control. It was observed that, COD removal of SISO GMV electrical conductivity controller is 4.2% lower than that of SISO GMV pH controller, energy consumption value was calculated 4.5% lower as well. Besides, SISO GMV temperature control enhanced COD removal as 4.07% and decreased energy consumption by 13.26% compared with uncontrolled treatment. As a result, pH control is found to be the key factor for COD removal improvement in EC processes, while electrical conductivity control reduces energy consumption. It is concluded that

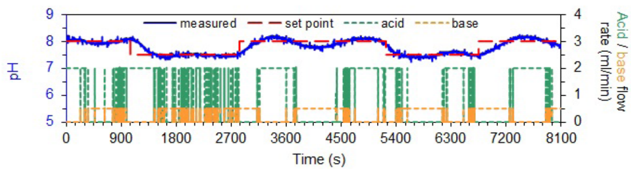


(a)

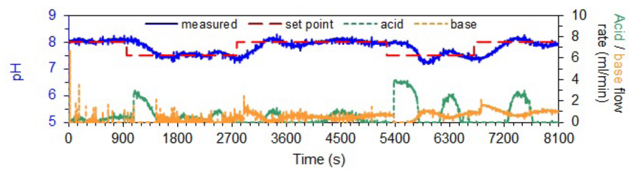


(b)

Fig. 9. (a) MIMO GMV control of electrical conductivity, pH and temperature ($\lambda_{conductivity} = 0.0005$, $\lambda_{pH} = 0.0000001$, $\lambda_{temperature} = 0.00001$) (b) MIMO AGMV control of electrical conductivity and pH (electrical conductivity: P = 5, Q = 1, R = 5, pH: $P_A = 2$, $Q_A = 1$, $R_A = 2$, $P_B = 2$, $Q_B = 0.8$, $R_B = 2$).



(a)



(b)

Fig. 10. Coordinated servo (a) GMV (b) AGMV control of pH.

Table 4
Pollutant removal and energy consumption for controllers

Controller	COD removal (%)	Color removal (%)	Turbidity removal (%)	TSS removal (%)	Energy consumption (kWh/kgCOD)
SISO GMV electrical conductivity	39.50	100	99.27	98.81	84.89
SISO GMV pH	43.70	100	99.61	100	88.93
SISO GMV temperature	38.65	99.62	98.86	100	111.24
MIMO GMV	44.54	98.47	99.65	100	80.17
MIMO AGMV	42.86	97.92	99.24	96.43	93.30

MIMO control of the three operating parameters is necessary in terms of simultaneous pollution removal improvement and energy consumption reduction.

According to the results shown in Table 4, there is a 9.96% increase in COD removal when MIMO GMV controller performance is compared with uncontrolled treatment. There is no significant difference in COD removal in GMV and AGMV controllers. Thus, it can be stated that the increase in COD removal is not directly related to the controller performance, and that process control as an operational action is sufficient to increase the efficiency. It is observed that control action has no enhancing effect on color, turbidity and TSS removal in comparison to uncontrolled treatment since the removal of these pollutants can be achieved with high efficiency in EC method. The lowest energy consumption per kg COD removed was calculated as 80.17 kWh/kg COD and 37.25 kWh/kg COD using constant current power supplies MAY 11-PS and SUNLINE PS 305 D, respectively. Energy consumption per kg COD removed is reduced by 37.49% and 27.25% with GMV and AGMV controllers respectively compared with uncontrolled treatment implying that control action and controller performance have a significant effect on the consumed energy. It was also observed that MIMO GMV controller showed a reducing effect on the energy consumption of the process by the synergy of the pH and electrical conductivity controllers, with a reduction of 4.72 kWh/kg COD when compared to SISO GMV electrical conductivity controller.

Fig. 11 shows the variations in COD and color removal with time for MIMO GMV control. As can be seen from the figure, COD removal was mostly provided within the first 10 min of treatment, whereas color removal did not show any improvement after 14 min.

According to the results, it is observed that online update of the model parameters has a disturbing effect on the controller performance in the EC process. Therefore, the GMV controller is more efficient than the AGMV controller when the controller performances, pollutant removal efficiency and energy consumption values are assessed together.

The result of this work is compared with the previously published studies in Table 5. Aghdam et al. [1] studied the effects of process parameters on the reduction of COD from PPIW by EC and observed a COD removal of 75% at pH 8. Soloman et al. [53] applied EC to PPIW as a pre-treatment method and studied the effects of operating parameters by the application of Box-Behnken experimental design. According to the results, 55% COD removal was reached at pH 8. Shankar et al. [54] investigated the optimum process conditions of PPIW through EC via Central Composite Design (CCD) and obtained 68.5% COD removal at pH 8. Asaithambi [55] examined EC treatment of PPIW by considering the effects of operational variables and experimental results showed that 80% COD removal was achieved at pH 8. Jaafarzadeh et al. [56] investigated the treatability of PPIW by integrated EC and UV/persulfate or UV/peroxymonosulfate method in terms of COD removal. EC studies were carried out by the application of Box-Behnken experimental design and a COD removal of 56% was observed at pH 8. In the present study, 78.09% and 44.54% COD removal based on initial wastewater characteristics (before and after sedimentation, respectively) was achieved using EC treatment with GMV control action at pH 8. The result of this study was found compatible with the above-stated studies in terms of COD removal.

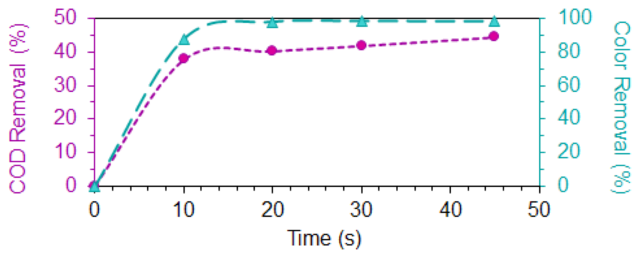


Fig. 11. Variation of COD and color removal with time under MIMO GMV controlled EC treatment.

Table 5
Comparison of results of PPIW treatment with EC at pH 8

Research	Electrode material	Current density	Electrolysis time	COD removal (%)
[1]	Al and Fe	4.167 mA/cm^2	60 min	75
[53]	Fe	112.9 A/m^2	10 min	55
[54]	Al	110 mA/cm^2	60 min	68.5
[55]	Fe	0.40 A/dm^2	120 min	80
[56]	Fe	5 mA/cm^2	45 min	56
This work	Al	5.56 mA/cm^2	45 min	78.09

4. Conclusion

In this study real-time experimental GMV and AGMV control of electrical conductivity, pH and temperature in an EC process for PPIW treatment were carried out successfully. The following conclusions can be drawn from the results.

- Temperature and pH increase with simultaneous electrical conductivity decrease occur during the uncontrolled EC treatment process [57].
- Control study results revealed that control of operating parameters increased COD removal efficiency simultaneously with energy consumption reduction compared with uncontrolled treatment.
- It is determined that control action had no enhancing effect on color, turbidity and TSS removal in comparison to uncontrolled treatment since the removal of these pollutants can be achieved with high efficiency by means of EC.
- According to MIMO and SISO control results, it is observed that MIMO control of operational parameters has a positive effect on individual electrical conductivity and pH controller performances.
- Coordinated GMV and AGMV pH control study with positive and negative step changes to set point were carried out successfully showing the robustness of the controllers.
- GMV controller was found to be more effective than AGMV controller when considering pollutant removal and controller performance results.
- In order to obtain better electrical conductivity and pH control performance, temperature must be kept constant during EC treatment process.
- Electrical conductivity control is the main factor in reducing energy consumption. Gao et al. [58] stated that electrical conductivity decreases during treatment due to chlorine gas formation and causes an increase in electrical resistance.
- Control of pH at 8 as constant set point is the main factor for improvement of the COD removal. Oncel et al. [51] stated that above pH 8, the formation of soluble $Al(OH)_4^-$ which leads to a decline in EC efficiency, will be observed.

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Symbols

A — Monic polynomial in the backward shift operator representing the poles of the discrete-time system
B — Polynomial in the backward shift operator representing the zeros of the discrete-time system
C — Monic polynomial in the backward shift operator representing the zeros of the process noise
$[COD]_0$ — COD value of the influent
$[COD]_t$ — COD value of the effluent
d — Offset
E — Polynomial in GMV control algorithm
$e(t)$ — Noise of the system
F — Polynomial in GMV control algorithm
G — Polynomial in GMV control algorithm
H — Polynomial in GMV control algorithm
I — Current intensity
J — Cost function
k — System delay
n_a — Order of the A polynomial
n_b — Order of the B polynomial
n_c — Order of the C polynomial
P — Filtering actions of system output
Q — Weighting polynomial acting on control input
R — Weighting polynomial acting on set point
$r(t)$ — Set point at time t
t — Duration of treatment
$u(t)$ — Input signal of the system at time t
V_E — Volume of treated wastewater
V_m — Mean potential difference
$y(t)$ — Output signal of the system at time t
z^{-1} — Backward shift operator
— Expectation
λ — Control weighting coefficient
$\Delta u(t)$ — Incremental controller output signal
$\varphi(t+k)$ — Pseudo system output

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