Integrated Electroplating System Modeling and Simulation for Near Zero Discharge of Chemicals and Metals

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The optimality of design and operation of an electroplating system determines largely coating quality, productivity, and waste reduction efficiency. Industrial practice shows that, in a usual operation, the solution loss from an electroplating unit through drag-out can be as high as 30% of overall consumption. This has dramatically increased operating cost as well as waste treatment cost. On the other hand, plating quality in terms of coating thickness on workpieces is always a concern in plants. To improve the economic and environmental performance, a key step is to have a deep understanding of the system. Model-based simulation has proven to be a cost-effective approach along this venue. This paper introduces a fundamental-based general modeling methodology for characterizing an integrated electroplating system that consists of a plating unit and a solution recovery subsystem. The methodology allows detailed system analysis and complete process information integration, which will be crucial for optimal design and operation of a closed-loop electroplating for prevention of plating solution loss and assurance of coating thickness on workpieces. A case study on an alkaline zinc electroplating system will demonstrate the efficacy of the model-based design and operation approach.

Introduction

Virtually all manufacturing of precious metal products involves electroplating. In the nation, there are over 8000 electroplating plants that provide numerous types of plated parts to the electronics, automotive, aerospace, and other manufacturing industries.1,2 These plants have been generating huge amounts of waste in the forms of wastewater, sludge, and spent solutions.3,4 The waste usually contains over 100 chemical, metal, and nonmetal contaminants.5,6 A continuous generation of these wastes has led the industry to the second most regulated one in the nation.2,7,8

A usual electroplating line consists of different types of cleaning, many steps of rinsing, and a core operation of electroplating. In an electroplating unit, a selected type of metal is electrochemically deposited onto the surface of workpieces. In operation, the workpieces, loaded either in barrels or on racks, are immersed in the electrolyte. The metal deposition thickness, a key indicator of plating quality, is largely determined by electrolyte composition, current density, and plating time.9,10 It is known that the workpiece rejection rate due to coating thickness problems is frequently above 5% in usual production. The rework of the rejected workpieces may involve costly stripping and replating. In addition to the quality issue, plating solution loss in operation is a very serious problem. Industrial practice has shown that the loss through drag-out can be commonly as high as 30% of overall consumption.11 In a case study on a zinc acid plating line with the production rate of 11 barrels per hour (220 lbs of workpieces per barrel), the solution loss was about 104 000 gallons per year, on a basis of 300 production days per year.12 The lost solutions usually enter wastewater streams from relevant rinse units. Note that plating solution contains a number of valuable chemicals and metals, and the treatment of the wastewater stream containing those chemicals and metals is always very expensive. Thus, the prevention of solution loss into wastewater is of great economic and environmental significance.13–15

The reduction of chemical/metal loss through drag-out from plating units has drawn great attention over the past two decades.2,16 Various drag-out reduction approaches have been practiced in plants, such as the use of a longer drainage time, a higher solution temperature, a lower surface tension, and an improvement of barrel design.6,11 However, the exact relationships of these parameters with plating quality and solution reduction are unknown.17–19 In addition to drag-out reduction, a reversed-drag-out technique was introduced a decade ago.11 By this technique, the rinse unit is immediately pumped back to the plating unit. While this technique sounds attractive, the system design and operation are only experience based. There are various technical difficulties yet to overcome, which are related to the effectiveness of solution loss reduction and the assurance of plating quality. As such, this technique has not been well adopted in plants.20

This paper introduces a general integrated system modeling methodology for characterizing the dynamic behavior of a closed-loop plating—rinsing system that can recover very effectively the lost chemical/metal-containing solution from the plating unit due to drag-
Freshwater is periodically fed into the rinse unit and uses periodic water adding in a cascade mode. That is, each rinse unit in the system must be equal to the amount evaporated in the plating unit. The plated workpieces then return to the rinse tanks is negligible. Thus, energy balance is not considered.

**General System Modeling**

As an IES consists of two entirely different subsystems, the modeling methods will be presented as two separate efforts. The construction of an integrated model will be presented according to system configuration.

**Electroplating Subsystem (EPS) Modeling.** In an electroplating unit, a direct electric current passes through the solution so that chemical reactions take place. This will lead to the deposition of a thin layer of metal on the negative electrode (cathode, which is always workpieces to be plated). Note that the positive electrode (anode) can be either a metal, possibly impure, that is dissolved through chemical reactions into the solution in operation or a material that is not dissolved but is for the passage of the current, acting as an “inert” anode. A number of first-principles-based modeling methods have been introduced for characterizing various types of metal plating systems, the modeling methods will be presented as two separate efforts. The construction of an integrated model must consist of two types of submodels: the one for characterizing solution composition and the one for describing metal deposition on workpieces.

**Chemical/Metal Dynamics.** Figure 2 illustrates a general plating unit where system component balance related factors are depicted: (i) chemical reaction related, (ii) recovered solution related, (iii) solution drag-out related, and (iv) solution drag-out related. Note that chemical/metal loss through evaporation can be safely omitted, as the evaporation contains almost all water. With these analyses, a general chemical dynamics model can be structured as follows:

\[
\frac{dC_j^E(t)}{dt} = f_j(R_a(t),R_c(t)) A_{p_j} \left( U(t - t_{is}^E) - U(t - t_{is}) \right) - P \sum_{k=1}^{N} (U(t - t_{is}^E) - U(t - t_{is}^E)) \]

where

1. **Drag-in**
2. **Reaction**
3. **Recovery-in**
4. **Drag-out**
5. **Evaporation**
where $C^R_j(t)$ is the concentration of component $j$ in the plating unit, mol/L; $C^{fr}_j(t)$ the concentration of component $j$ in the $k$th rinse unit, mol/L; $f_j(R_{al}(t), R_c(t))$ the reaction rate function of component $j$, mol/C; $R_{al}(t)$ the anode current efficiency; $R_c(t)$ the current efficiency of the cathode; $V^E$ the volume capacity of electroplating unit, L; $A_p$ the total surface area of the workpieces, m$^2$; $i$ the current density, A/m$^2$; $j$ the component species index; $k$ the rinse unit index; $F_r$ the flow rate of recovery, L/min; $D$ the flow rate of drag-in or drag-out, L/min; $y^k$ the binary variable; $U(t - t_{os})$ the unit step function occurred at the time instant, $t_{ri}$, $t_{ini,os}$ the starting time of the initial drag-out from the $k$th rinse unit, respectively; $t_{tie}$, $t_{toe}$ the starting and ending time of drag-in to the plating unit, respectively; $t_{tie}$, $t_{toe}$ the starting and ending time of drag-out from the plating unit, respectively, min; and $N$ the number of rinse units.

Note that $y^k$ is a binary variable for rinse unit $R_k$ (equal to 1 if $R_k$ is selected for rinse before plating; 0 otherwise). Since only one rinse unit can be designed for rinse before plating (see Figure 1b), the following constraint should be satisfied:

$$\sum_{k=1}^{N} y^k = 1 \quad (2)$$

Equation 1 contains a number of pulse functions in the form of $U(t - t_{os}) - U(t - t_{os})$ (with magnitude of 1 in the time period between $t_{os}$ and $t_{oi}$, or 0 otherwise). Thus, a phenomenon occurring only in a specific time interval can be expressed by the product of a function describing the phenomenon and the pulse function for the specific time interval. For instance, the last term on the right-hand side of eq 1 indicates that the drag-out, $D$, lasts in the time interval between $t_{tie}$ and $t_{toe}$ only. Also note that in eq 1 the reaction rate function, $f_j(R_{al}(t), R_c(t))$, is always nonlinear and is determined by the current efficiencies of the anode and the cathode, $R_{al}(t)$ and $R_c(t)$, and the chemical/metal species involved in the reactions.

**Solution Recovery Subsystem (SRS) Modeling.**

The lost solution from the EPS is recovered in the SRS, which is essentially a multistep rinse system as depicted in Figure 1b. A general SRS model can be developed on the basis of the models for each rinse unit. The rinse units can be functionally classified into two types: one for rinsing after plating only and the other for rinsing both before and after plating. Figure 3 illustrates the two types where chemical/metal flows in each are plotted. Note that evaporation of chemicals/metal in each rinse unit can be safely neglected, particularly due to the rinse water at room temperature. In any case, the component balance is determined by the recovered solution into and out of the unit and the amounts of drag-in and drag-out. If the unit is used also for rinse before plating, then that drag-in and drag-out should all be counted. Therefore, a general dynamics model for a rinse unit can be formulated as follows.

$$\frac{dC^R_j(t)}{dt} = F_j(C^R_j(t) - C^E_j(t)) + DC^fr_j(U(t - t_{ri}^{R_k}) - U(t - t_{os}^{R_k})), \quad (3)$$

$$C^R_j(t) = C^E_j(t) \quad (4)$$

$$C^R_j(t) + C^fr_j = 0 \quad (5)$$

where $V^R$ is the capacity of each rinse unit, L; $D$ the flow rate of drag-in to the $k$th rinse unit, respectively, min; $t_{ri}$, $t_{os}$ the starting and ending time of the drag-in to the $k$th rinse unit, respectively, min; and $t_{ini,os}$ the starting and ending time of the drag-out from the $k$th rinse unit, min.

Equation 4 suggests that the drag-in solution to $R_1$ is actually from plating unit $E$, while eq 5 means that the solution flowing into $R_1$ comes from the freshwater that is usually chemicals/metals free. The unit-based model in eq 3 can be used to construct a system model for a SRS that may contain any number of rinse units. The general IES modeling is an extension of the existing rinse system modeling work by Zhou et al.,26,27 where no plating solution is involved and each rinse unit is only for the rinse either before or after plating, but not both.

**Modeling of an Alkali Zinc Plating System.**

Alkaline zinc plating has been widely used to deposit a thin layer of zinc metal on numerous types of workpieces. The IES modeling method is used to study this particular type of plating system for solution recovery. It is to show how the information generated from the integrated model can help design and operate a most effective IES or, more specifically, determine a system configuration and develop operational strategies so that the solution lost from the plating unit can be recovered to the maximum extent, while the plating quality can be ensured. The IES exemplified here is the one with a plating unit $E$ and three rinse units: $R_1$ for both pre- and postplating rinse and $R_2$ and $R_3$ for postplating rinse. Figure 4 provides a processing procedure of the workpieces either in barrel or on rack for this IES. It shows that for any barrel or rack of workpieces it is rinsed in $R_1$ first and then plated in $E$. After plating, it is rinsed in $R_1$, $R_2$, and $R_3$ in sequence. The time instants for each operation are defined in the figure. For instance, the duration between $t_{init}^{fr}$ and $t_{oe}^{fr}$ is the plating
time, and the duration between \( t_{i}^{E} \) and \( t_{i}^{E:1} \) is the time for moving the workpieces from plating unit \( E \) to rinse unit \( R_{1} \).

**Electrochemical Reactions and Plating System Modeling.** Figure 5 gives a sketch of an alkaline zinc plating unit, where the reactions take place around the electrodes, with the main ones as follows:28–31

**anode reactions:**

\[
\text{Zn} + 4\text{OH}^{-} \rightarrow \text{Zn(OH)}_{4}^{2-} + 2e^{-} \quad (6)
\]

\[
2\text{OH}^{-} \rightarrow \frac{1}{2}\text{O}_2 + \text{H}_2\text{O} + 2e^{-} \quad (7)
\]

**cathode reactions:**

\[
\text{Zn(OH)}_{4}^{2-} + 2e^{-} \rightarrow \text{Zn} + 4\text{OH}^{-} \quad (8)
\]

\[
2\text{H}_2\text{O} + 2e^{-} \rightarrow \text{H}_2 + 2\text{OH}^{-} \quad (9)
\]

The above electrochemistry shows that there is a net depletion of zinc and an evolution of oxygen at the anode and an evolution of hydrogen and a net depletion of water at the cathode. When a substantial external current goes through the plating solution, zinc will be continuously dissolved into the electrolyte from the anode. Meanwhile, an almost equivalent amount of zinc will leave the solution and be deposited on the cathode. Note that the combined effects of the electrode reactions and electrolyte ion migration result in composition change of electrolyte in different scales. At the local scale, the regions surrounding the anode and the cathode and the central region (solution) have complex chemical/metal concentration distributions. Process modeling in this work focuses on the distributions at the global scale.

**Electrolyte Concentration.** The concentrations of chemicals/metal in the plating unit are determined by the rate of dissolution at the anode and the rate of deposition at the cathode, as well as those dragged into and out of the plating unit. It is assumed that the solution in the plating unit has a perfect mixing. The dynamics of dissolved zinc in the plating unit can be described as

\[
\rho \frac{dC_{Zn}^{E}(t)}{dt} = \frac{(R_a(t) - R_c(t))}{2F} A_{pl} j(U(t - t_{i}^{E}) - U(t - t_{i}^{E:1})) + F C_{NaOH}(t) + DC_{NaOH}(t_{i}^{E}) U(t - t_{i}^{E}) - U(t - t_{i}^{E:1})) - DC_{NaOH}(t_{i}^{E}) U(t - t_{i}^{E}) - U(t - t_{i}^{E:1})) \quad (10)
\]

where \( C_{Zn}^{E}(t) \) is the concentration of \( \text{Zn}^{2+} \) in plating unit \( E \), mol/L, and \( F \) is Faraday’s constant (96 485 C/mol).

Note that caustic is also consumed during the reaction. On the basis of the cathode and anode reactions in (6) through (9), the dynamics of its concentration can be described by a similar model structure to that for zinc.

\[
\rho \frac{dC_{NaOH}^{E}(t)}{dt} = \frac{(1 + R_a(t) - 2R_c(t))}{F} A_{pl} j(U(t - t_{i}^{E}) - U(t - t_{i}^{E:1})) + F C_{NaOH}(t) + DC_{NaOH}(t_{i}^{E}) U(t - t_{i}^{E}) - U(t - t_{i}^{E:1})) - DC_{NaOH}(t_{i}^{E}) U(t - t_{i}^{E}) - U(t - t_{i}^{E:1})) \quad (11)
\]

where \( C_{NaOH}^{E}(t) \) is the concentration of \( \text{NaOH} \) in plating unit \( E \), mol/L.

Note that \( \text{Na}_2\text{CO}_3 \) is not involved in reactions 6–9. The dynamics of the concentration of this component can be described as follows:

\[
\rho \frac{dC_{Na_2CO_3}^{E}(t)}{dt} = F C_{Na_2CO_3}(t) + DC_{Na_2CO_3}(t_{i}^{E}) U(t - t_{i}^{E}) - U(t - t_{i}^{E:1})) - DC_{Na_2CO_3}(t_{i}^{E}) U(t - t_{i}^{E}) - U(t - t_{i}^{E:1})) \quad (12)
\]

where \( C_{Na_2CO_3}^{E}(t) \) is the concentration of \( \text{Na}_2\text{CO}_3 \) in plating unit \( E \), mol/L.

The current efficiencies, \( R_c(t) \) and \( R_a(t) \), are largely determined by electrolyte compositions. Wery et al. identified a regression expression as follows:30

\[
R_c(t) = 0.927 + 0.037C_{Zn}^{E}(t) - 0.031C_{NaOH}^{E}(t) - 1.3C_{Na_2CO_3}(t) + 3.4C_{Zn}^{E}(t)C_{Na_2CO_3}(t) - 2.0C_{NaOH}^{E}C_{Na_2CO_3}(t) + 1.4C_{Zn}^{E}C_{NaOH}^{E}C_{Na_2CO_3}(t) \quad (13)
\]

This expression is restricted to a certain concentration range of each component in the plating unit. Table 1 gives the lower and upper boundaries, \( C_{ih} \) and \( C_{ub} \),
respectively, of these components. A simple way for deriving \( R_s(t) \) can be as follows:

\[
R_s(t) = (1 + \alpha) R_c(t) \tag{14}
\]

where \( \alpha \) is a constant.

**Thickness Dynamic Model.** According to Faraday's law, zinc deposition dynamics can be obtained as follows:

\[
\frac{dm(t)}{dQ} = \frac{R(t)M}{2F} \tag{15}
\]

where \( m(t) \) is the mass of zinc deposited on the cathode, \( kg; \) \( M \) the molecular weight of zinc, \( kg/mol; \) and \( Q \) the amount of charge, \( C. \) Note that

\[
dQ = A_j \ dt \tag{16}
\]

If the zinc deposition is assumed uniform on the workpiece surfaces during plating, a simplified zinc thickness dynamic model is derived:

\[
\frac{d\theta(t)}{dt} = \left( \frac{R(t)M}{2F \rho} \right) \tag{17}
\]

where \( \theta(t) \) is the deposit thickness, \( m; \) and \( \rho \) is the zinc density, \( kg/m^3. \) It is worth noting that earlier studies provided the relationship of plating thickness vs operating parameters in the stand-alone electroplating tank. However, there is no integrated dynamic model to exploit the intrinsic relationship between plating and rinsing. Hitherto, plating solution loss reduction is only based on experience, and it is far from optimal.

**Modeling for Solution Recovery.** In operation, the workpieces in barrel or on rack are first dipped in rinse unit \( R_1 \) and then loaded into plating unit \( E. \) After plating, the workpieces are rinsed in rinse units \( R_1, R_2, \) and \( R_3 \) in sequence. In this subsystem, freshwater is fed into rinse unit \( R_3, \) with the amount of \( F_r \) equal to the potential accumulation of salts from municipal water, deionized water is recommended. The amount of rinse water same as that of freshwater is pumped from \( R_3 \) to \( R_2, \) from \( R_2 \) to \( R_1, \) and finally from \( R_1 \) to \( E. \) This is a three-step solution recovery mechanism that is operated periodically. The model for each rinse step is as follows.

unit \( R_3: \)

\[
\nu \frac{dC_{R_3}(t)}{dt} = F_r(C_j(t) - C_{R_3}(t)) + DC_{R_3}(t) \left( U(t - t_{R_3}^{tie} - U(t - t_{R_3}^{tie}) - D(t_{R_3}^{tie} - U(t - t_{R_3}^{tie}))) \right) \tag{18}
\]

unit \( R_2: \)

\[
\nu \frac{dC_{R_2}(t)}{dt} = F_r(C_j(t) - C_{R_2}(t)) + DC_{R_2}(t) \left( U(t - t_{R_2}^{tie} - U(t - t_{R_2}^{tie}) - D(t_{R_2}^{tie} - U(t - t_{R_2}^{tie}))) \right) \tag{19}
\]

unit \( R_1: \)

\[
\nu \frac{dC_{R_1}(t)}{dt} = F_r(C_j(t) - C_{R_1}(t)) + DC_{R_1}(t) \left( U(t - t_{R_1}^{tie} - U(t - t_{R_1}^{tie}) - D(t_{R_1}^{tie} - U(t - t_{R_1}^{tie}))) \right) \tag{20}
\]

where subscript \( j \) is designated for Zn\(^2+\), NaOH, and Na\(_2\)CO\(_3\).

**System Model.** The IES model for this particular plating system consists of eqs 10–14 and eqs 17–20. Since there are three components in each rinse unit, the alkali zinc plating system model contains a total of 15 equations. The system model can be used to describe the dynamic behavior of electrodeposition and chemical/metal concentration changes in the plating and rinse units for the production of any number of barrels or racks of workpieces.

**System Simulation and Analysis.** A main focus of the model-based simulation is to demonstrate the ability of an IES for near zero discharge of chemicals and metals as compared to the traditional design. To facilitate identification of an optimal IES design, different design and operational strategies need to be studied in detail. The study is also expected to generate general guidelines for design and operation of the most effective IES for solution recovery and coating quality control in electroplating systems.

**Parameter Setting.** In the dynamic simulation, initial conditions, such as component compositions, are set to the nominal values. Table 1 lists those for the initial conditions for the three rinse units. A suggested method is to calculate them based on the mass balance of units \( R_1, R_2, \) and \( R_3 \) at steady state, such as follows.

for unit \( R_1: \)

\[
2p_{D_1}^{R_1}C_{j,0}^{R_1} + F_rTC_{j,0}^{R_1} = p_{D_1}^{R_1}C_{j,0}^{E} + F_rTC_{j,0}^{R_2} \tag{21}
\]

for unit \( R_2: \)

\[
F_{D_1}^{R_2}C_{j,0}^{R_2} + F_rTC_{j,0}^{R_2} = F_rC_{j,0}^{R_3} + F_rTC_{j,0}^{R_3} \tag{22}
\]

for unit \( R_3: \)

\[
F_{r}C_{j,0}^{R_3} + F_rTC_{j,0}^{R_3} = F_{D_1}^{R_3}C_{j,0}^{R_2} \tag{23}
\]

where

\[
F_{r}D_{i} = D(U(t - t_{o_3}^{tie}) - U(t - t_{o_3}^{tie})) = D(t_{o_3}^{tie} - t_{o_3}^{tie}) \tag{24}
\]

\[
F_{r}D_{i} = D(U(t - t_{i_3}^{tie}) - U(t - t_{i_3}^{tie})) = D(t_{i_3}^{tie} - t_{o_3}^{tie}) \tag{25}
\]

For simplicity, reasonable assumptions can be made as follows:

\[
\Delta t_{D} = t_{i_3}^{tie} - t_{o_3}^{tie} = t_{i_3}^{tie} - t_{o_3}^{tie} \tag{26}
\]

\[
F_{D} = F_{D_1}^{R_3} \tag{27}
\]
Solving eqs 21–27 gives

\[ C_{j,0}^{R1} = \frac{F_D C_{j,0}^{E}}{2F_D + F_rT - \frac{F_D F_rT}{F_D + F_rT}} \]  

(28)

\[ C_{j,0}^{R2} = \frac{F_D C_{j,0}^{R1}}{F_D + F_rT - \frac{F_D F_rT}{F_D + F_rT}} \]  

(29)

\[ C_{j,0}^{R3} = \frac{F_D C_{j,0}^{R2}}{F_D + F_rT} \]  

(30)

When \( C_{j,0}^{E} \) is given, \( C_{j,0}^{R1} \), \( C_{j,0}^{R2} \), and \( C_{j,0}^{R3} \) can be determined uniquely. Table 1 shows the calculated initial values for the three rinse units.

**Simulation-Based Design Comparison.** The comparison is conducted through simulating four designs: a traditional design (with three rinse tanks) and the IES’s with three rinse units (design A), two rinse units (design B), and one rinse unit (design C). For all the four designs, the total flow rinse time is fixed for 2 min so that the production rates are the same. Each system runs for processing 120 barrels of workpieces, and the production periods are the same. The operational parameters other than the rinsing time assignments are the same for all the designs (see Table 2, part A). In addition, it is assumed that the volume of drag-out solution from the plating unit is 2 L per barrel.

**Comparison of Design A with the Traditional Design.** Design A has been extensively simulated. As shown in Figure 6a–c, the concentration of \( \text{Zn}^{2+} \) is increased nearly linearly from 0.21 to 0.232 mol/L, while the concentrations of \( \text{NaOH} \) and \( \text{Na}_2\text{CO}_3 \) are decreased gradually from 3.251 and 0.280 mol/L to 3.21 and 0.277 mol/L, respectively. Note that all these three curves are not smooth; this is because every time when a barrel is loaded into unit \( E \), the drag-in solution from unit \( R_1 \) has the concentrations of all three components much lower than those in unit \( E \), which dilutes the plating solution initially. When each barrel leaves unit \( E \), the component concentration is increased to a certain level. This situation repeats for every barrel of processing. As to the final coating thickness of the workpieces in 120 barrels, it is maintained almost the same (12.0 \( \mu \)m), which indicates excellent plating quality (see Figure 6d).

In the rinse units, it is expected that the concentration of each component be decreased. These general trends are confirmed in Figures 7–9, except for Figure 7a. In Figure 7a, the \( \text{Zn}^{2+} \) concentration is decreased initially, and at around the 5000th minute, the concentration moves back slowly. This indicates that the initial \( \text{Zn}^{2+} \) concentration set for simulation is too high. The simulation also shows that each rinse step can significantly reduce the concentration of each component. For instance, at the time instant of the 5000th minute, the concentrations for \( \text{Zn}^{2+} \), \( \text{NaOH} \), and \( \text{Na}_2\text{CO}_3 \) are about 0.0298, 0.448, and 0.0386 mol/L, respectively, in unit \( R_1 \). In unit \( R_2 \), these concentrations are reduced to

Table 2. Simulation Related Parameters

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<th>( F_r )</th>
<th>( D )</th>
<th>( V^E )</th>
<th>( V^R )</th>
<th>( i )</th>
<th>( M )</th>
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![Figure 6. Dynamics of electroplating unit E in design A.](image)

![Figure 7. Dynamics of rinse unit R1 in design A.](image)
0.00543, 0.0834, and 0.0072 mol/L, respectively. In unit $R_3$, these concentrations are further reduced to 0.000 841, 0.0130, and 0.001 12 mol/L, respectively. All these indicate that each rinse step can reduce the concentration of each component by 81–85%. Almost equivalently, the chemical and metal loss after each rise step is reduced by 81–85%.

The traditional design is also simulated on the same basis as design A. Table 3 (columns 3 and 4) lists the chemical/metal loss and recovery data for the two designs. As shown, the recoveries of $\text{Zn}^{2+}$, $\text{NaOH}$, and $\text{Na}_2\text{CO}_3$ by design A are at least 99.5%. Obviously, design A has demonstrated the capability of near zero discharge of chemicals and metals.

Further Study. While design A gives superior performance for chemical/metal recovery, a simplified IES (with a reduced number of rinse units) can also provide very impressive results. In this study, design B (with two static rinse units) and design C (with one static rinse unit) are simulated. The processing parameter values for the traditional design and design A shown in Table 2 are also used for designs B and C. Table 2 also lists the unit processing times for each of these two new designs.

The system model for designs B is the same as that for design A, except for excluding eq 20, while the model for design C should exclude eqs 19 and 20. The model-based simulation results have been listed in Table 3 (columns 5 and 6). It shows that the chemical/metal loss by designs B and C can be reduced by at least 97.6% and 86.2%, respectively, regardless of the types of chemicals and metals. Although the chemical and metal recovery efficiency of either of these designs is not as impressive as design A, the capital cost for the SRS can be reduced by 33.3% (design B) or 66.5% (design C).

Figure 10 summarizes the general trend for chemical/metal loss of an IES with the increasing number of rinse units.

In these simulations, a Runge–Kutta method\textsuperscript{21} was proven efficient. If an IES is more complicated, e.g., if the reactions in the electrolyte are very complicated, then some other numerical methods might be deployed.\textsuperscript{32,33}

General Guidelines. With the case studies shown above, several general conclusions can be made as follows:

(a) The design of the SRS of an IES with three rinse units after plating should be preferred since it can gives a truly near zero discharge of valuable plating solutions, if the physical accommodation of these units, associated with their cost, is not an issue.

(b) An SRS with more than three rinse units is not recommended for two reasons: (i) the gain for further reduction of chemical/metal loss becomes negligible, (ii) it is usually not practical to expect any plant to have the space to accommodate four rinse units after plating, and (iii) it becomes very difficult for production scheduling.

<table>
<thead>
<tr>
<th>component</th>
<th>solution loss and recovery</th>
<th>traditional design</th>
<th>design A</th>
<th>design B</th>
<th>design C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Zn}^{2+}$</td>
<td>loss (mol/barrel)</td>
<td>0.446</td>
<td>0.0017</td>
<td>0.0094</td>
<td>0.053</td>
</tr>
<tr>
<td></td>
<td>recovery (%)</td>
<td>99.6</td>
<td>97.9</td>
<td>97.9</td>
<td>88.1</td>
</tr>
<tr>
<td>$\text{NaOH}$</td>
<td>loss (mol/barrel)</td>
<td>6.49</td>
<td>0.026</td>
<td>0.13</td>
<td>0.81</td>
</tr>
<tr>
<td></td>
<td>recovery (%)</td>
<td>99.6</td>
<td>97.9</td>
<td>97.9</td>
<td>87.5</td>
</tr>
<tr>
<td>$\text{Na}_2\text{CO}_3$</td>
<td>loss (mol/barrel)</td>
<td>0.507</td>
<td>0.0023</td>
<td>0.012</td>
<td>0.070</td>
</tr>
<tr>
<td></td>
<td>recovery (%)</td>
<td>99.5</td>
<td>97.6</td>
<td>97.6</td>
<td>86.2</td>
</tr>
</tbody>
</table>

Note: (1) Results are based on the production of 120 barrels of parts. (2) The cycle time is 55.6 min for each design. (3) The recovery percentage is based on the traditional design.
(c) In any case, the commonly used electroplating system with flow rinse after plating should be replaced by an IES. As shown, an IES with only one rinse unit can still recover at least 80% of the solution otherwise to be lost into the wastewater system. As we all know, to treat wastewater stream with high chemical/metal concentration is always expensive, and if the recovery of those chemicals and metals from the wastewater is required, then additional economic burden will be even more expensive.

Concluding Remarks

Chemical and metal loss in electroplating systems is always significant, which has caused tremendous profit loss and environmental burden. This paper has introduced a general modeling methodology for characterizing dynamically the operations of electroplating and rinsing. The modeling methodology plays a key role in developing an integrated electroplating system (IES) that consists of an electroplating subsystem (EPS) and a solution recovery subsystem (SRS). Extensive model-based simulations have clearly demonstrated that the integrated IES modeling method can greatly help identify an economically and environmentally highly desirable system design and operational strategy. This modeling and simulation methodology is general and can be employed for any type of electroplating system.

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Literature Cited


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