Devise of a W Serpentine Shape Tube Heat Exchanger in a Hard Chromium Electroplating Process

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Abstract

In a hard chromium electroplating process, a heat exchanger is employed to remove the heat produced from the high current intensity in an electroplating bath. Normally, a conventional U shape heat exchanger is installed in the bath but it provides low heat removal. Thus, this study designs a novel W serpentine shape heat exchanger with identical heat transfer area to the conventional one for increasing heat removal performance. The performance of the heat exchange is tested with various flow velocities in a cross-section in range of 1.6 to 2.4 $m \cdot s^{-1}$. Mathematical models of this process have been formulated in order to simulate and evaluate the heat exchanger performance. The results show that the developed models give a good prediction of the plating solution and cooling water temperature and the novel heat exchanger provides better results at any flow velocity. In addition, the W serpentine shape heat exchanger has been implemented in a real hard chromium electroplating plant. Actual data collected have shown that the new design gives higher heat removal performance compared with the U shape heat exchanger with identical heat transfer area; it removes more heat out of the process than the conventional one of about 23%.

Keyword: W serpentine shape; Hard chromium electroplating; Mathematical modeling; Simulation; Heat exchanger.

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1. Introduction

A hard chromium electroplating process is one kind of chromium electroplating. This process is usually applied for protecting the surface of base materials against a harmful environment, extending the maintenance time and increasing the material properties *i.e.* corrosive resistance, wear resistance and shear stress [1, 2]. In the hard chromium electroplating process, the workpieces such as pistons, rollers, gaskets, vehicle molds and electrical parts, etc. are coated with the chromium metal from 2.5 to 500 μm in thickness [3]. Generally, the performance of this plating and the probability of defect occurrence on coated products are depended on the operating conditions during the plating period such as the concentration of plating solution, current density, power voltage and temperature [4, 5]. To provide the best quality of the coated products, the optimal range for the hard chromium electroplating is in range of (50 ± 3) °C [5, 6]. All unit operations in the hard chromium electroplating process are shown in Fig. 1. This process comprises of an electroplating bath with an immersed tube heat exchanger that is also connected to a cooling tower. The cooling water is a media to deliver the heat from the bath and to cool the plating solution through the heat exchanger. When the cooling water temperature is high after flowing through the electroplating bath, the cooling tower takes away the heat and supplies the low temperature cooling water to the bath again.

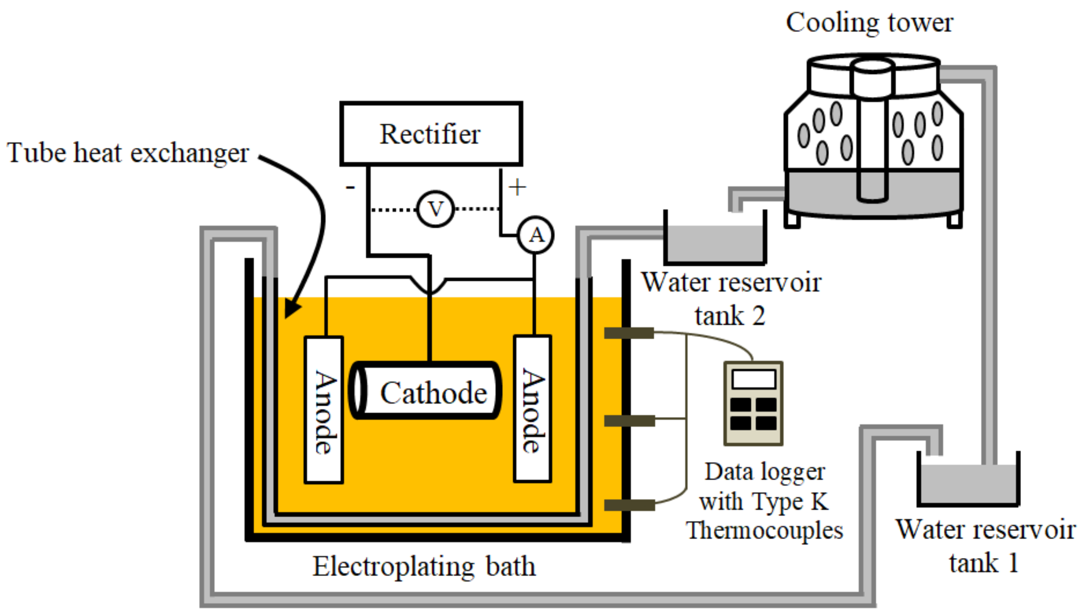


Fig. 1 Hard chromium electroplating process with the cooling system.

However, the main factor affected on the product quality is the temperature of the plating solution during the operation. Due to the fact that the plating solution temperature is continually raised by the heat produced from the high current load during the plating time, then the accumulated heat of plating solution can cause the defects on the surface of products. When this problem takes place, the defected products are recoating again [7]. Since this high temperature problem is normally found in the hard chromium electroplating plant, an effective heat exchanger is needed to keep the plating solution temperature in the optimal range around 47 to 53 °C along the plating period [8].

In general, a conventional U shape tube heat exchanger is installed at the wall of the electroplating bath. This pipe is made of the titanium to protect against the corrosion from the chromic acid. Normally, the U shape tube heat exchanger in the bath is placed in parallel with the direction of heat flow which directly affects to heat transfer coefficient [9]. Then, it leads to the thermal resistance film that reduces the heat transfer between two fluids, at the outer surface of the tube [10]. In order to improve the heat transfer coefficient of the tube heat exchanger, piping patterns or shape of heat exchangers reported by recent literatures such as a spiral corrugated tube [11, 12], a curved tube [13, 14], an inserted triangle coil tube [15, 16] and a vibrating tube [17, 18] have been studied. To evaluate the performance of the heat exchanger, mathematical models of the process and heat exchangers are also developed.

The objective of this work is to devise a novel heat exchanger for the hard chromium electroplating process to improve the heat transfer coefficient. In addition, the mathematical models of the hard chromium electroplating process and the heat exchangers have been developed and validated with the actual data. The developed models have been used to study the temperature profile and the heat removal performance of the conventional U shape and the novel design heat exchangers. Finally, the novel design heat exchanger has been implemented in the bath and its performance has been evaluated.

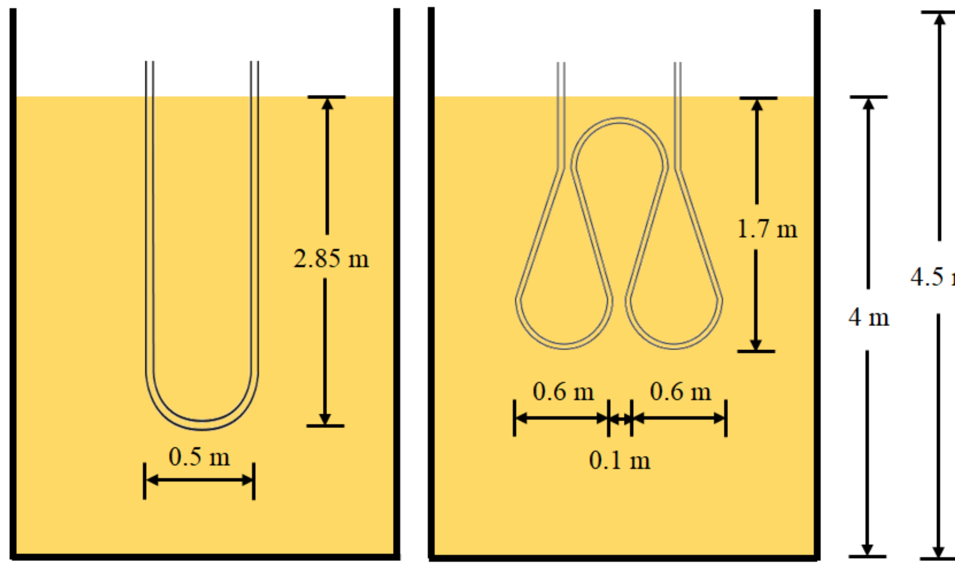
2. Methods

2.1 Process overview

A hard chromium electroplating process in this study consists of an electroplating bath (1.7 m diameter and 4.5 m height), a tube heat exchanger, two reservoir tanks of cooling water and a cooling tower as shown in Fig.1. In this process, the height of plating solution is 4 m from the bottom of the bath and the objects to be plated are connected with the rectifier and are submerged into the plating solution. The conventional U shape tube heat exchanger (2.54 cm diameter and 30 m in total length) with cooling water as the medium is installed inside the bath for removing any heat generated from the electrical current. Then, the high temperature cooling water from all electroplating baths collected at the first water reservoir tank are fed into the cooling tower in order to cool down its temperature to about 34 °C. After that, the cooling water is recirculated to the electroplating bath again. Some amounts of cooling water are loss from the drag out, wind and evaporation at the reservoir tanks and the cooling tower. In order to collect the data from the real plant, a data logger connected with Type K Thermocouples is used for this purpose. Three thermocouples are placed at 1 m, 2 m and 3.5 m from the plating solution surface in order to observe the temperatures in the bath during 8 hours of the operation and the plating bath temperatures can be collected and used to validate the mathematical models of the bath.

2.2 Devise of the W serpentine shape tube heat exchanger

The novel heat exchanger of this work is devised with a pattern of W serpentine shape [Fig. 2(b)]. This new design attempts to prevent the thermal resistance film formulation by introducing inclined and curve shapes that give the unparalleled flow direction of the cooling water and the plating solution. Thus, the W shape heat exchanger has less the thermal resistance film formulation at the outer tube surface resulting in more heat transfer rate than the original one. In addition, the curve design of the W shape induces the secondary flow of the cooling water inside the tube [19, 20] that enhances the heat transfer rate between the plating solution and the cooling water [21, 22]. Titanium is chosen as the piping material for this novel heat exchanger. In this study, the W serpentine shape heat exchangers with 1.27 and 2.54 cm diameter, which have the identical heat transfer area as to the U shape heat exchanger, are designed to compare the performance. Furthermore, the heat exchangers are tested with various flow velocities in a cross-section at 1.6, 2.0 and 2.4 $m \cdot s^{-1}$ for evaluating its performance. In order to obtain the same flow velocity in each heat exchanger, the volumetric water flow rates at 1.55×10^{-4}, 1.94×10^{-4} and 2.32×10^{-4} $m^3 \cdot s^{-1}$ are used for the 1.27 cm diameter heat exchanger and the volumetric water flow rates at 7.12×10^{-4}, 8.9×10^{-4} and 10.68×10^{-4} $m^3 \cdot s^{-1}$ are used for the 2.54 cm diameter heat exchanger.



(a) (b)

Fig. 2 Illustration of the heat exchangers inside the hard chromium electroplating bath: (a) U shape heat exchanger and (b) W serpentine shape heat exchanger.

2.3 Assumptions

To derive the equations for the hard chromium electroplating process, the following assumptions are made as follows,

- The variation of the plating solution concentration is negligible.
- The physical and chemical properties of the plating solution such as density or heat capacity are constant along the plating period.
- The electroplating bath is well-mixed.
- The heat generated from electroplating current load is remarkably significant compared to heat released from chemical reactions.
- Heat loss of the cooling water in the heat exchanger outside the bath to the surrounding is negligible.

2.4 Mathematical modeling of the hard chromium electroplating process

Mathematical models of the electroplating bath and cooling water system in this study (Fig. 3) are based on the principle of mass and energy conservation [23, 24].

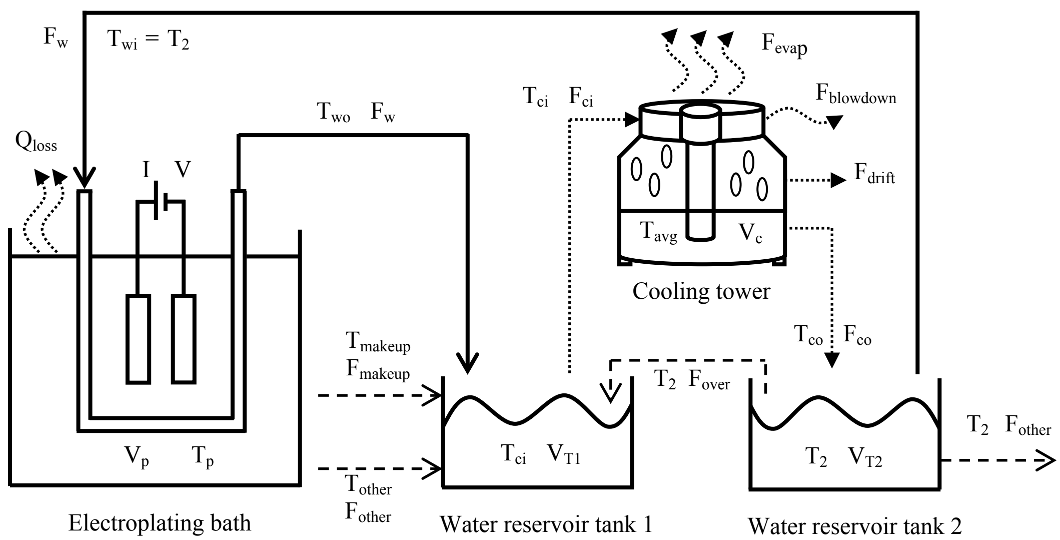


Fig. 3 Schematic diagram of the hard chromium electroplating process with mass and energy balance.

2.4.1 The electroplating bath

Mass conservation equation

$$\frac{\mathrm{d}\left(\rho_{\mathrm{p}} V_{p}\right)}{\mathrm{d}t} \quad (1)$$

Energy conservation equation

$$\frac{\mathrm{d}T_{\mathrm{p}}}{\mathrm{d}t} = \frac{IV - Q_{\mathrm{loss}} - F_{\mathrm{t}} U_{0} A_{\mathrm{ht}} \Delta T_{\mathrm{lm}}}{\rho_{\mathrm{p}} C_{pp} V_{\mathrm{p}}} \quad (2)$$

The equation of energy conservation in Eq. (2) contains the heat production owing to the power current load, the heat loss at the upper surface of the plating solution to the surrounding and the term related to heat transfer between the electroplating bath and the heat exchanger. The

Q_{loss} term related on the power current load and plating solution temperature is calculated from Eq. (3).

$$Q_{\text{loss}} = f(IV) + \left(0.0196T_{\text{p}}^{2.8806} + 2.1527T_{\text{p}} - 32.655\right)A_{\text{sur}} \quad (3)$$

In Eq. (3), the function of $f(IV)$ can be obtained by the least squares method with the relation of the actual data between the plating solution temperature and the current load.

2.4.2 The tube heat exchanger

The energy conservation equation of the tube heat exchanger that immersed in the electroplating bath is applied using a lumped model [25], while a constant volumetric water flow rate is considered on the mass balance.

Mass conservation equation

$$\frac{\mathrm{d}\left(\rho_{\text{w}}V_{\text{tube}}\right)}{\mathrm{d}t} = 0 \quad (4)$$

Energy conservation equation

$$\frac{\mathrm{d}T_{\text{wo}}}{\mathrm{d}t} = \frac{F_{\text{w}}\left(T_{\text{wi}} - T_{\text{wo}}\right)}{L_{\text{tube}}A_{\text{o}}} + \frac{F_{\text{t}}U_{\text{o}}A_{\text{ht}}\Delta T_{\text{lm}}}{\rho_{\text{w}}C_{\text{pw}}L_{\text{tube}}A_{\text{o}}} \quad (5)$$

Where U_{o} refers to the overall heat transfer coefficient, ΔT_{lm} expresses to the logarithmic mean temperature and can be computed by Eq. (6). The right term of energy balance in Eq. (5) is constituted of the different of heat flow between outlet and inlet tube heat exchanger and the heat exchanged with the electroplating bath and heat exchanger.

$$\Delta T_{\text{lm}} = \frac{T_{\text{wo}} - T_{\text{wi}}}{\ln\left[\dfrac{T_{\text{p}} - T_{\text{wi}}}{T_{\text{p}} - T_{\text{wo}}}\right]} \quad (6)$$

2.4.3 The cooling system

The cooling system composes two water reservoir tanks and a cooling tower. The water flowing from the tube heat exchanger to a tank 1 is delivered to the cooling tower in order to reduce its temperature. The cooling water flows from the cooling tower to a tank 2 before entering to the electroplating bath. Eq. (7) to Eq. (9) provide the mass conservation equations for both tanks and the cooling tower, respectively.

Mass conservation equations

$$F_{\mathrm{co}}=F_{\mathrm{ci}}-F_{\mathrm{makeup}} \quad (7)$$

$$F_{\mathrm{over}}=F_{\mathrm{co}}-F_{\mathrm{w}}-F_{\mathrm{other}} \quad (8)$$

$$F_{\mathrm{makeup}}=F_{\mathrm{blowdown}}+F_{\mathrm{evap}}+F_{\mathrm{drift}} \quad (9)$$

The water makeup of the cooling tower in Eq. (9) consists of the summation of blowdown, evaporation loss and drift loss [26]. Blowdown discards a portion of the concentrated circulating water due to the evaporation process in order to lower the system solid concentration. Drift loss is entrained water that carried out from the cooling tower by the wind.

Energy conservation equations

$$\frac{\mathrm{d}T_{\mathrm{ci}}}{\mathrm{d}t}=\frac{F_{\mathrm{w}}T_{\mathrm{wo}}+F_{\mathrm{makeup}}T_{\mathrm{makeup}}-F_{\mathrm{ci}}T_{\mathrm{ci}}}{V_{\mathrm{T1}}}+\frac{F_{\mathrm{other}}T_{\mathrm{other}}+F_{\mathrm{over}}T_{2}}{V_{\mathrm{T1}}} \quad (10)$$

$$\frac{\mathrm{d}T_{2}}{\mathrm{d}t}=\frac{F_{\mathrm{co}}T_{\mathrm{co}}-F_{\mathrm{w}}T_{2}-F_{\mathrm{over}}T_{2}-F_{\mathrm{other}}T_{2}}{V_{\mathrm{T2}}} \quad (11)$$

$$\frac{\mathrm{d}T_{\mathrm{co}}}{\mathrm{d}t}=\frac{F_{\mathrm{ci}}T_{\mathrm{ci}}-F_{\mathrm{co}}T_{\mathrm{co}}-F_{\mathrm{makeup}}T_{\mathrm{avg}}-\frac{h_{\mathrm{A}}A_{\mathrm{s}}(T_{\mathrm{avg}}-T_{\mathrm{air}})}{\rho_{\mathrm{w}}C_{\mathrm{pw}}}-\frac{F_{\mathrm{evap}}\lambda_{\mathrm{evap}}}{C_{\mathrm{pw}}}}{V_{\mathrm{c}}} \quad (12)$$

The three terms in the energy conservation equation of the cooling tower as shown in Eq. (12) demonstrate the difference of heat flow between outlet and inlet of the cooling tower with the last two terms showing the heat transferred by convection and evaporation, respectively. Term of $h_A A_s$ can be obtained by the least squares method with the water temperature profile at the cooling tower. The T_{avg} in the above equation is calculated by

$$T_{avg} = \frac{T_{ci} + T_{co}}{2} \quad (13)$$

The overall heat transfer coefficient of tube heat exchanger involves two convective and one conductive resistance, while the fouling is negligible. In case of both U shape and W shape tube heat exchangers, the overall heat transfer coefficients are calculated by optimization based on actual data. The optimization problem can be formulated as follows:

Objective function: $$\min_{U_\mathrm{o}} \sum_{i=0}^{t_\mathrm{f}} \{T_{\mathrm{p,actual}}(i) - T_{\mathrm{p,simulation}}(i)\}^2 \quad (14)$$

Subject to process models from Eq. (1) to Eq. (13).

The physical properties, geometric characteristics and operating conditions used in this work are summarized in Table 1 to Table 3. In the model validation, the simulation results are validated with the actual data collected from a real plant and demonstrated in Fig. 4.

Table 1

Physical properties [27, 28].

Physical property	Value
Density of water/kg·m^{-3}	992.25
Density of plating solution/kg·m^{-3}	1,174.4
Heat capacity of water/kJ·kg^{-1}·°C^{-1}	4.181
Heat capacity of plating solution/kJ·kg^{-1}·°C^{-1}	4.917
Latent heat of vaporization of water/kJ·kg^{-1}	2,260
Thermal conductivity of titanium/kW·m^{-1}·°C^{-1}	0.0206

Table 2

Simulation system geometric characteristics.

System characteristic	**Value**
Inner diameter of a 1.27 cm diameter tube heat exchanger/m	0.0111
Outer diameter of a 1.27 cm diameter tube heat exchanger/m	0.0127
Inner diameter of a 2.54 cm diameter tube heat exchanger/m	0.0238
Outer diameter of a 2.54 cm diameter tube heat exchanger/m	0.0254
Volume of an electroplating bath/m^3	9.3062
Volume of a water tank 1/m^3	2.1155
Volume of a water tank 2/m^3	2.5663
Volume of a cooling tower/m^3	0.3771

Table 3

Operating conditions for simulation.

Operating condition	Value
Outlet water temperature to other electroplating baths/°C	44.1

Water make up temperature/°C	34.9
Air temperature/°C	30
Volumetric flow rate of cooling water in other electroplating baths flow to a cooling tower/$m^3 \cdot s^{-1}$	4.3364×10^{-4}
Water make up to a cooling tower/$m^3 \cdot s^{-1}$	7.7597×10^{-6}
Water evaporation rate in a cooling tower/$m^3 \cdot s^{-1}$	4.3238×10^{-6}
Water blow down rate of a cooling tower/$m^3 \cdot s^{-1}$	1.0809×10^{-6}
Water drift loss of a cooling water/$m^3 \cdot s^{-1}$	2.3550×10^{-6}

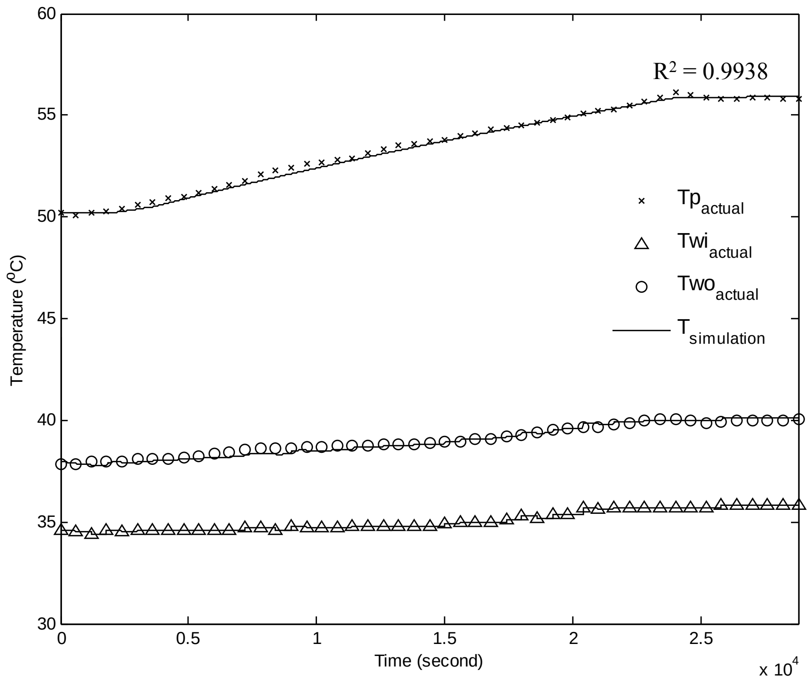


Fig. 4 Comparison results between simulation and actual data of plating solution temperature and water temperature at inlet and outlet of the electroplating bath.

Since the workpieces require a high thickness of hard chromium coating, the current load of electroplating is supplied at a high rate. The high current load can lead to the increase in the plating solution temperature if the heat removed out of the solution by the heat exchanger is lower than that of the heat generated from the current load. Fig. 4 shows a good agreement between simulation results and the actual data with the coefficient of determination (R^2) of more than 90% so the mathematical models of this process can be used to predict the temperature profile of the process.

3. Results & Discussion

3.1 Simulation results

Fig. 5 and Fig .6 demonstrate the temperature profile of the plating solution, water inlet and outlet at the electroplating bath for the W serpentine shape with diameters of 1.27 and 2.54 cm comparing to the conventional U shape tube heat exchanger. To test the heat exchangers, the cooling water flow velocities of 1.6, 2.0 and 2.4 m·s^{-1} are introduced in this study. These results show that the plating solution temperature profiles of both sizes of the W serpentine shape are lower than that of the U shape heat exchanger. Since, the new design has the combination of the inclined and curved shapes which makes an unparalleled flow direction between the cooling water and the plating solution inside the bath. This prevents the formulation of thermal resistance film at the outer tube surface that resulting in enhances the heat transfer rate [10].

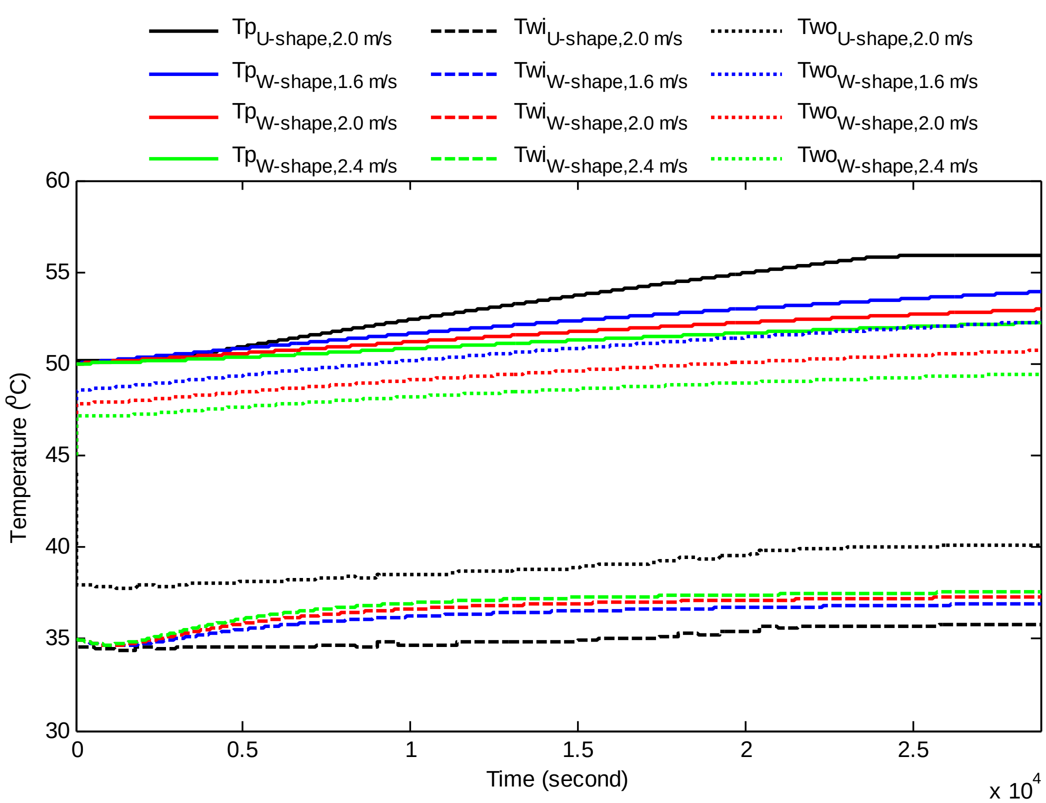


Fig. 5 The temperature profile of plating solution, water inlet and outlet at the electroplating bath for 1.27 cm diameter of W serpentine shape tube heat exchanger at various water velocities.

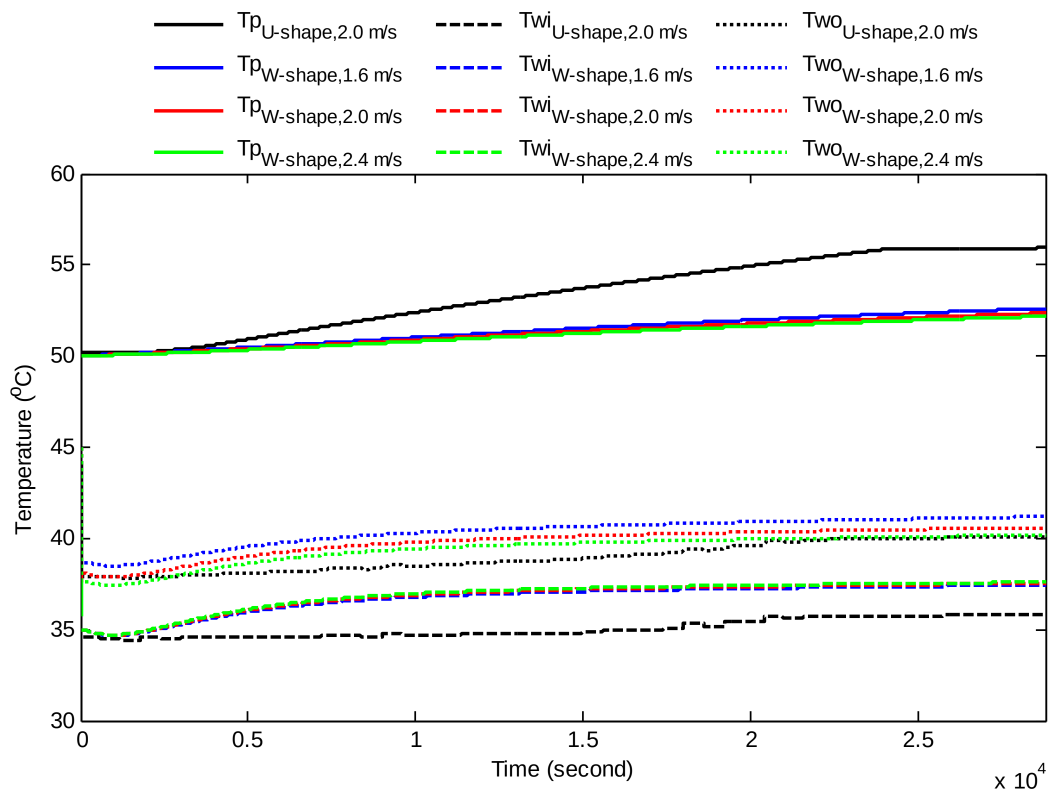


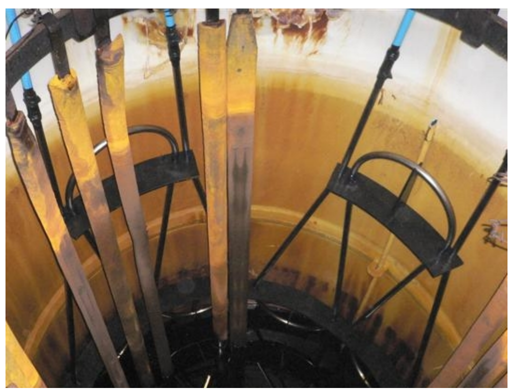
Fig. 6. The temperature profile of plating solution, water inlet and outlet at the electroplating bath for 2.54 cm diameter of W serpentine shape tube heat exchanger at various water velocities.

Furthermore, the curve shape of this devised heat exchanger increases the heat transfer rate between the plating solution and the cooling water from the secondary flow of the cooling water inside the tube [20, 21, 22]. In Fig. 5, when current load is applied to the electroplating bath during the 8 hours of operation, the 1.27 cm diameter of the W shape heat exchanger with 2.4 $m \cdot s^{-1}$ of flow velocity can adequately remove the heat that generated from the bath and the temperature of the plating solution can be maintained in the optimal range of (50±3)°C. However, in the case of 1.6 $m \cdot s^{-1}$ of flow velocity, the temperature difference between plating solution and water at the outlet is small. As a consequence, the heat removal is insufficient to maintain the plating solution temperature at the optimal range; the temperature of the bath is more than 53 °C. Nevertheless, the result of the W serpentine shape with 2.54 cm diameter in Fig. 6 shows that the cooling water at all velocities can remove the generated heat from the process and the plating solution temperature can be kept at the optimal range along the electroplating period; the maximum temperature of the plating solution is 52.6, 52.3 and 52.2°C at 1.6, 2.0 and 2.4 $m \cdot s^{-1}$ of flow velocities, respectively. With these results, thus the W serpentine shape with 2.54 cm diameter is selected for implementation at the real plant.

3.2 Implementation results of the W serpentine shape tube heat exchanger

According to the simulation study, the W serpentine shape tube heat exchanger requires the 2.54 cm diameter and 30 m in total length. However, in practical and due to the limitations of the free space for installation inside the real electroplating bath, this heat exchanger is divided into four pieces. Each piece has a diameter of 2.54 cm and a length of 7.5 m (Fig. 7), which is conveniently implemented in the real bath. Each heat exchanger is immersed in half of plating solution depth because a large amount of heat from the hard chromium electroplating process releases at this position. The end of both sides is connected with a polyvinylchloride (PVC) tube to supply and recirculate the cooling water.

(a) The W serpentine shape tube heat exchanger.



(b) The installation of the W serpentine shape tube heat exchanger in the electroplating bath.

Fig. 7 The implementation of W serpentine shape tube heat exchanger.

Fig.8 demonstrates the actual data after the implementation of the W serpentine shape tube heat exchanger and the U shape tube heat exchanger. The result indicates that the W serpentine shape tube heat exchanger can keep the plating solution temperature during the plating period lower than the original one. The plating solution temperature can be kept in the range of 50 - 53°C during the plating period and the water outlet temperature is about 39 - 42°C. With the collected data, the novel W serpentine shape tube heat exchanger removes more heat out of the process than the conventional heat exchanger around 23%.

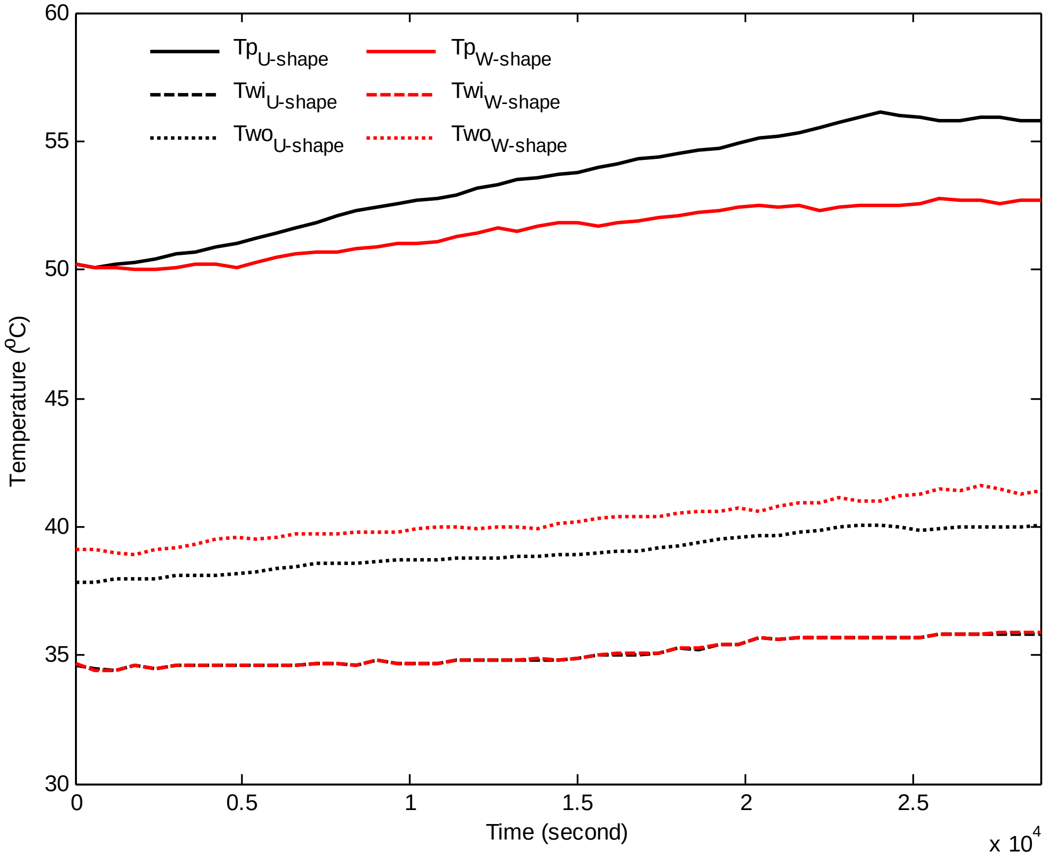


Fig. 8 Comparison of temperature profile of plating solution, water inlet and outlet at the electroplating bath with the cooling water flow velocity at 2.0 m·s^{-1}.

4. Conclusions

To control the temperature of the hard chromium electroplating bath, an effective heat exchanger is needed to remove heat occurred during the electroplating process. In this work, heat removals of two tube heat exchangers have been compared. In addition, mathematical models of the hard chromium electroplating process have been formulated to predict the dynamics temperature of the electroplating bath and evaluate the heat exchanger performance. Unknown parameters in the developed models are determined based on the actual plant data. The simulation results show that the developed models can give a good accurate prediction of the plating solution temperature with the coefficient of determination (R^2) of more than 90%. The heat removal performances of 1.27 and 2.54 cm diameter of the W serpentine shape tube heat exchangers with the flow velocity in a cross-section at 1.6, 2.0 and 2.4 $m \cdot s^{-1}$ are compared. The simulation results indicate that the W serpentine shape with 2.54 cm diameter is applicable to maintain the plating solution temperature at the desired range at any flow velocity. Furthermore, four W serpentine shape tube heat exchangers with identical heat transfer area to the U shape tube heat exchanger (2.54 cm diameter and 30 m in total length) are implemented in the real electroplating bath. The plating solution temperature after the implementation can be kept at the range. Moreover, the novel design provides higher heat removal than the conventional U shape tube heat exchanger around 23%.

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Nomenclature

A_{ht}	Heat transfer area of a tube heat exchanger, m^2
A_{o}	Cross section area of a tube heat exchanger, m^2
A_{sur}	Contacted area of the surface of plating solution with surroundings, m^2
A_{s}	Surface area between water droplet and air, m^2
$C_{p\mathrm{p}}$	Specific heat capacity of plating solution, $kJ \cdot kg^{-1} \cdot {}^{\circ}C^{-1}$
$C_{p\mathrm{w}}$	Specific heat capacity of water, $kJ \cdot kg^{-1} \cdot {}^{\circ}C^{-1}$
F_{blowdown}	Water blowdown rate of a cooling tower, $m^3 \cdot s^{-1}$
F_{ci}	Inlet volumetric water flow rate of a cooling tower, $m^3 \cdot s^{-1}$
F_{co}	Outlet volumetric water flow rate of a cooling tower, $m^3 \cdot s^{-1}$
F_{drift}	Water drift loss of a cooling water, $m^3 \cdot s^{-1}$
F_{evap}	Water evaporation rate in a cooling tower, $m^3 \cdot s^{-1}$
F_{makeup}	Water makeup to a cooling tower, $m^3 \cdot s^{-1}$
F_{other}	Volumetric flow rate of cooling water from other electroplating baths to a cooling tower, $m^3 \cdot s^{-1}$
F_{over}	Volumetric flow rate of cooling water from a water reservoir tank 2 overflows to a water reservoir tank 1, $m^3 \cdot s^{-1}$

F_{w}	Volumetric flow rate of cooling water, $m^3 \cdot s^{-1}$
F_{t}	Heat exchanger correction factor
h_{A}	Heat transfer coefficient of convection between water and air, $W \cdot m^{-2} \cdot {}^{\circ}C^{-1}$
I	Electric current, A
L_{tube}	Length of a tube heat exchanger, m
Q_{loss}	Heat loss from an upper surface of the plating solution to surroundings, W
T_{air}	Air temperature, °C
T_{avg}	Average different water temperature at a cooling tower, °C
T_{ci}	Water temperature at a water reservoir tank 1, °C
T_{co}	Outlet water temperature in a cooling tower, °C
t_{f}	Total operation time, s
T_{makeup}	Water makeup temperature, °C
T_{other}	Outlet water temperature from other electroplating baths, °C
T_{p}	Plating solution temperature, °C
$T_{\mathrm{p,actual}}$	Plating solution temperature which collected from a real plant, °C
$T_{\mathrm{p,simulation}}$	Plating solution temperature from simulation, °C
$T_{\mathrm{simulation}}$	Temperature results from the simulation, °C
T_{wi}	Inlet cooling water temperature, °C
$T_{\mathrm{wi,actual}}$	Inlet cooling water temperature which collected from a real plant, °C
T_{wo}	Outlet cooling water temperature, °C
$T_{\mathrm{wo,actual}}$	Outlet cooling water temperature which collected from a real plant, °C
T_{2}	Water temperature at a water reservoir tank 2, °C

ΔT_{lm}	Logarithmic mean temperature at a tube heat exchanger, °C
v	Flow velocity in a cross-section of a tube heat exchanger, $m \cdot s^{-1}$
V	Electrical voltage, V
V_{c}	Volume of a cooling tower, m^3
V_{p}	Volume of an electroplating bath, m^3
V_{T1}	Volume of a water reservoir tank 1, m^3
V_{T2}	Volume of a water reservoir tank 2, m^3
V_{tube}	Volume of a tube heat exchanger, m^3
U_{o}	Overall heat transfer coefficient, $kW \cdot m^{-2} \cdot °C^{-1}$
λ_{evap}	Latent heat of vaporization of water, $kJ \cdot kg^{-1}$
ρ_{p}	Density of plating solution, $kg \cdot m^{-3}$
ρ_{w}	Density of water, $kg \cdot m^{-3}$
μ_{w}	Dynamic viscosity of water, $kg \cdot m^{-1} \cdot s^{-1}$

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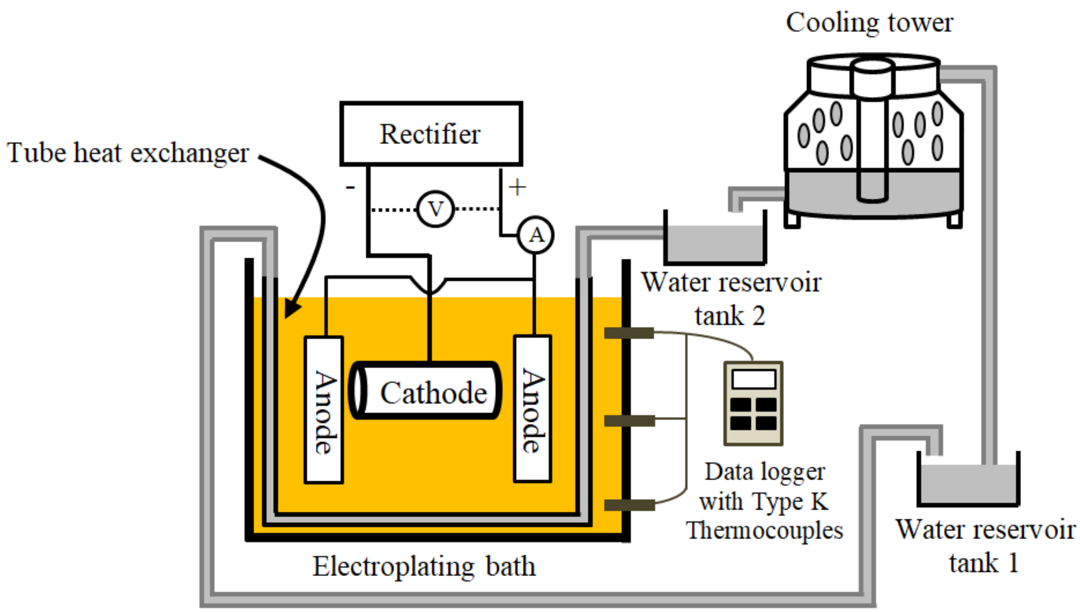


Fig. 1 Hard chromium electroplating process with the cooling system.

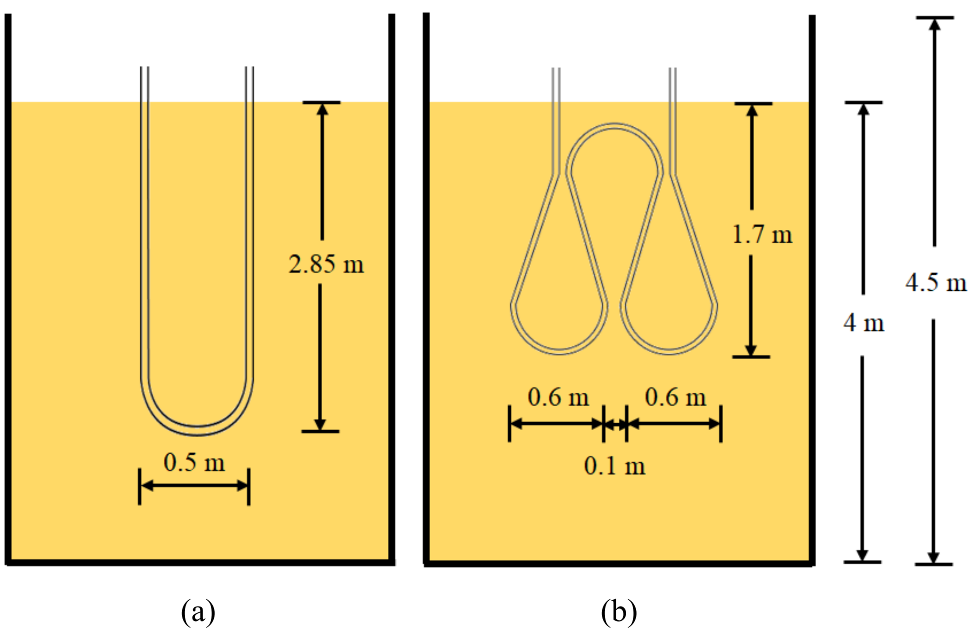


Fig. 2 Illustration of the heat exchangers inside the hard chromium electroplating bath: (a) U shape heat exchanger and (b) W serpentine shape heat exchanger.

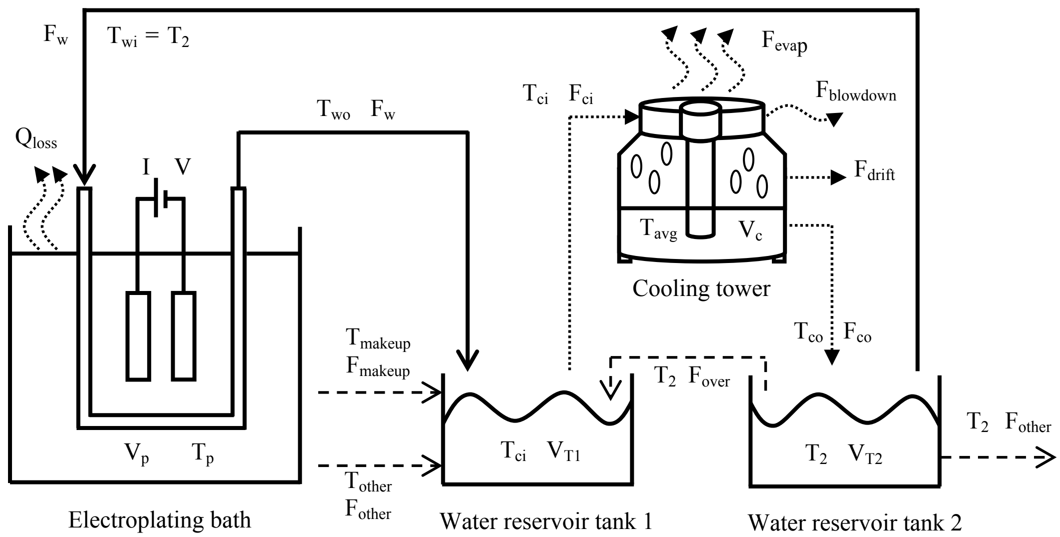


Fig. 3 Schematic diagram of the hard chromium electroplating process with mass and energy balance.

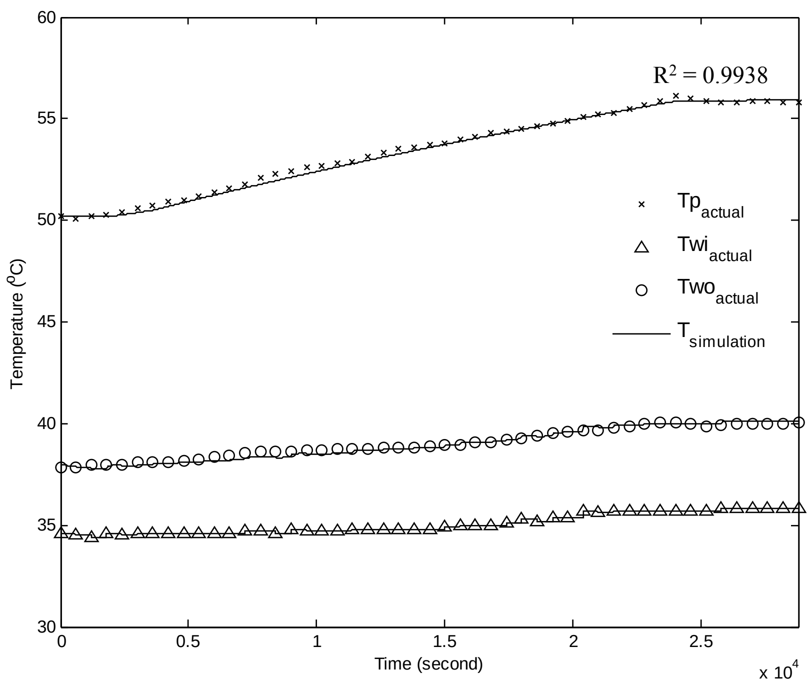


Fig. 4 Comparison results between simulation and actual data of plating solution temperature and water temperature at inlet and outlet of the electroplating bath.

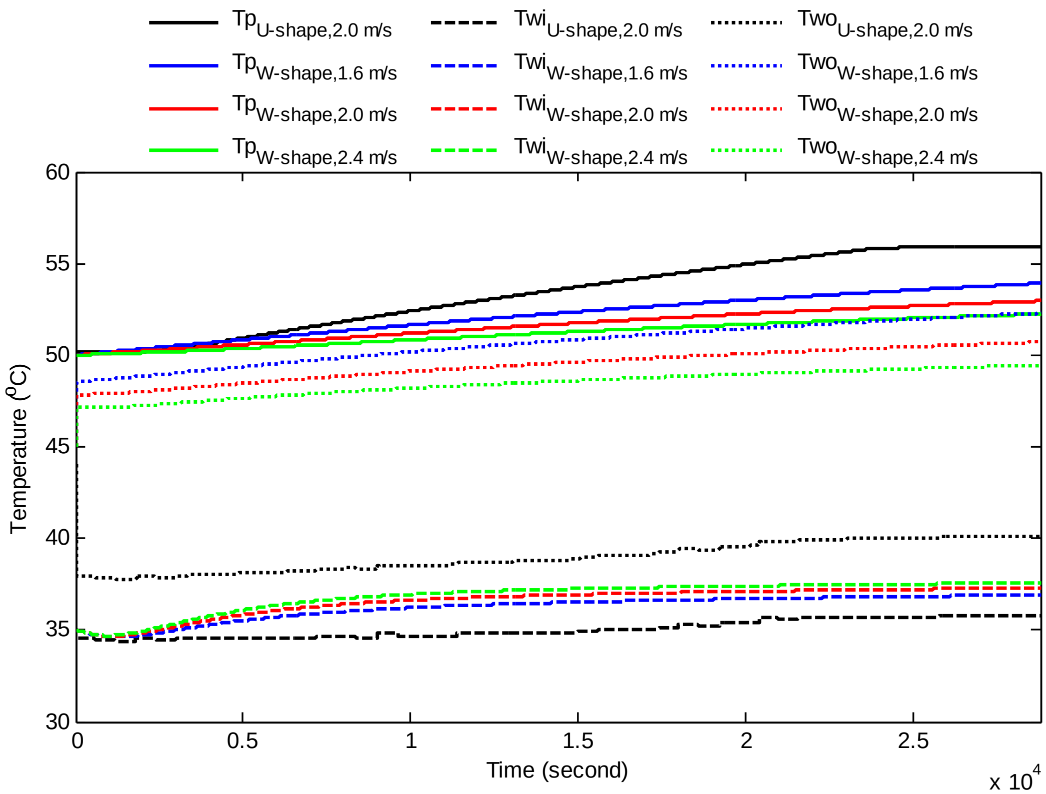


Fig. 5 The temperature profile of plating solution, water inlet and outlet at the electroplating bath for 1.27 cm diameter of W serpentine shape tube heat exchanger at various water velocities.

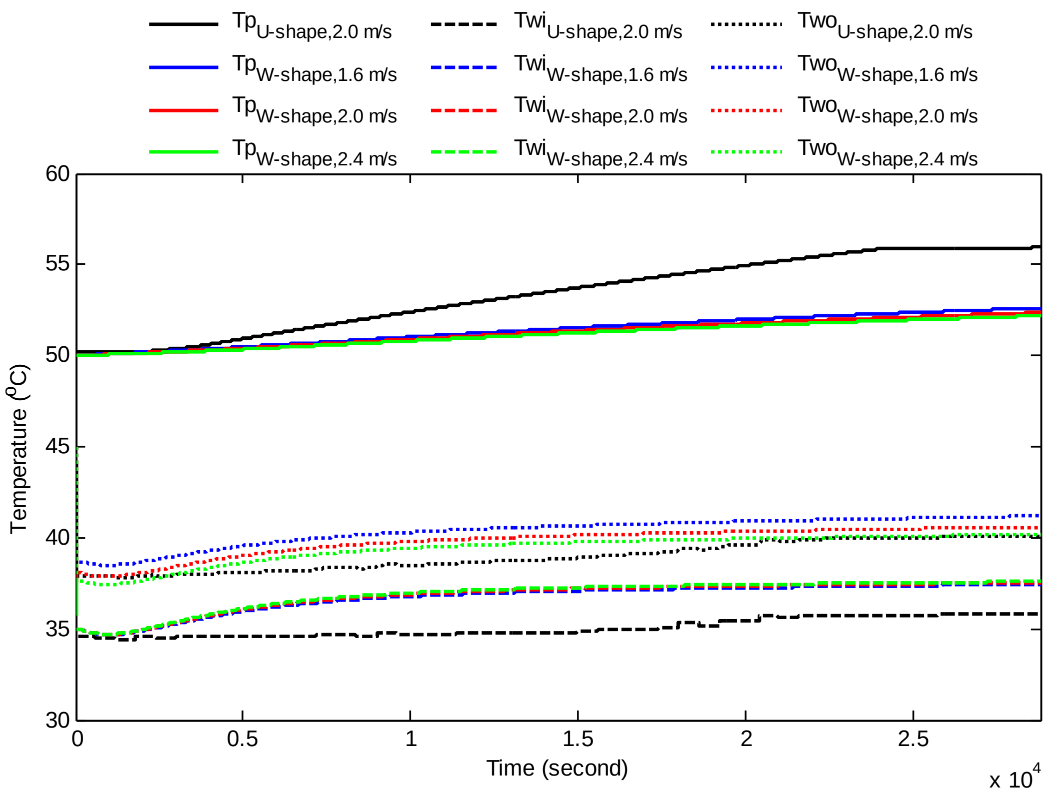
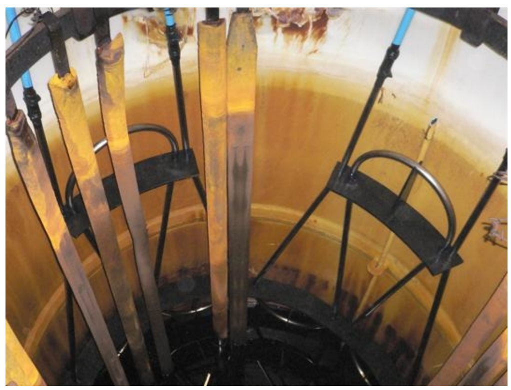


Fig. 6. The temperature profile of plating solution, water inlet and outlet at the electroplating bath for 2.54 cm diameter of W serpentine shape tube heat exchanger at various water velocities.

(a) The W serpentine shape tube heat exchanger.



(b) The installation of the W serpentine shape tube heat exchanger in the electroplating bath.

Fig. 7 The implementation of W serpentine shape tube heat exchanger.

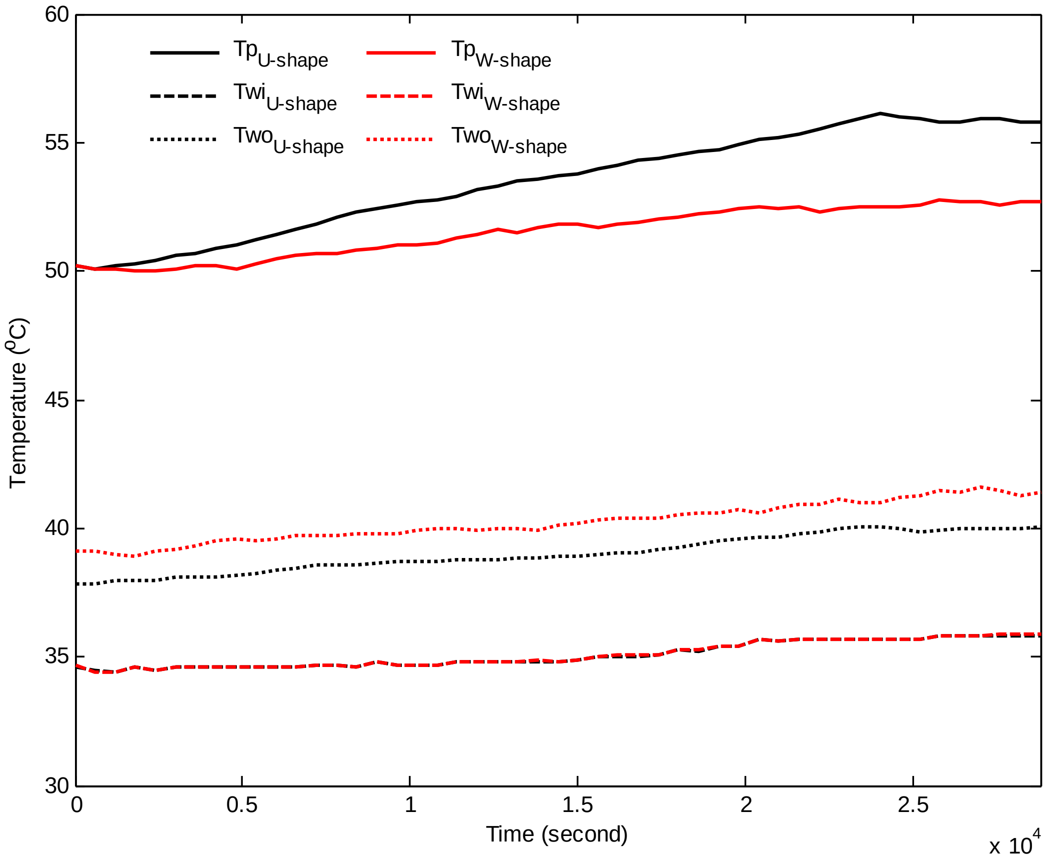


Fig. 8 Comparison of temperature profile of plating solution, water inlet and outlet at the electroplating bath with the cooling water flow velocity at 2.0 m/s.

Table 1

Physical properties [27, 28].

Physical property	Unit	Value
Density of water	kg/m^3	992.25
Density of plating solution	kg/m^3	1,174.4
Heat capacity of water	kJ/kg·°C	4.181
Heat capacity of plating solution	kJ/kg·°C	4.917
Latent heat of vaporization of water	kJ/kg	2,260
Thermal conductivity of titanium	kW/m·°C	0.0206

Table 2

Simulation system geometric characteristics.

System characteristic	Unit	Value
Inner diameter of a 1.27 cm diameter tube heat exchanger	m	0.0111
Outer diameter of a 1.27 cm diameter tube heat exchanger	m	0.0127
Inner diameter of a 2.54 cm diameter tube heat exchanger	m	0.0238
Outer diameter of a 2.54 cm diameter tube heat exchanger	m	0.0254
Volume of an electroplating bath	m^3	9.3062
Volume of a water tank 1	m^3	2.1155
Volume of a water tank 2	m^3	2.5663
Volume of a cooling tower	m^3	0.3771

Table 3

Operating conditions for simulation.

Operating condition	Unit	Value
Outlet water temperature to other electroplating baths	°C	44.1
Water make up temperature	°C	34.9
Air temperature	°C	30
Volumetric flow rate of cooling water in other electroplating baths flow to a cooling tower	m^3/s	4.3364×10^{-4}
Water make up to a cooling tower	m^3/s	7.7597×10^{-6}
Water evaporation rate in a cooling tower	m^3/s	4.3238×10^{-6}
Water blow down rate of a cooling tower	m^3/s	1.0809×10^{-6}
Water drift loss of a cooling water	m^3/s	2.3550×10^{-6}