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Pinch point analysis of heat pump air-heating electroplating wastewater treatment system based on thermodynamics

Jing Yu, Sumin Jin*, Liang Chen

School of Energy Science and Engineering, Nanjing Tech University, NO.30 Puzhu Road(S), Nanjing, 211816, China, Tel. +86 18251853848, email: 18251853848@163.com (J. Yu), Tel. +86 13809049685, email: smjin@njtech.edu.cn (S. Jin), Tel. +86 18751945135, email: chen_liang08@163.com (L. Chen)

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ABSTRACT

Traditional evaporation technology — mechanical vapor re compression crystallization (MVR), which is mainly utilized to deal with electroplating wastewater, has a serious problem of the direct contact of the compressor with steam, which does harm to the equipment life severely. A novel heat pump air-heating electroplating wastewater treatment system (HPAH-EWTS) is proposed in this paper. The heat pump system is used to dispose the recirculating air to serve the evaporating separation process. HPAH-EWTS is analyzed based on thermodynamics in this paper by varying factors such as pinch point temperature differences and different refrigerants. The results show that no matter utilizing what kinds of refrigerants, reducing the pinch point temperature differences of evaporator is more important to improve the system treatment efficiency (STE). There exists the reverse heat transfer in evaporator when non-azeotropic refrigerant is applied in HPAH-EWTS, and it is necessary to keep a high condensing temperature(≥ 40°C) and suitable pinch point temperature differences in this condition. In addition, when condensing temperature is low (≤ 50°C), R407 c could be the best choice of HPAH-EWTS due to its highest STE in different refrigerant systems. While the condensing temperature becomes high (≥ 50°C), R717 system would be the optimum.

Keywords: Evaporation crystallization; Electroplating wastewater; Heat pump; Pinch point temperature differences; Refrigerant; System treatment efficiency

1. Introduction

With the development of industrialization, the discharge of industrial sewage from all over the country has been gradually increased, and the problem of water pollution has become a very important link in environmental pollution. Electroplating wastewater is one of the components of industrial wastewater. It contains complex inorganic compounds, including high concentrations of heavy metals salts, cyanide and thiocyanate [1,2]. Some components in electroplating wastewater, especially heavy metal salts, can cause damage to the water body and surrounding ecological environment. Toxic heavy metal ions can also enter the human body through the food chain, which can have a serious impact on human health [3]. The treatment of electroplating wastewater with its operation complexity and its cost issues are great challenges. Moreover, to prevent secondary pollution, the ultimate goal of treatment should be to achieve zero emission of waste liquid.

At present, the traditional treatment methods of electroplating wastewater can be mainly divided into chemical precipitation method, electrochemical method, adsorption method and evaporation method [4]. Chemical precipitation is one of the most commonly used treatment in industry. This method uses the chemical reaction to produce the precipitated metal salts which can be separated by filtration. The application of chemical precipitation method in electroplating wastewater treatment industry has been very mature, so the research mainly focuses on the application of the combination with other methods. For exam-

*Corresponding author.

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ple, C. Peng combines chemical precipitation with electro dialysis to process electroplating wastewater containing Cr (VI) and the result shows that about 95% Cr (VI) can be removed [5].Although chemical precipitation method has the characteristics of simple operation and mature development, it is necessary to add various agents when treating wastewater containing a variety of heavy metal ions. In addition, this method cannot achieve zero discharge and has certain limitation.

Electrochemical method is another widely used electroplating wastewater treatment. Its universality is superior to chemical precipitation method due to the versatility of electrochemical reactions. Weng made studies on the regeneration of Zn-saturated granular activated carbon using electrochemical method, and got the result that electrically assisted regeneration has much higher regeneration efficiency than acid washing [6]. NadKarlo also studied the combined electrochemical and ozonation methods [7]. However, electrode modification has little development, so electrochemical method is still restricted [8]. It's also cannot treat electroplating wastewater completely, and it needs to provide additional electric energy compared to chemical precipitation method.

In recent years, the research of adsorption method on the treatment of electroplating wastewater has increased, and it is gradually replacing the traditional chemical precipitation method. The adsorption method uses some natural or synthetic materials to adsorb certain metal ions in electroplating wastewater. Due to some new adsorption materials, the processing cost can be reduced [9–12]. In order to reduce the cost of treating electroplating wastewater, many researchers devote themselves to developing new natural adsorption materials. Martín-Lara studied the processing properties of olive stone as adsorption materials, and the results showed that the treatment efficiency was high when it was used to absorb the electroplating wastewater containing trivalent chromium and hexavalent chromium ions [13]. Rao studied removal abilities of fruit peel of Litchi chinensis in dealing with electroplating wastewater with Cr(VI), results indicate that this material has certain value in the treatment of chromium electroplating wastewater [14]. The adsorption method has the advantages of low cost and simple operation in the treatment of electroplating wastewater. But the target is too strong. One kind of adsorption material just can only be aimed at absorbing one or several specific heavy metal ions. In addition, all the adsorption materials so far cannot fully absorb the heavy metal ions in electroplating wastewater. In order to achieve zero emission treatment, the adsorption method often needs to be supplemented by subsequent treatment.

Evaporation method has been investigated and utilized widely in the field of wastewater treatment. Evaporation separation (ES) technology is used here to remove water from electroplating wastewater by evaporating process. Applications of this technology can be traced back to 5000 years ago when it was used to produce table salt. The original evaporation method consumes a lot of energy. At present, due to its maturity and seeking high efficiency, multi-effect evaporation (MEE) has become the most commonly used ES technology. MEE is mainly composed of several series of single-effect evaporator and the end condenser. The solution will be heated to boil and produce secondary vapor as the heating vapor for the next evaporator. Since the significant reduction in new steam consumption, MEE has the advantage of lower energy consumption and faster processing than single-effect evaporation [15,16]. However, the disadvantage of MEE is obvious. MEE has complex system, complicated operation and need external heating vapor. In addition, although the MEE system is more energy efficient than the original single-effect evaporation system, its energy consumption is still huge. Mechanical vapor recompression (MVR) has also become an alternative technology and has been rapidly developed. In recent years, MVR has been considered as an alternative measure to deal with high concentrations wastewater [17,18]. In the MVR system, the vapor produced by evaporation in the evaporator is compressed by the compressor to increase its enthalpy. The compressed secondary vapor is reused as the heated fluid for the feed solution, which offers a higher efficient of MVR system than that of MEE system [19,20]. Han et al. [21] studied the MVR system on the treatment of ammonium sulfate wastewater. And Zhou et al. [22] developed a comprehensive design model to predict the characteristics of the single-effect MVR system. Since the advantages of high thermodynamic efficiency and low running cost than traditional evaporation system, MVR has been utilized widely [23,24]. Nevertheless, due to the direct contact of the compressor with steam, MVR cannot provide a stable and long-term operation [22].

Of the four common electroplating wastewater treatment methods mentioned above, the evaporation separation method is the only one that can achieve zero discharge. However, both MEE system and MVR system have the problems of high energy consumption and great equipment maintenance costs. In this paper, HPAH-EWTS is investigated and analyzed in detail using thermodynamics method. HPAH-EWTS can effectively solve the problem of high cost in traditional evaporation separation method. It provides another choice for electroplating wastewater treatment. A certain theoretical analysis of this system has also been investigated and the results can provide theoretical basis for the design of actual system, including the condenser and evaporator design in heat pump, and the refrigerant choices.

2. System description

2.1. System introduction

The schematic of HPAH-EWTS is illustrated in Fig. 1. Differing from heat pump water-heating electroplating wastewater treatment system (HPWH-EWTS), the heat pump is utilized to heat the air in HPAH-EWTS. This heating type can avoid the problem that wastewater of HPHW-EWTS carries insufficient heat in the process of once-through evaporation. At the same time, wastewater recycling can also be eliminated in HPAH-EWTS, and the system structure is simpler.

As is shown in Fig. 1, evaporating separator where electroplating wastewater evaporating separation process is completed plays an indispensable role in HPAH-EWTS. w1 represents the suppled electroplating wastewater, and w2 stands for the crystalline salt discharged from the evaporating separator. The heat pump system is used to dispose the

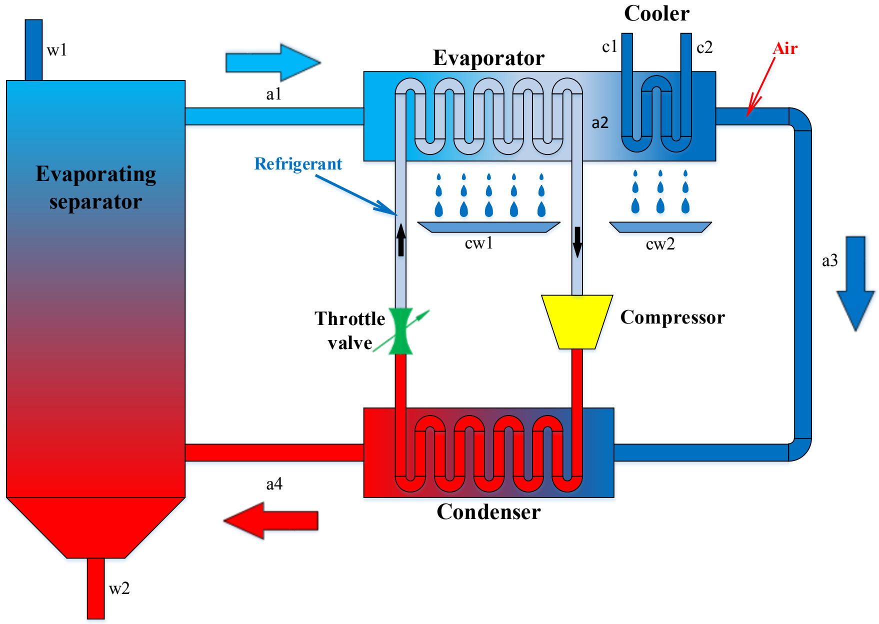


Fig. 1. Schematic diagram of Heat pump heating air-electroplating wastewater treatment system (HPAH-EWTS).

recirculating air. Due to the characteristics of the heat pump system and in order to ensure the balance of the entire system, the cooler must be added in HPAH-EWTS. The air circulation process is a1→a2→a3→a4→a1. The condenser is utilized to heat the recirculating air while the evaporator and the cooler cool the air at the outlet of the evaporating separator and condense the vapor in air. The separation of the crystalline salt and water in the electroplating wastewater is achieved by the cycle of air formation and the heat-and-mass transfer in the evaporating separator.

2.2. Comparison with other methods

As shown in Table 1, the advantages and disadvantages of various electroplating wastewater treatment methods are given here. Evaporation method is the only effective method that can achieve zero emission. However, the current evaporation method, such as MEE and MVR, has certain limitation. The HPAH-EWTS, a novel evaporation method, can efficiently treat wastewater. Although HPAH-EWTS still need additional electric energy and its cost is higher than absorption method, zero emission requirement can be achieved by this method.

3. Hypothesis and mathematical model

3.1. Hypothesis

Before the thermodynamic analysis, some assumptions were involved first. The following six assumptions are given here.

1. It is assumed that the heat and mass transfer of the working fluid in the evaporating separator is adequately sufficient and the relative humidity (RH) of the outlet air of a1 is approximately close to saturation. The relative humidity is set: $\phi_{a1} = 0.95$. The relative humidity of the outlet air of the evaporator and the cooler is basically saturated. So the relative humidity is set: $\phi a2 = 0.95$, $\phi a3 = 0.95$.
2. The moisture carried off by the air which result from the mass transfer process in evaporating separator is equal to the amount of condensate discharged from the cooler and the evaporator.
3. The air after the cooler basically reaches the ambient temperature. So it can be assumed: $t_{a3} = t_0$.
4. The heat loss of the system to the environment can be ignored and the ambient temperature t_0 is 16°C.
5. The overheating and under cooling condition are ignored during the refrigeration cycle. The adiabatic efficiency of the compressor is set to 1. In this study, the common refrigerant is exemplified by R22, while the R407c is as the case of non-azeotropic refrigerant.

3.2. Mathematical model

The analytical methods in this study were based on thermodynamic analysis. The energy and mass balance equations for the components in the system are described in detail.

The energy and mass balance equations of evaporating separator can be expressed as:

$$m_{w1} = m_d\left(1-c\right)\left(w_{a4} - w_{a1}\right) \tag{1}$$

$$m_{w2} = c \cdot m_{w1} \tag{2}$$

$$m_{w1}h_{w1} + m_d h_{a4} = m_{w2}h_{w2} + m_d h_{a1} \tag{3}$$

Table 1
Comparison of various electroplating wastewater treatment methods

Treatment methods of electroplating wastewater		Advantages	Disadvantages
Chemical precipitation method		• Simple operation. • Mature applicability.	• Cannot meet zero emission requirements. • Cannot target complex heavy metal ions and the treatment has limitations. • The treatment requires additional chemical agents, which may cause secondary contamination.
Electrochemical method		• Strong versatility. • Simple operation.	• Cannot meet zero emission requirements. • Additional electric energy is necessary. • Electrode modification has little development,which restrict this method.
Adsorption method		• Simple operation. • Low treatment cost.	• Cannot meet zero emission requirements. • Too targeted and impossible to treat wastewater containing many heavy metal ions simultaneously.
Evaporation method	MEE	• Mature applicability. • Zero emission.	• Complex system. • Complicated operation. • External heating vapor is required. • Energy consumption is huge
	MVR	• Zero emission. • high thermodynamic efficiency. • low running cost than traditional evaporation system.	• Complex system. • The system needs high vacuum degree, the high requirement for equipment. • The direct contact of the compressor with steam causes that MVR cannot provide a stable and long-term operation.
	HPAH-EWTS	• Zero emission. • high thermodynamic efficiency. • Operating under normal temperature and pressure, low requirement for equipment. • Lower energy consumption than MVR and MEE. • The system is not too complicated and the service life is longer.	• Electric energy is necessary compared with chemical precipitation method and adsorption method.

The energy and mass balance equations of evaporator is given as follow:

$$m_d\left(w_{a1}-w_{a2}\right)=m_{cw1} \tag{4}$$

$$m_d h_{a1}=Q_e+m_d h_{a2}+m_{cw1}h_{cw1} \tag{5}$$

$$Q_e=m_r\left(h_{r4}-h_{r3}\right) \tag{6}$$

The energy and mass balance equations of cooler are listed:

$$m_d\left(w_{a2}-w_{a3}\right)=m_{cw2} \tag{7}$$

$$m_d h_{a2}=Q_{coo}+m_d h_{a3}+m_{cw2}h_{cw2} \tag{8}$$

And the energy and mass balance equations of condenser are expressed:

$$w_{a3}=w_{a4} \tag{9}$$

$$m_d h_{a3}+Q_c+m_d h_{a4} \tag{10}$$

$$Q_c=m_r\left(h_{r5}-h_{r2}\right) \tag{11}$$

In addition, some evaluation indicators for system performance are given. The compressor power consumption is expressed firstly.

$$W_p=Q_c-Q_e \tag{12}$$

And the wastewater treatment load (WTL) of HPHW-EWTS is calculated as:

$$WTL=3600\cdot m_{w1} \tag{13}$$

The above two indicators only reflect the evaluation of the heat pump system, which cannot be utilized to assess the performance of the whole system. The definition of the system treatment efficiency (STE) is given below to evaluate the performance of the system for wastewater treatment.

$$STE = \frac{3600 m_{w1}(1-c)}{W_p} \tag{14}$$

STE can effectively reflect the amount of wastewater that the system can treat per kilowatt-hour of electricity at different operating conditions. As an evaluation index of system performance, STE well reflects the operating efficiency of different systems.

Based on the presented thermodynamic mathematical models, numerical simulation for the performance of the desalination system is iteratively achieved through the platform of EES.

3.3. Confirmatory experiment

A confirmatory experiment was implemented to prove the validity of this mathematical model. The mathematical model can be divided into two parts: evaporation separation process and heat pump air treatment process. The heat pump air treatment process adopts ideal compression steam refrigeration cycle. This part of the model is relatively clear, and its application in the refrigeration industry is very common. there will be no mistakes in this part. Therefore, the emphasis of the verification experiment should be on the evaporation separation process.

The evaporation spray separation tower was built and the photographic view of the experiment is shown in Fig. 2. The evaporation spray separation tower is designed as evaporating separator. Air heaters are used here to simulate the process of heating air in the heat pump condenser. In the experiment, the air temperature was measured by PT100 thermistor (accuracy ± 0.1°C) and the flow rate of air is metered by differential pressure flow meter (accuracy ± 0.1 L/s). In addition, the spray flow rate and pressure are obtained by turbine flow meter (accuracy ± 0.1 L/h) and piezometer (accuracy ± 1.6 kPa) respectively. 20% mass concentration of calcium chloride solution was used instead of electroplating wastewater for experimental verification.

Fig. 2. Photographic view of evaporation spray separation tower.

4. Pinch point analysis

Through investigating the temperature pinch point of HPAH-EWTS, the most optimal conditions in the heat transfer process under actual conditions can be determined. There are two temperature pinch point in this system (HPHW-EWTS), namely the pinch point of the heat pump condenser and the pinch point of the heat pump evaporator. The influence of pinch point temperature differences on the system performance under different working conditions is analyzed here.

Compared with common refrigerants, non-azeotropic refrigerant temperature in the process of condensation and evaporation is constantly changing. Therefore, the location of the temperature pinch point in the heat transfer process innon-azeotropic refrigerant system is also different from that in common refrigerant system. It is necessary to analyze the system using non-azeotropic refrigerant separately. In this part, R22 is selected as a representative of the common refrigerant and R407c is choose for non-azeotropic refrigerant.

4.1. pinch point analysis of HPAH-EWTS using R22

Fig. 3a illustrates the t-H diagram of the air and refrigerant flowing process of the system using common refrigerant when pinch point temperature differences exist. For the air heating section, air is heated by the heat pump condenser from a3 to a4. The minimum temperature differences in this process appear at r1, and the temperature differences between r1 and a′ is the pinch point temperature differences (Δt_{pc} in the figure). The process of a4 to a1 is the heat and mass transfer process in the evaporation separator. The air in the evaporation separator not only reduces the temperature but also absorbs the moisture from the wastewater, so the air enthalpy of this process is slightly improved. The change from a1 to a2 is the air cooling process in the evaporator accompanied by water vapor condensation in air. The temperature pinch point appears at a2, and the pinch point temperature differences are Δt_{pe}. Another air cooling process of a2 to a3 is carried out in the cooler. Besides,due to the differences between heat transfer of evaporator and cooler, the slope of a2 to a3 is different from that of a1 to a2. In addition, the enthalpy differences between a1 and a2 is slightly larger

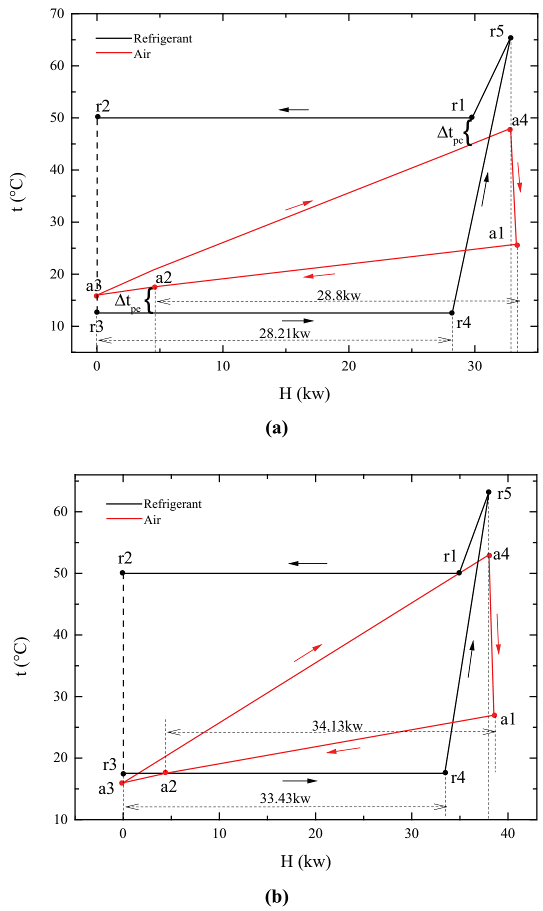


Fig. 3. t-H diagram of air and refrigerant in HPAH-EWTS when using common refrigerant (R22): a) Δt_{pc}=5°C and Δt_{pe}=5°C; b) Δt_{pc}=0°C and Δt_{pe}=0°C.

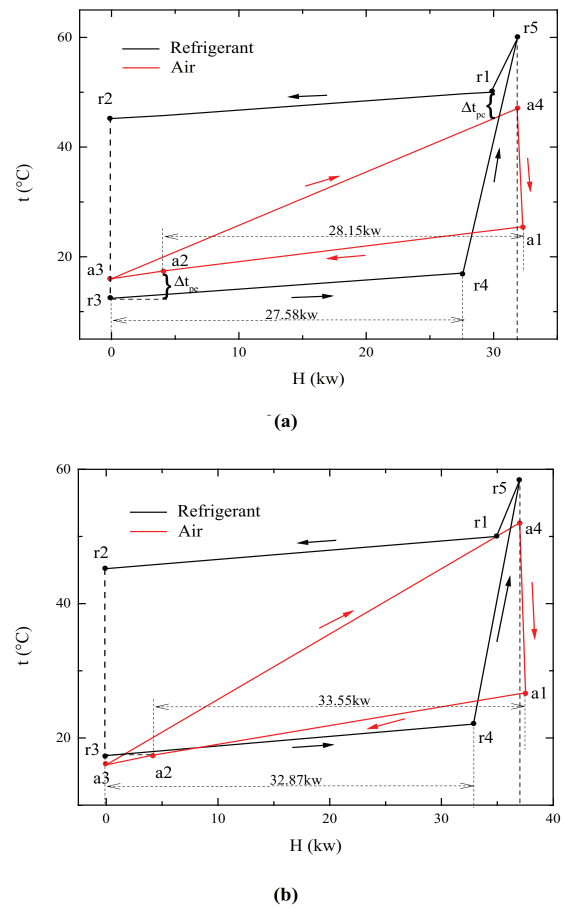


Fig. 4. t-H diagram of air and refrigerant in HPAH-EWTS when using non-azeotropic refrigerant in normal condition (R407c): a) Δt_{pc}=5°C and Δt_{pe}=5°C; b) Δt_{pc}=0°C and Δt_{pe}=0°C.

than that between r4 and r3. This is because there exists the condensate water discharged from the evaporator.

Fig. 3b shows the t-H diagram of the air and refrigerant flowing process of the system using common refrigerant when pinch point temperature differences are equal to 0°C. Compared with Fig. 2a, for the circulation of the refrigerant, the condenser side does not change significantly and the evaporation temperature is higher than the case with the pinch point temperature differences. For the circulation of the air, air temperature of a4 exceeds the condensation temperature. This is due to the counter current condenser arrangement and the higher temperature of the inlet refrigerant.

Therefore, the pinch point temperature differences will have a certain impact on the system. Reducing the pinch point temperature differences of condenser (Δt_{pc}) can increase the outlet air temperature of the condenser (maybe make it higher than condensation temperature) and reduce the difference between condensation temperature and evaporation temperature.

4.2. Pinch point analysis of HPAH-EWTS using R407c

Fig. 4a and Fig. 4b show the t-H diagram of the air and refrigerant flowing process of the system using non-azeotropic refrigerant in normal condition. Fig. 4a represents the process with pinch point temperature differences, while Fig. 4b represents the process that the pinch point temperature differences are equal to 0. The heat transfer process of system using non-azeotropic refrigerant in normal condition is similar to the process of system with common refrigerant. But due to using non-azeotropic refrigerant, the temperature of the phase change process of the refrigerant in the evaporator and the condenser is constantly changing.

Fig. 5a and Fig. 5b illustrate the t-H diagram of the air and refrigerant flowing process of the system using non-azeotropic refrigerant when system running in abnormal condition. When the dew point temperature at the refrigerant condensing pressure is small (lower than 30°C), the temperature of r4 is higher than the temperature of a1 and the temperature of r3 is lower or equal to the temperature of a2. Because of this condition, there exists the reverse heat transfer between the air and the refrigerant in the evaporator, which cannot appear in the actual operation. The reason for the above-mentioned reverse heat transfer process is that the dew point temperature at the refrigerant condensing pressure is too low. In addition, two pinch point temperature differences could also influence this abnormal

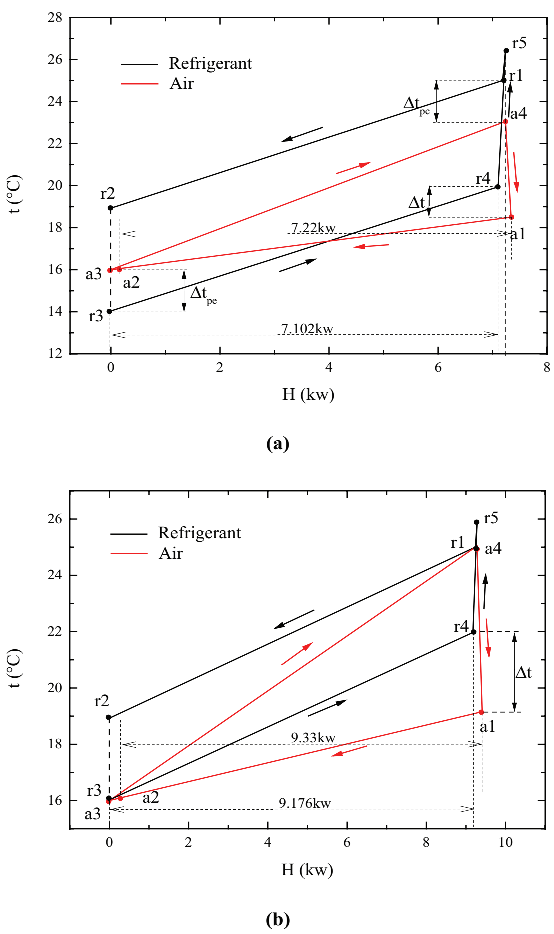


Fig. 5. t-H diagram of air and refrigerant in HPAH-EWTS when using non-azeotropic refrigerant in abnormal condition (R407c): a) Δt_{pc}=5°C and Δt_{pe}=5°C; b) Δt_{pc}=0°C and Δt_{pe}=0°C.

condition. How to prevent the reverse heat transfer would be discussed in the next section.

5. Result and discussion

The consequence of the system pinch point analysis on the effect of common refrigerant or non-azeotropic refrigerant systems are discussed here.

5.1. Experimental verification of mathematical model.

The data obtained from the verification experiment and mathematical model are shown in Table 2. The comparisons between experiment data and model data are based on outlet air temperature of the tower (t_{a1}) and mass rate of evaporation (m_e). From the perspective of heat and mass transfer, the temperature difference between a1 and a4 is the driving force of the whole separation process. Therefore, when inlet air temperature of tower (t_{a4}) is determined, comparison of t_{a1} can directly reflect the accuracy of the model. In addition, m_e is directly related to the WTL for this system. It can be seen from the table that the error of t_{a1} is less than 2% and that of m_e is less than 6%. So the hypothesis and thermodynamic model of evaporation separation process are basically correct.

5.2. The effect of pinch point when system using common refrigerant (R22)

Fig. 6a and Fig. 6b show the effect of the pinch point temperature differences of condenser and evaporator on wastewater treatment load respectively. With the pinch point temperature differences of condenser (Δt_{pc}) increase, the WTL gradually decreased. The increase in Δt_{pc} leads to the decrease in the outlet air temperature of the condenser and the heat carried by the air, which results in the decrease in the mass

Table 2
Experimental verification of thermodynamic model of evaporation separation process

Inlet air temperature of the tower t_{a4} (°C)	humidity ratio of inlet air w_{a4} (kg/kg)	Mass flow rate of air m_d (kg/h)	Outlet air temperature of the tower t_{a1}(°C)			Mass rate of evaporation m_e(kg/s)		
			Experiment value	Model calculation value	Error (%)	Experiment value	Model calculation value	Error (%)
70.38	0.01266	66.89	41.77	41.05	1.7237	0.0007704	0.0007299	5.2570
65.70	0.01266	66.84	41.06	40.68	0.9255	0.0007298	0.0007093	2.8090
59.85	0.01266	66.87	40.39	40.25	0.3466	0.0006937	0.0006866	1.0235
55.09	0.01265	66.89	39.85	39.9	–0.1255	0.0006657	0.0006682	–0.3755
50.09	0.01263	66.85	39.51	39.53	–0.0506	0.0006482	0.000649	–0.1234
70.13	0.01266	83.08	39.72	40.01	–0.7301	0.0008183	0.0008369	–2.2730
65.14	0.01267	83.09	38.99	39.6	–1.5645	0.0007724	0.0008107	–4.9586
59.92	0.01266	83.12	38.55	39.17	–1.6083	0.0007462	0.000784	–5.0657
54.98	0.01266	83.09	38.27	38.76	–1.2804	0.0007292	0.0007585	–4.0181
49.92	0.01265	83.15	37.68	38.33	–1.7251	0.0006957	0.0007332	–5.3903
70.12	0.01268	99.03	39.62	39.22	1.0096	0.0009672	0.0009375	3.0707
65.14	0.01267	99.21	38.49	38.77	–0.7275	0.0008860	0.0009062	–2.2799
59.93	0.01266	98.97	38.05	38.31	–0.6833	0.0008532	0.0008713	–2.1214
54.98	0.01264	99.16	37.97	37.84	0.3424	0.0008498	0.0008410	1.0355
49.92	0.01266	99.24	37.18	37.37	–0.5110	0.0007963	0.0008093	–1.6326

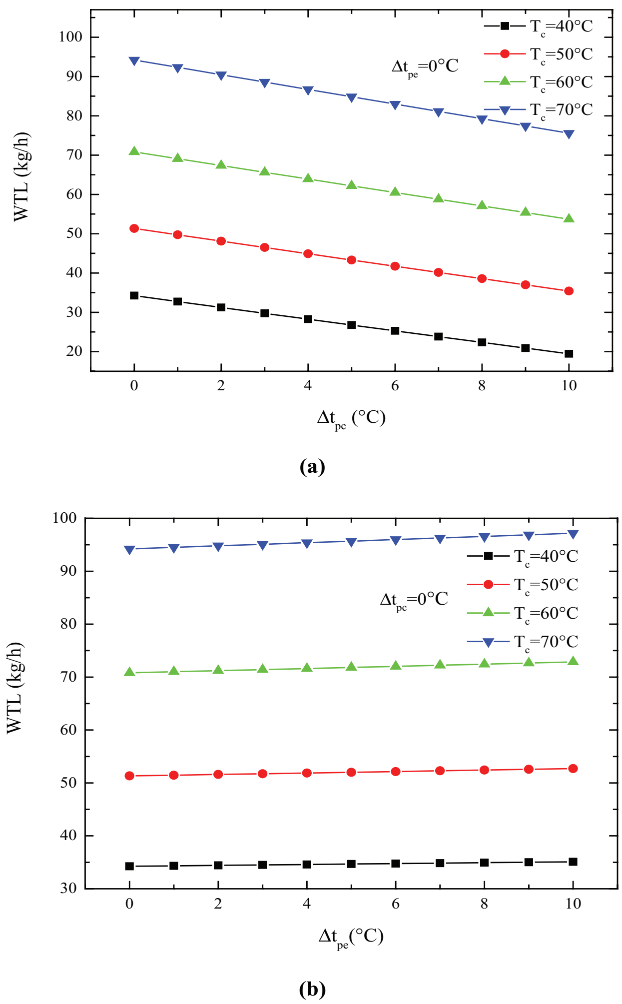


Fig. 6. The influence of pinch point temperature differences on WTL when using common refrigerant (R22): a) pinch point temperature differences of condensation; b) pinch point temperature differences of evaporation.

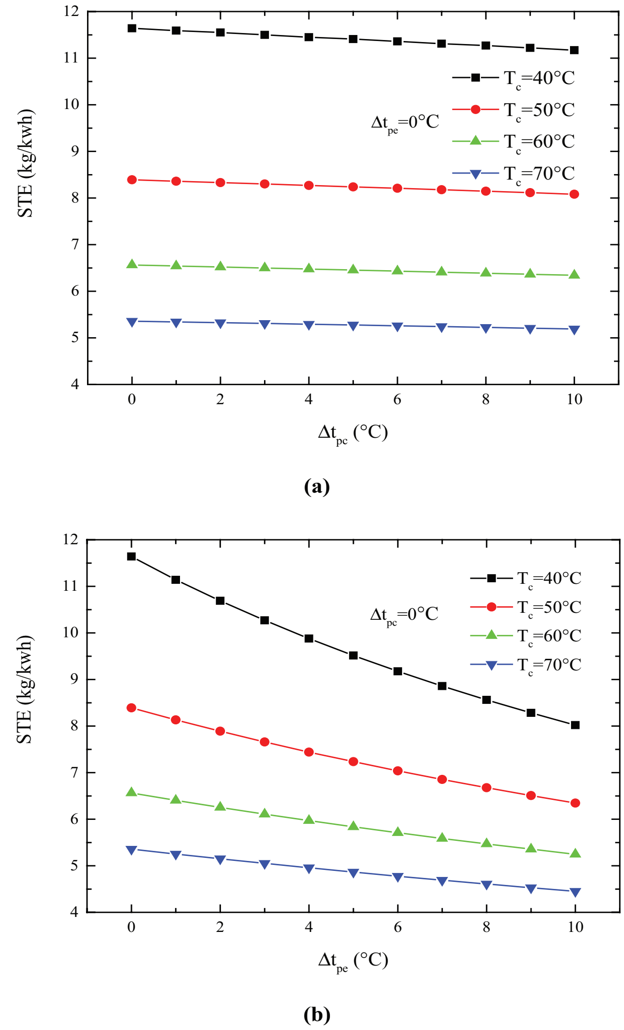


Fig. 7. The influence of pinch point temperature differences on STE when using common refrigerant (R22): a) pinch point temperature differences of condensation; b) pinch point temperature differences of evaporation.

transfer of air and wastewater in the evaporation separator. With the increase of pinch point temperature differences of evaporation (Δt_{pe}), the WTL increased slightly. The increase of Δt_{pe} results in the decrease of evaporation temperature, which leads to a slight increase of the heat exchange of condenser that can improve the heat carried by the air.

Fig. 7a and Fig. 7b indicate the influence of the pinch point temperature differences of condenser and evaporator on the system treatment efficiency. STE decreases with the increase of Δt_{pc}, and decreases with the increase of Δt_{pe}. When Δt_{pc} increases, the outlet air temperature of the condenser decreases, which results in the decrease of mass transfer in the evaporation separator. Besides, when Δt_{pe} raises, the evaporation temperature drops, which results in the increase in the compressor power consumption. Through the comparison of Fig. 7a and Fig. 7b, Δt_{pe} has a greater impact on STE, while the impact of Δt_{pc} is relatively small.

In actual system, it is necessary to reduce pinch point temperature differences of both condensation and evaporation. And improving the heat transfer process of evaporator is more important.

5.3. Measures to prevent abnormal condition when system using non-azeotropic refrigerant (R407c)

Fig. 8 indicates the influence of refrigerant dew temperature under condensation pressure on evaporator air inlet temperature and refrigerant dew temperature under evaporation pressure, in four different Δt_{pe}. The reverse heat transfer happens when the evaporator air inlet temperature is lower than the refrigerant dew temperature under evaporation pressure. With Δt_{pe} increasing, the intersection of two curves, which represents the limit condition that the reverse heat transfer of evaporator does not occur, gradually shifted to the left. Therefore, as Δt_{pe} increases, the ultimate condensation temperature of the heat transfer reversal will gradually decrease. Appropriate increase in Δt_{pe} and the condensation temperature can avoid heat transfer reversal.

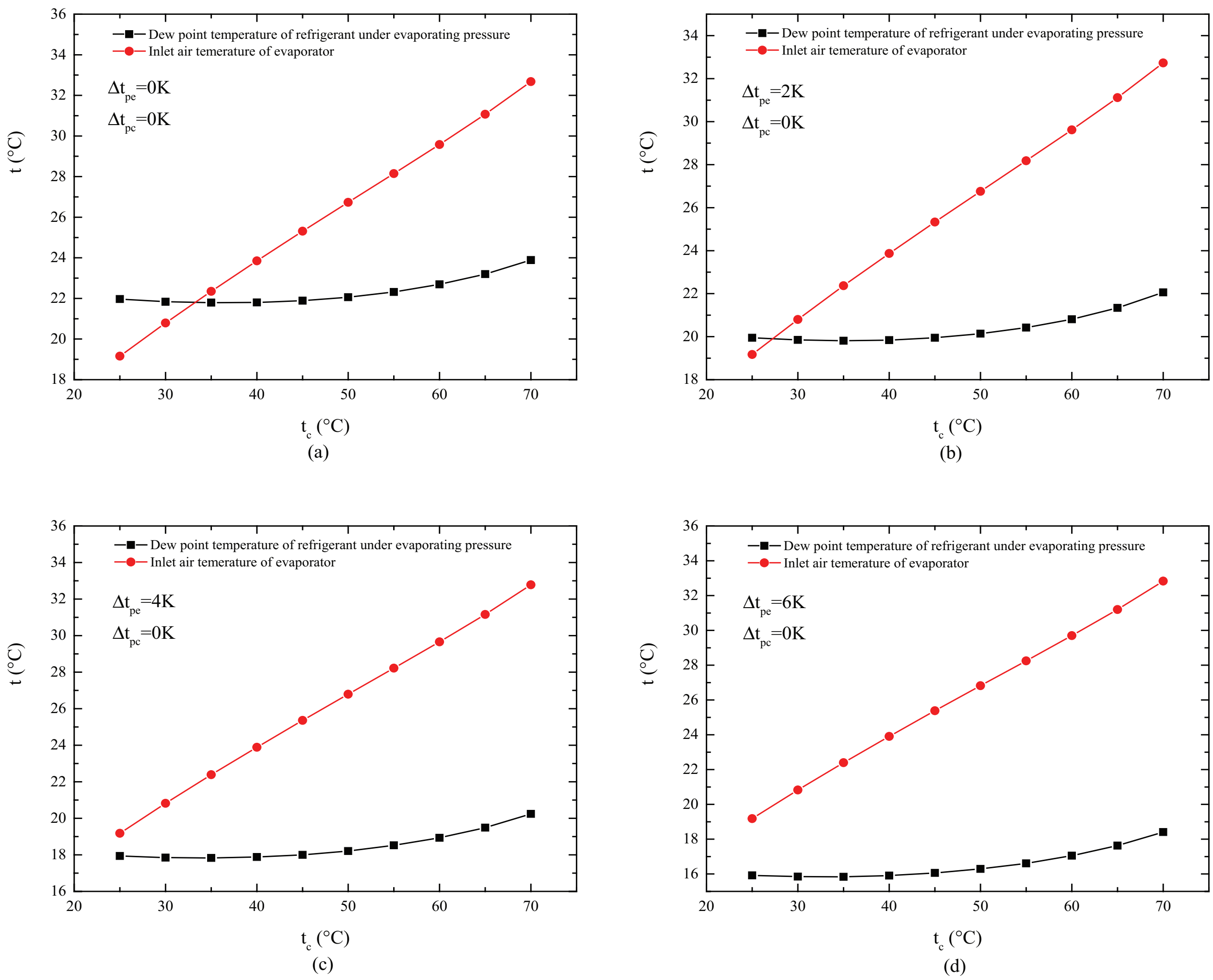


Fig. 8. The influence of refrigerant dew temperature under condensation pressure on the evaporator air inlet temperature and the refrigerant dew temperature under evaporation pressure when $\Delta t_{pc} = 0°C$: a) $\Delta t_{pe} = 0°C$; b) $\Delta t_{pe} = 2°C$; c) $\Delta t_{pe} = 4°C$; d) $\Delta t_{pe} = 6°C$.

Fig. 9 shows the changes of evaporator air inlet temperature and refrigerant dew temperature under evaporation pressure with the refrigerant dew temperature under condensation pressure, in four different pinch point temperature differences of condensation. With Δt_{pc} increasing, the intersection of two curves gradually shifted to the right. This condition indicates that with Δt_{pc} increases, the ultimate condensation temperature of the heat transfer reversal will gradually increase. So the influence of Δt_{pc} is opposite to Δt_{pe} and decreasing Δt_{pc} would be necessary.

To prevent the reverse heat transfer in evaporator, it is indispensable to keep a higher condensing temperature (higher than 40°C). When a low condensing temperature (such as 35°C) must be chosen, decreasing Δt_{pc} and increasing Δt_{pe} can prevent this abnormal condition.

5.4. The effect of pinch point when system using non-azeotropic refrigerant (R407c) in normal condition

As is shown in Fig.10, the effect of the pinch point temperature differences of condensation and evaporation on WTL is indicated respectively in non-azeotropic refrigerant system. Similar to the common refrigerant system, the increase of Δt_{pc} causes the decrease of WTL, while the increase of Δt_{pe} will slightly enhance WTL in the system using non-azeotropic refrigerant in normal condition.

Fig. 11 illustrates the influence of the pinch point temperature differences of condensation and evaporation on STE. The effect of the pinch point temperature differences on STE of the non-azeotropic refrigerant system is also similar to that of the common refrigerant system. The trend of change refers to the system of common refrigerant.

5.5. Comparison of different refrigerant systems

In this part, four different refrigerants are involved in order to select a refrigerant that is most suitable for the system. Fig. 11 shows the comparison of the wastewater treatment load of four refrigerant systems. They include three different common refrigerants (R22, R134a and R717) and a non-azeotropic refrigerant (R407c).

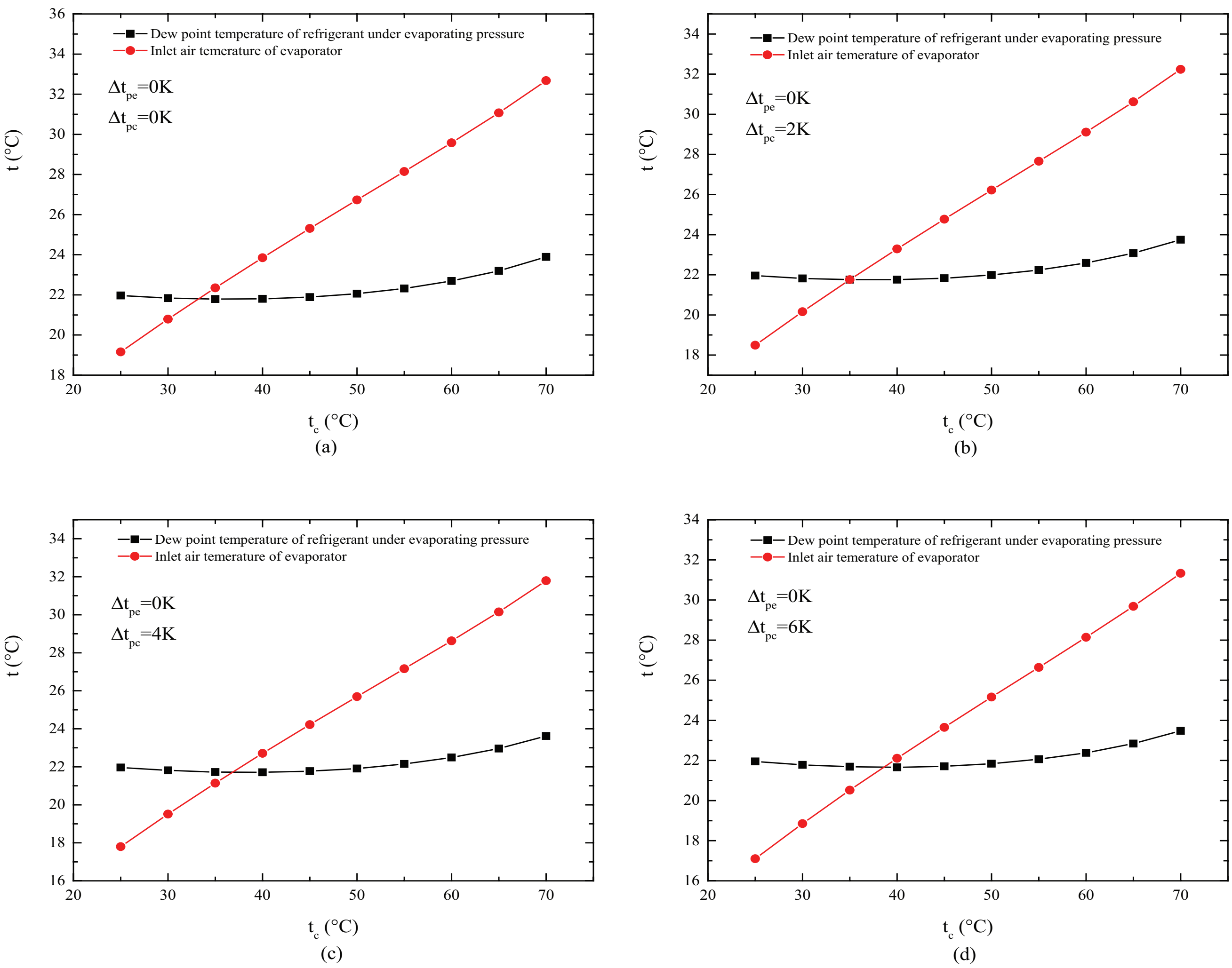


Fig. 9. The influence of refrigerant dew temperature under condensation pressure to the evaporator air inlet temperature and the refrigerant dew temperature under evaporation pressure when $\Delta t_{pe} = 0°C$: a) $\Delta t_{pc} = 0°C$; b) $\Delta t_{pc} = 2°C$; c) $\Delta t_{pc} = 4°C$; d) $\Delta t_{pc} = 6°C$.

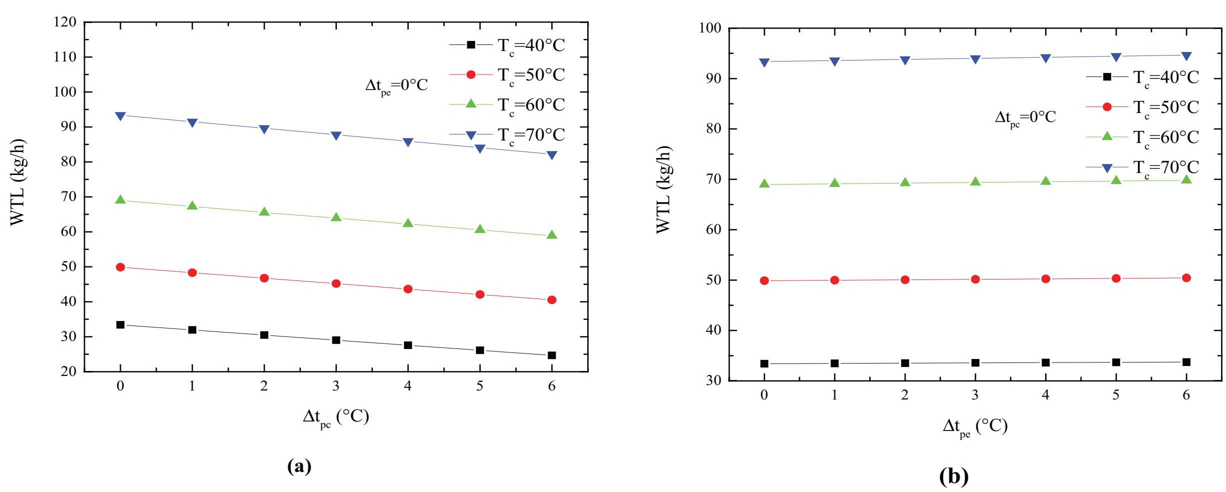
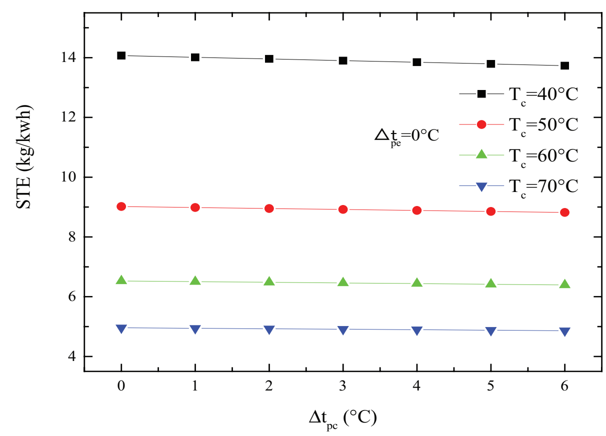
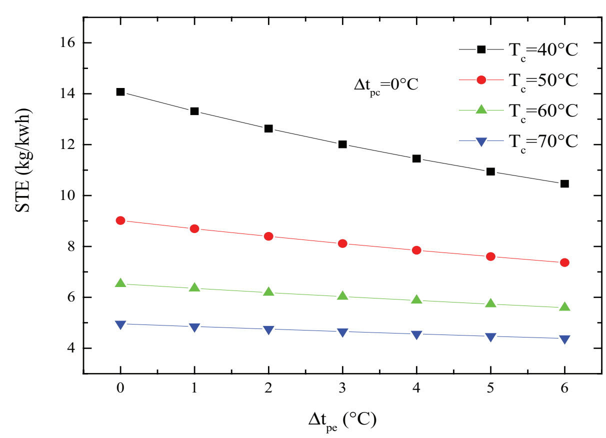


Fig. 10. The influence of pinch point temperature differences on WTL when using non-azeotropic refrigerant (R407c): a) pinch point temperature differences of condensation; b) pinch point temperature differences of evaporation.

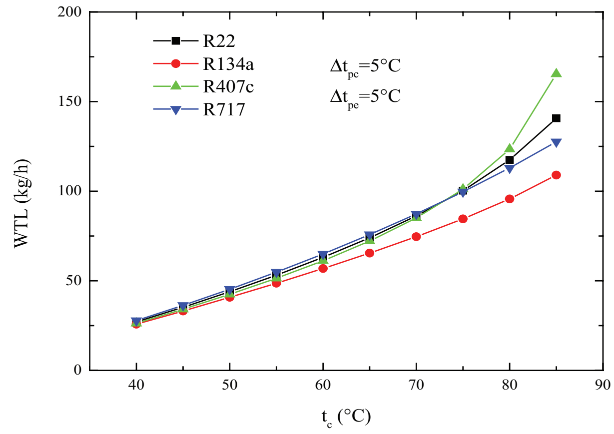


(a)

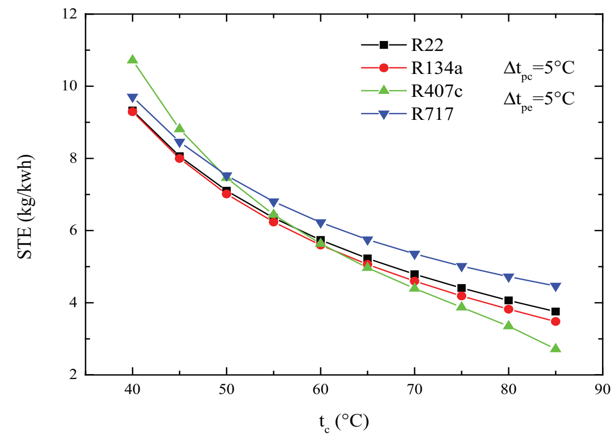


(b)

Fig. 11. The influence of pinch point temperature differences on STE when using non-azeotropic refrigerant (R407 c): a) pinch point temperature differences of condensation; b) pinch point temperature differences of evaporation.



(a)



(b)

Fig. 12. Comparison of 4 different refrigerant systems: a) WTL b) STE.

In Fig. 12a, the comparison of wastewater treatment load is given. Whichever refrigerant is used, the WTL increases with the raise of the condensing temperature. When the condensing temperature is lower than 70°C, the WTL of those four refrigerants system is approximate. The WTL of the system using R717 is slightly higher than that of R22 and R407. However, when the condensing temperature is higher than 75°C, the WTL of the non-azeotropic refrigerant (R407c) system is much higher than that of R22 system and R717 system. That is to say: when the condensing temperature is high, the use of R407c system of wastewater treatment may be the best choice in terms of WTL. Besides, no matter how the condensing temperature changes, the WTL of R134a system is lowest.

Fig. 12b shows the system treatment efficiency comparison of these four systems. Four systems have the same commonality. With the increase of condensing temperature, the STE decreases gradually. For three common refrigerant systems, regardless of the condensing temperature, the R717 system has the best STE, followed by R22 system, and lowest R134a system. R407c system has higher STE than R717 system, when the condensing temperature is lower than 50°C. And STE of R407c system is also higher than that of R22 system and R134 a system when the condensing temperature is lower than 55°C.

So different refrigerants have different influences. At low condensing temperatures (less than 50°C), systems utilizing R407c has a higher STE, and its WTL are not much lower than other systems (basically quite). It can be concluded that when choosing low condensing temperature in HPAH-EWTS, the non-azeotropic refrigerant R407c would be the best choice. When the condensing temperature becomes higher than 50°C, R717 system would be the optimum. In addition, when the condensing temperature is higher than 75°C, the WTL of R407c system is higher than that of R717 system. However, the STE of R717 system is much higher, so in this condition, the choice of R717 is still first-rank. For example, when the temperature is 85°C, the WTL of R407c system is 165.4 kg/h, and that of R717 system is 127.6 kg/h, while the STE of R407c system is just 2.715 kg/kw h, only about 60 percent of STE of the system utilizing R717 (4.467).

6. Conclusion

HPAH-EWTS is analyzed in this paper, including the effect of pinch point temperature differences and different refrigerants. The corresponding conclusions are enumerated as follows:

1. A novel HPAH-EWTS is proposed in this paper. It provides another effective method to treat electroplating wastewater.
2. Pinch point temperature differences of evaporator (Δt_{pe}) plays a more important role than that of condensation (Δt_{pc}) in the STE. Therefore, it is more necessary to enhance the heat exchange of evaporator.
3. The reverse heat transfer in evaporator may happen in the system utilizing non-azeotropic refrigerant (for example, R407c). To prevent this situation, it is indispensable to keep a higher condensing temperature.
4. When choosing low condensing temperature (lower than 50°C), the system using non-azeotropic refrigerant R407c has the highest STE and it could be the best choice of HPAH-EWTS. On the other hands, when the condensing temperature is higher than 50°C, R717 system would be the most optimal choice because of its highest STE and higher WTL.

Acknowledgements

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Symbols

t_0	—	Ambient temperature (°C)
t	—	Temperature (°C)
Δt_{pc}	—	Pinch point temperature differences of condenser (°C)
Δt_{pe}	—	Pinch point temperature differences of evaporator (°C)
ϕ	—	Relative humidity (–)
m_d	—	Mass flow rate of dry air (kg/s)
m	—	Mass flow rate (kg/s)
h	—	Specific enthalpy (kJ/kg)
H	—	Enthalpy (kJ)
Q	—	Heat load (kw)
W_p	—	Compressor work (kw)
c	—	Salt concentration of wastewater (–)
WTL	—	Wastewater treatment load (kg/h)
STE	—	System treatment efficiency (kg/kw h)

Subscripts

a	—	Air
w	—	Wastewater
r	—	Refrigerant
c	—	Condenser
e	—	Evaporator
coo	—	Cooler

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