Optimal design of advanced distillation configuration for enhanced energy efficiency of waste solvent recovery process in semiconductor industry

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ABSTRACT

The semiconductor industry is one of the largest industries in the world. On the other hand, the huge amount of solvent used in the industry results in high production cost and potential environmental damage because most of the valuable chemicals discharged from the process are incinerated at high temperatures. A distillation process is used to recover waste solvent, reduce the production-related costs and protect the environment from the semiconductor industrial waste. Therefore, in this study, a distillation process was used to recover the valuable chemicals from semiconductor industry discharge, which otherwise would have been lost to the environment. The conventional sequence of distillation columns, which was optimized using the Box and sequential quadratic programming method for minimum energy objectives, was used. The energy demands of a distillation problem may have a substantial influence on the profitability of a process. A thermally coupled distillation and heat pump-assisted distillation sequence was implemented to further improve the distillation performance. Finally, a comparison was made between the conventional and advanced distillation sequences, and the optimal conditions for enhancing recovery were determined. The proposed advanced distillation configuration achieved a significant energy saving of 40.5% compared to the conventional column sequence.

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1. Introduction

The semiconductor industry is one of the largest industries in the world, comprising more than $304 billion and representing close to 10% of the world gross domestic product. The global semiconductor industry is dominated by United State of America (U.S.), South Korea, Japan, Taiwan, Singapore, and the European Union. South Korea has a market share about 9%, and the semiconductor industry has been declared one of the most important and a growth power of the nation [1].

Flat panel displays, such as liquid crystal displays (LCD), plasma display panels (PDP), and light emitting diodes (LED), which are used widely in everyday life, have replaced the cathode ray tubes because they are lighter, thinner, have low-power consumption, and are less harmful to the environment compared to cathode ray tubes. A huge amount of various chemicals are used in the manufacture of thin film transistor (TFT) LCD devices. Chemical waste material discharged from the production volume and the manufacturing process of these related products transfer has been rapidly increasing [2,3]. Therefore, it is very important for TFT-LCD manufacturers to reduce the production-related costs and protect the environment from industrial waste. One approach is to collect and reuse process chemicals. From the viewpoint of the cost-competitive pressures and environmental issues, the most effective way is to reclaim (or regenerate) process chemicals to control the chemical cost and minimize the chemical waste and liabilities. In manufacturing, this industry uses large quantities of solvents that are not treated well. So far, most industrially popular method to treat the waste photoresist stripper solvent is incineration where waste solvents are incinerated at very high temperature [4]. However, the high energy cost and secondary pollutants from incineration facilities...
are problematic environmental hazards. To solve this cost and environmental problem in the treatment by incineration, several methods have been explored to recycle or recover organic solvents in the waste photoresist stripper, which include distillation, adsorption, membrane separation, extraction, freeze concentration, photolysis, melt crystallization, and some hybrid processes [5–9]. Among them, distillation has a great potential as a cost effective and environmentally benign way to recover the waste solvent. On the other hand, distillation design involves several parameters and obtaining a cost effective and competitive design is not trivial. Recently, Kim et al. [10] reclaimed 1-hydroxyethylpiperazine (HEP) and methyl diglycol (MDG) from waste photoresist stripper by a packed bed vacuum column at lab-scale experiments. Chaniago et al. [11] proposed conventional distillation sequences to recover the waste organic solvent including HEP and MDG. However, they only recommended a conventional sequence among several conventional sequences based on design heuristics and shortcut methods, and thus left many possibilities for increasing energy efficiency apparently by further rigorous optimization and advanced distillation.

Distillation is one of the most common and energy-intensive separation processes, and one of the most widely-used separation processes in the chemical industry. Although this unit operation has many advantages, one of major drawback is its large energy requirement [12]. Distillation process is responsible for approximately 3% of the total U.S. energy consumption, more than 90% of all product recovery and purification separations in the U.S., and more than 95% of chemical industry consumption worldwide. Therefore, huge energy savings will be provided by any small improvement in distillation [13]. Optimal design is one consideration for a desired sequence. The optimal design for a conventional column can be achieved using an optimization algorithm.

1.1. Thermally coupled distillation column

Increasing cost of energy has pushed industry to reduce distillation energy consumption as well as the tighter environmental regulations have generated the need to exert efficient separation methods [14,15]. The direct conventional distillation sequence for multi component mixture is shown in Fig. 1 where A, B, and C denote the most volatile, middle, and least volatile components, respectively. A is removed in the first column, and then B and C are separated in the second column. In the direct sequence, the composition of middle component in the first column increases below the feed until reaching a peak, and then decreases by the remixing effect which mainly results in inefficiency in the separation. In the conventional distillation sequence, every column contains a condenser and a reboiler for heat transfer. On the other hands, it is possible to use a material flow to provide some of necessary heat transfer by direct contact; it is known as thermal coupling [16]. Thermally coupled distillation (TCD) system can be constructed through the carrying of two interconnecting streams (one in the liquid phase and the other in the vapor phase) between the two columns. One of the most popular TCD configurations is the sequence with a side rectifier, which is illustrated in Fig. 2(a) [17–20]. The side rectifier has topologically and thermodynamically equivalent to the thermally coupled direct sequence as shown in Fig. 2(b) but has a practical difficulty in engineering. The equivalent one or thermally coupled direct sequence is easier to be analyzed than the side rectifier [21]. Component A as the most volatile is recovered on the top product of first column, B is separated in the next separation and C is either in the first column or in the next separation with absence of one reboiler in the operation. These sequences can provide significant energy saving compared to conventional direct sequences [22–24]. The thermally coupled direct sequence was applied in the simulation.

1.2. Thermal integration of heat pump assisted distillation

Standalone unit operations, such as distillation columns, are thermodynamic systems comprised of a heat source (condenser) and heat sink (reboiler). Conventional column utilizes hot utility to supply heat to the bottom reboiler and wastes heat to cold utility at the overhead condenser. An obvious way to reduce the energy consumption is to integrate heat remove at the condenser.
to the reboiler which represent the major energy source and sink, respectively. Among various heat integrated distillation techniques, the heat pumping system has emerged as one of widely accepted schemes for continuous distillation columns [25]. These systems can be represented graphically on a temperature–enthalpy diagram known as the column grand composite curve (CGCC) [26–32]. The $T$–$H$ curve is drawn from generating envelops over a column section from a chosen stage to the top of each column. The net enthalpy deficit at each stage is calculated according to the mass and energy conversation law. The opportunities for implementing the side heating or cooling operations in the column can be determined from the shape of the CGCC. The large shift in the heat load shows that there is a large amount of heat transfer from the vapor phase to the liquid phase in the column, and there is the potential to provide heat or remove the heat at these temperatures. To make heat pump work properly in distillation process, the system must operate between small temperatures. A more detailed description about CGCC can be read elsewhere [26]. A systematic flow chart has already been proposed and can be used to quick determine a configuration. This chart mostly represents vapor recompression column or heat pump assisted distillation [33].

The objective of the present work is to study advanced distillation configurations with enhanced energy efficiency for waste solvent recovery from the semiconductor industry that would otherwise have been lost to the environment or incinerated. An optimal distillation design was proposed with the proper conditions for reclaiming many organic solvents. To the best of the authors’ knowledge, this is the first report to explore advanced distillation schemes for reclaiming the organic solvent from semiconductor industry waste. Aspen Hysys as a powerful tool was used to simulate all the designs.

2. Optimization and design methodology

This study is based on the report by Chaniago et al. [11]. Laboratory experiment was conducted to identify components of waste solvent. The result showed mixture composition, separation feasibility and also includes process constraint. Compositions contain isopropanolamine (IPA), water (H$_2$O), monoisopropanolamine (MIPA), methyl diglycol (MDG), N-methylformamide (NMF), 1-piperazineethanol (HEP), and Photoresist Removal (PR). Table 1 lists the waste solvent feed compositions in mass % used in this study.

The initial process was developed using a short-cut column design method. The Fenske–Underwood–Gilliand (FUG) estimation was used to estimate the optimal design by fixing the reflux ratio of the reflux minimum to 1.1. All components recovered for sale purposes must have more than 98 wt.% purity and a water content of less than 0.1 wt.% Because H$_2$O has some undesirable side reactions (e.g., side reactions with NMF at above 200 °C, thermal decomposition or deformation of HEP at above 160–200 °C, resulting in a color change to yellow), it should be first removed from the 1st column operated at temperatures less than 80 °C, so the product after the first column contains a water impurity of less than 2–3 wt.%. All subsequent columns should be operated below 180–190 °C to avoid side reactions using vacuum columns [10]. Some heuristics were applied to establish the distillation sequences [34]. Previous work concluded that a modified direct sequence was the best option in terms of the reboiler duty, purity and main product recovery among several conventional distillation sequences [11]. Note that the energy efficiency of the proposed conventional sequence can be further improved by rigorous optimization and proper application of advanced distillation techniques.

In the modified direct sequence, the relative volatility between NMF–HEP is quite high; NMF and HEP can be separated at column-3. The result is similar to the direct sequence, but there is some improvement in the main product purity and total reboiler duty. In the column of this sequence, close boiling point components, MDG and NMF, are treated in a single column, and improvements become more attractive because this structure is suitable for vapor recompression.

The non-random two liquid model (NRTL) fluids package was used as a thermodynamic method of simulation in this work. The UNIQUAC Functional-group Activity Coefficient (UNIFAC) method was applied to estimate the missing parameters of the NRTL system.

<table>
<thead>
<tr>
<th>MDG</th>
<th>HEP</th>
<th>IPA</th>
<th>MIPA</th>
<th>NMF</th>
<th>H2O</th>
<th>PR</th>
</tr>
</thead>
<tbody>
<tr>
<td>33</td>
<td>21</td>
<td>3</td>
<td>12</td>
<td>15</td>
<td>12</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 1

Fig. 2. Thermally-coupled distillation sequences: (a) side rectifier configuration and (b) thermally coupled direct sequence.
Conventional distillation was first optimized in terms of reboiler duty. Several advanced configurations using the TCD were applied to enhance the energy efficiency. Optimization was then tried to find the lowest reboiler duty in each advanced distillation sequence examined. After the second optimization, columns in the advanced design were further improved by applying a heat pump technique to maximize energy efficiency. Fig. 3 illustrates the outline of design and optimization methodology mentioned above.

3. Optimization of conventional column sequence

In this study, the modified direct sequence shown in Fig. 4 [11] was chosen as a base case and rigorously optimized for further comparison study. The purpose of this conventional sequence is to recover MIPA, NMF, MDG, and HEP where MDG and HEP are main targets. Water and IPA are completely removed from the first column so that the bottom product from column-1 contains water less than 0.01 wt.%, which secures a required water impurity level of less than 0.1 wt.% for every recovered product in the next columns. Column-2 separates MIPA on the top product and its bottom product is then introduced to column-3. MDG and NMF are recovered from column-4 and HEP is recovered from column-5. All conventional columns were designed to meet all the process constraints listed in Table 2.

Distillation column has several variables that need to be optimized. To optimize the conventional sequence in Fig. 4, conventional columns were optimized to minimize the reboiler duty. Because one column affects the other subsequent columns in the system, the column result should be under constraint. Otherwise, the final target product will not be satisfied and recovery is smaller. Every column has temperature constraints and a minimum required purity for each product except for the PR. Minimization of the reboiler duty itself does not guarantee that the final result will be satisfactory. Every column optimization needs to satisfy the next column minimum specification product in this optimization, particularly the purity of the main component products, HEP, and MDG. The first column optimized should meet the minimum product requirements and temperature constraints of the subsequent columns. For column-2, optimization also follows the same rule. This column optimization should also meet the minimum product requirement and temperature constraints of the next columns. Column-1 optimization must meet the constraints of column-2, 3, 4, and 5. In the next column optimization, column-2 optimization must also meet the constraints of column-3, 4, and 5, and column-3 optimization must also meet the constraints of column-4 and 5.

Optimization of heat duty of the column can be expressed as

\[
\min(Q) = f(R, P_c, T_F, N_F, N_T)
\]

where \( R \) is the reflux ratio, \( P_c \) is the column pressure (atm), \( T_F \) is the feed temperature (°C), \( N_F \) is the location of feed stage, and \( N_T \) is the number of column stages. These five variables were used only in the first column because \( T_F \) for the next column is comprised of the defendable variables from the previous column. Only four variables were thus adjusted for the next columns; \( R, P_c, N_T \), and \( N_T \).

The Box method [35, 36] was applied to optimize all the conventional sequence columns because it is easy to use as it is already implemented in Aspen Hysys. This built-in optimization method can utilize variables of optimization and the constraints in a simple procedure. In the built-in optimization in Aspen Hysys, every optimizing variable can be linked in the optimization spreadsheet and set in one optimizer-variables window. The benefit of this simple method is all the column constraints can be set altogether in one optimization run and it clearly presents and solves the optimization problem in a simple procedure. Convergence problem may occur because the strict constraints can inflict severe difficulties on minimizing the objective function. Product from columns-1, 2 and 3 are not the main column products, but the product purity is still considered in column-2; a minimum purity of 98 mass %. In optimization, the purity constraint was set to 98.9%, which is considered an intermediate value between 98% and 99.99%, because although it is possible to make a side product purity of 99.9%, it will waste considerable energy while the minimum requirement for selling purposes is 98%.

All conventional sequence columns were set to obtain the minimum reboiler duty without violating the constraints. All constraints are an inequality, and the Box method had no big difficulty in optimizing the conventional sequence columns. Fig. 5 outlines the optimization strategy for a conventional column. Dash line in Fig. 5 represents the boundary of each column.
optimization which will be continued to the next column if one column optimization finishes.

Each column has 4 variables to be optimized except column-1 which has 5 variables. \(N_f\) was optimized manually and the other variables were optimized in Hysys. In the first column, the initial feed stage was 11 and this stage number was fixed in the first step optimization of column-1 while the other optimization variables (**T**\(_p\), **R**, \(N_f\) and \(N_t\)) in the columns were optimized simultaneously by the simulator using an optimizer. Feed stage optimization has 5 runs, 2 different stages below the initial stage and 2 others above the initial stage. Optimization would move to another feed stage after the initial feed stage was optimized. Every column has 5 runs for optimization and the column condition might be reset to be initial condition for every trial. The lowest reboiler duty was then

![Fig. 4. Modified conventional direct sequence of waste solvent separation.](image)

![Fig. 5. Optimization scheme of conventional columns.](image)

<table>
<thead>
<tr>
<th>Column-1 (C1)</th>
<th>Column-2 (C2)</th>
<th>Column-3 (C3)</th>
<th>Column-4 (C4)</th>
<th>Column-5 (C5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top temperature &lt; 80 °C</td>
<td>Mass Frac MIPA &gt; 98.9%</td>
<td>Bottom temperature &lt; 188.9 °C</td>
<td>Mass Frac MDG &gt; 98.9%</td>
<td>Mass Frac HEP &gt; 98.9%</td>
</tr>
<tr>
<td>Bottom temperature &lt; 188.9 °C</td>
<td>Bottom temperature &lt; 188.9 °C</td>
<td>Bottom temperature &lt; 188.9 °C</td>
<td>Bottom temperature &lt; 188.9 °C</td>
<td>Bottom temperature &lt; 188.9 °C</td>
</tr>
<tr>
<td>H(_2)O mass flow top &gt; 118 kg/h</td>
<td>Mass Frac MIPA &gt; 98.9%</td>
<td>Bottom temperature &lt; 188.9 °C</td>
<td>Mass Frac NMF &gt; 98.9%</td>
<td>Mass Frac HEP &gt; 98.9%</td>
</tr>
</tbody>
</table>

Table 2
Overall constraints of conventional distillation optimization, (top pressure < bottom pressure).
columns is not as exhaustive as complex methods that work with specific set of external coding, it has solved complex problem.

Total reboiler duty after optimization reduced to 826.6 kW with MDG product purity of 99.00 wt.% and HEP of 98.90 wt.%.

Optimization result is shown in Table 3.

Table 3

<table>
<thead>
<tr>
<th>Variables</th>
<th>Optimal value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Column-1</td>
</tr>
<tr>
<td>Reflux ratio (Molar base)</td>
<td>0.480</td>
</tr>
<tr>
<td>Top pressure (Atm)</td>
<td>0.65</td>
</tr>
<tr>
<td>Bottom pressure (Atm)</td>
<td>0.80</td>
</tr>
<tr>
<td>Number of stages</td>
<td>24</td>
</tr>
<tr>
<td>Feed stage</td>
<td>12</td>
</tr>
<tr>
<td>Reboiler duty (kW)</td>
<td>219.1</td>
</tr>
</tbody>
</table>

4. Design of advanced distillation configuration

Energy efficiency can be improved by enhancing the distillation column. Many studies have confirmed that TCD system can reduce the column energy consumption [37–43]. The TCD sometimes only produces small energy savings for an optimized system. Another configuration can also achieve more energy saving in limited cases. Several direct sequences exist and one binary column with a close boiling point in this system can achieve energy saving improvement by proper configuration. Fig. 7 presents the possible energy improvement in the system. Although the current optimal conventional sequence can be improved in terms of energy efficiency, none of the improvements should violate the hard constraints of this system.

In the conventional sequence, there are four regions for possible enhancement that are represented by dotted squares in Fig. 7. Regions 1, 2 and 3 are direct sequences and would be enhanced by thermal coupling. Region 4 would be analyzed by the column grand composite curve (CGCC) before enhancing.

4.1. Advanced design with thermal coupling of column-1 and column-2

Advanced design 1 is to couple columns-1 and column-2 at region 1, as shown in Fig. 8. This thermal coupling meets more than 3 hard constraints, i.e., the column 1–2 constraints and the column-3, 4 and 5 constraints. The problem with this design is that the column-1 bottom column pressure is higher than column-2 pressure when they are coupled. Difficulties occur in meeting the required bottom product composition of column-2 if columns-1 and column-2 have a uniform pressure. This issue affects the next column product purity. Thermally-coupled distillation integrating columns-1 and column-2 (TCD 1–2) has 288.3 kW and the total reboiler duty of the optimal column-1 and column-2 are 287.1 kW. This design is not recommended because TCD 1–2 fails to improve the energy savings and there are many hard constraints.
4.2. Advanced design with thermal coupling of column-2 and column-3

The next configuration based on region 2 is to couple columns-2 and column-3, as depicted in Fig. 9. This coupled column has 3 hard constraints, i.e., the column 2–3, columns-3 and column-5 constraints. This configuration also has same problem as advanced design I. The column-2 bottom pressure is higher than column-3 when they are coupled. The vapor split returns from column-3 to column-2 through the higher pressure of bottom column-2. The column-2 top purity will decrease if the pressure of column-2 value decreases toward to the column-3 pressure value. Fig. 9 shows the resulting advanced design with a slight improvement.
in the total energy duty compared to the optimal conventional design and also with the higher bottom pressure of column-2 than column-3.

4.3. Advanced design with thermal coupling of column-3 and column-5

The possible TCD configuration on region 3 has more benefit, because the pressure difference between column-3 and column-5 is small enough. A large pressure difference often causes a problem in implementing the uniform pressure for the TCD. The other problems are purity and temperature constraints. Those hard constraints must also be fulfilled when the column configuration is changed. The pressure increase of column-5 is not a good option to make the pressure uniform with column-3. The column-5 bottom temperature will violate the temperature constraint below 190 °C if the column-5 pressure increases. The column-3 pressures can be decreased to satisfy the required purity. The resulting reboiler duty of TCD 3–5 was 123.9 kW which is equivalent approximately to 15% energy saving compared to that of columns-3 and column-5 in the optimal conventional sequence, which was 145.8 kW. Fig. 10 presents the advanced design with TCD 3–5.

A minor problem occurs for this configuration. The MDG purity of column-4 decreases to 98.95% from 99% with the same column specification compared to the optimal conventional column-4. This slight problem can be solved by increasing the reflux ratio of column-4 in the new configuration. This configuration still contains non-optimal TCD and targeted product should be 99% or little more than 99% if there is convergence problem to make fair comparison with previous design. As a consequence, the reboiler duty column-4 increases but the total reboiler duty in the new configuration is still lower than the optimal conventional column.

Table 4 compares the reboiler duties of the optimal conventional column sequence and advanced column design I, II, and III.

<table>
<thead>
<tr>
<th>Optimal conventional</th>
<th>Advanced design I</th>
<th>Advanced design II</th>
<th>Advanced design III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Column Duty (kW)</td>
<td>Column Duty (kW)</td>
<td>Column Duty (kW)</td>
<td>Column Duty (kW)</td>
</tr>
<tr>
<td>1 219.1</td>
<td>288.3</td>
<td>1 219.1</td>
<td>1 219.1</td>
</tr>
<tr>
<td>2 68.0</td>
<td>176.1</td>
<td>2 68.0</td>
<td>2 68.0</td>
</tr>
<tr>
<td>3 112.4</td>
<td>3 112.4</td>
<td>3 112.4</td>
<td>3 112.4</td>
</tr>
<tr>
<td>4 393.6</td>
<td>393.6</td>
<td>4 393.6</td>
<td>4 393.6</td>
</tr>
<tr>
<td>5 33.5</td>
<td>33.5</td>
<td>5 33.5</td>
<td>5 33.5</td>
</tr>
<tr>
<td>Total (kW)</td>
<td>826.6</td>
<td>827.8</td>
<td>822.3</td>
</tr>
</tbody>
</table>
4.4. Optimization of TCD 3–5 based on the response surface methodology

The response surface methodology (RSM) was implemented successfully to optimize the structure of the dividing wall column (DWC) in previous studies [44,45]. The main advantage of the RSM is its ability to gain an understanding of the main factors and interactions that affect the studied response, which is used to generate the reduced process model. Furthermore, the RSM can be used as an alternative optimization methodology to reach pseudo-optimal solutions with a high statistical confidence for its results [46].

After determining the preliminary ranges of the variables through single-factor testing, a central composite design was used to determine how the variables interact as well as to optimize the system in terms of the reboiler duty. The simulation data was fitted to a second-order polynomial model and the regression coefficients were obtained. The generalized second-order polynomial model used in response surface analysis can be expressed as

\[ Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \sum_{j=i+1}^{k} \beta_{ij} X_i X_j + \varepsilon \]  

where \( Y \) is the predicted response (reboiler duty), \( X_i \) are the uncoded or coded values of the variables, \( \beta_0 \) is a constant, \( \beta_i \) and \( \beta_{ij} \) are the coefficients of the linear, quadratic and interactive terms, respectively, \( k \) is the number of main design variables, and \( \varepsilon \) is an error term.

After fixing the preliminary design of the TCD 3–5 structure in Fig. 11, the main design variables were then optimized including the internal vapor flow (FV) to the side rectifier, feed (N1) and vapor (N2) stream locations. Note vapor stage location in column 5 is same location with liquid input stage location in column 5. Thirteen simulations were run to optimize 2 parameters of the TCD structure: the feed (N1) and vapor (N2) stream location. For each run, the vapor flows to the side rectifier were then optimized using a rigorous simulation to minimize the reboiler duty, while maintaining satisfactory product purity. The simulation data was fitted to a second-order polynomial model and the regression coefficients were obtained. MINITAB software was used for both the response surface fitting and to optimize the reboiler duty. The generalized second-order polynomial model was obtained as follows:

\[
Y = 120.87 - 0.5346(N1) - 0.0862(N2) + 0.0137(N1)^2 \\
+ 0.0017(N2)^2 + 0.0004(N1)(N2)
\]  

where \( Y \) is the predicted response of the reboiler duty (kW), and N1 and N2 are the values of the vapor and feed stream locations, respectively. Fig. 12 shows the contour plot of the interaction between the main design variables, N1 and N2. As shown in Fig. 13, the lowest reboiler duty was observed at the number of trays for the feed rectifying section, and the vapor stream location of 19.2 and 23.0, respectively. Under these conditions of the optimized TCD, the predicted minimum reboiler duty was 114.8 kW (equivalent to 7% energy saving compared to the non-optimal TCD 3–5 of advanced design III).
4.5. Heat integration and heat pump assisted distillation

Energy efficiency of distillation column can be significantly improved by properly utilizing heat pump [47]. Heat integration and heat pump applications were examined for further enhancement of energy efficiency of advanced design III with TCD 3–5. Column-4 was retrofitted to a heat pump assisted distillation configuration. The CGCCs of column-4 were drawn and analyzed to search the opportunities for applying the heat pump with its proper location for implementation. As shown in Fig. 14, the temperature difference between top and reboiler stages was small enough while the heat load was equally high, which indicates that the system can take a clear advantage through heat pump implementation. A flat profile on both sides above and below the pinch point also suggests that the process is suitable for recovering the waste heat from the rectification section and its reuse in the stripping section of the column.

The column-3 top temperature of advanced design column III is 126°C, which is lower than the column-3 top product of the optimal conventional column. A lower feed temperature will increase the heat load from reboiler and increase reboiler duty. As the feed is cooled, the reboiler duty must increase. The opposite effect occurs as more heat is put into the feed, and less heat will need to be supplied by the reboiler [21]. Heat integration was applied to the advanced design III with the optimized TCD in such a way that the top product from column-3 is heated by heat exchange with the top stream of column-5. The top column-3 product as the column-4 feed was heated to 136°C and reduced the energy consumption of column-4 reasonably. Column-4 was then retrofitted to the heat pump configuration while maintaining the product specification. Under this configuration, the column-4 energy consumption was cut to 90.17 kW. This is equivalent to a 77.96% energy saving compared to the column-4 energy consumption of advanced design III or approximately 39.8% energy saving in terms of the total reboiler duty compared to advanced design III. Fig. 15 depicts a final configuration where heat integration and heat pump assisted distillation are applied to column-4 in advanced design III.
The energy efficiency of the waste solvent recovery process could be improved by utilizing advanced distillation techniques significantly. The complex thermally coupled distillation columns could be optimally designed using the response surface methodology based optimization in a simple and effective manner. Among several possible thermally coupled distillation configurations, thermally coupling columns 3 and 5 provided an attractive option for enhanced energy efficiency which were then further improved by proper application of heat integration and heat pump to columns 4. The proposed advanced distillation configuration achieved a significant energy saving of 40.5% compared to the conventional column sequence case.

Table 5 summarizes the reboiler duties of the optimal conventional column sequence, non-optimal, optimal, and heat pump assisted optimal advanced column design III cases.

5. Conclusions

In this study, the distillation technique was used to recover valuable components, such as monoisopropanolamine, methyl diglycol, N-methylformamide, and 1-piperazineethanol, from the waste photoresist stripper in the thin-film transistor light emitting diodes industry. The conventional sequence was rigorously optimized by the Box scheme without violating hard constraints. The Box scheme based built-in optimizer yields good starting points to solve optimization problems under hard constraints. The proposed systematic optimization procedure could address most of optimization problems of large scale complex distillation processes under strict constraints. The results showed that the optimal conventional design had a slight energy improvement. This was caused by the strict constraints of each column.

The energy efficiency of the waste solvent recovery process could be improved by using advanced distillation techniques significantly. The complex thermally coupled distillation columns could be optimally designed using the response surface methodology based optimization in a simple and effective manner. Among several possible thermally coupled distillation configurations, thermally coupling columns 3 and 5 provided an attractive option for enhanced energy efficiency which were then further improved by proper application of heat integration and heat pump to columns 4. The proposed advanced distillation configuration achieved a significant energy saving of 40.5% compared to the conventional column sequence case.

Acknowledgments

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References


Table 5

<table>
<thead>
<tr>
<th>Optimal conventional column</th>
<th>Advanced design III (before optimization)</th>
<th>Advanced design III (after optimization)</th>
<th>Advanced design III (with heat integration and heat pump)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Column Duty (kW)</td>
<td>Column Duty (kW)</td>
<td>Column Duty (kW)</td>
<td>Column Duty (kW)</td>
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<tr>
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<td>TCD 3–5</td>
<td>123.9</td>
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<td>393.6</td>
<td>408.6</td>
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<tr>
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<td>33.5</td>
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<tr>
<td>Total (kW)</td>
<td>826.6</td>
<td>811.1</td>
<td>492.1</td>
</tr>
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</table>

*a C-4 heat pump duty means the required compressor power.


