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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.

1. Introduction

The semiconductor industry is one of 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

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Nomenclature

CGCC	column grand composite curve
FV	internal vapor flow
k	number of main design variables
Min (Q)	objective function for Q (reboiler duty) minimization (kW)
$N1$	optimization parameter for feed location
$N2$	optimization parameter for vapor stream location
N_F	optimization variable for location of feed stage
N_T	optimization variable for number of column stages
NRTL	the non-random two liquid model
P	pressure
P_c	optimization variable for column pressure (atm)
Pcom	compressor power
Q_R	reboiler duty
R	optimization variable for distillation column reflux ratio
T_F	optimization variable for feed temperature of distillation column (°C)
TCD	thermally coupled distillation
T–H	temperature enthalpy relation
UNIFAC	the UNIQUAC Functional-group Activity Coefficient
X_i	uncoded or coded values of the variables
Y	the predicted response (reboiler duty) (kW)

Greek symbols

β_0	constant
β_i	coefficients of the linear
β_{ii}	coefficients of the quadratic
β_{ij}	coefficients of the interactive
ε	error term

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 striper 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

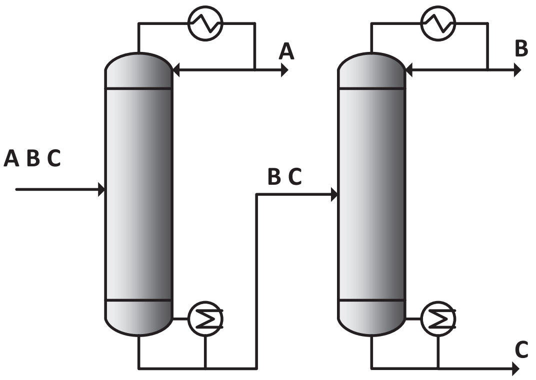

Fig. 1. Conventional distillation sequence: direct sequence.