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A hybrid design combining double-effect thermal integration and heat pump to the methanol distillation process for improving energy efficiency

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ABSTRACT

Despite the low energy efficiency of distillation, it remains the popular separation technology for methanol purification. Enlightened by progress in heat pump (HP) concepts, which have been proposed to upcycle waste heat and reduce energy consumption, this work introduces a hybrid methanol distillation process, which elaborately integrates the HP with double-effect thermal integration by designing an intermediate heater to shunt the heat load of the reboiler. Simultaneously, a corresponding optimization function and schematic solution procedure based on pinch technology are proposed to minimize the operational expenditure. The calculation results demonstrate the validity of the optimization method. Compared with the popular 4-column double-effect methanol distillation scheme, the hybrid scheme can considerably reduce utility depletion as well as operating costs, with an acceptable payback period for the compressor. As a result, the hybrid design that gets the advantage of both double-effect and HP is worth extending to the methanol community as well as to other industrial plants.

1. Introduction

As one of the most important and widespread thermal separation methods in the modern process industry, distillation has been widely applied in the petrochemical, chemical, metallurgic, food, and textile industries. Representing a large part of the global energy usage, it is estimated that approximately 43% of thermal energy is used for industrial applications [1]. In particular, distillation alone is responsible for approximately 40% of the thermal energy consumption in the chemical process industry [2,3], which is the impetus for various energy saving programs that have been launched for improving distillation performance. One major drawback of distillation lies in its low thermodynamic efficiency, requiring consumption of high-quality energy in the reboiler, while rejecting a similar amount of waste heat to the condenser at a lower temperature [4]. In order to improve energy efficiency in a distillation column, several heat pump (HP) candidates have been proposed to aid the upcycling of waste heat that is removed from the condenser and to reduce the consumption of valuable utilities [5]. It is predicted that under certain conditions, the margin of energy savings of heat pump assisted distillation (HPAD) can be approximately 20–50% [1].

In the methanol industry, many methods have been proposed for the synthesis of methanol [6,7]. However, these crude methanol products must be refined through a distillation scheme before further utilization [8–14]. To date, a 4-column double-effect methanol distillation scheme has been the most readily adopted and widely used in China [8,9]. By dividing the methanol refining column into a pressured column (PC) and an atmospheric column (AC), this double-effect scheme has been shown to considerably decrease energy consumption compared with earlier designs [12].

Although the 4-column scheme (designated as the prototype scheme) has resulted in a significantly greater decrease in energy consumption than that expected through double-effect thermal integration, it still consumes a considerable amount of hot utility in the PC reboiler (approximately 80% of the total hot utility consumption) and cold utility in the AC condenser (over 75% of all cold utility consumption) [8,11]. The literature surveys [8–12] demonstrated that previous works are mainly focused on using sole double-effect configuration to achieve higher energy efficiency, ignoring the application of HPAD. As a continuation of our previous efforts [8,11], we propose a hybrid 4-column methanol distillation scheme, combining double-effect and HP. The hybrid design attempts to make full use of the HP to cool part of the AC top vapor in parallel with the condenser, and it can upcycle the waste heat available for certain heat sinks at higher

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Nomenclature

Acronyms

AC	Atmospheric column
BF	Bottom flash
CGCC	Column grand composite curve
COP	Coefficient of performance
CS	Cold stream
CW	Cooling water
GCC	Grand composite curve
HEN	Heat exchanger network
HP	Heat pump
HPAD	Heat pump assisted distillation
HS	Hot stream
LEC	Light ends column
MOE	Minimum operational expenditure
MTC	Minimum thermodynamic condition
MVR	Mechanical vapor recompression
NLP	Nonlinear programing;
NRTL	Non-random two liquid
OE	Operational expenditures
PBP	Payback period
PC	Pressured column
PNMTC	Practical near-minimum thermodynamic condition
T-H	Temperature-enthalpy
TIC	Total investment cost
VC	Vapor compression
WC	Water column

Roman letters

D	Distillate molar flow rate
h_D	Enthalpy of distillate
h_L^*	Enthalpy of liquid stream
h_V^*	Enthalpy of vapor stream
$L_{\min}$	Minimum molar liquid flow rate
Q	Heat duty
T	Temperature
$V_{\min}$	Minimum molar vapor flow rate
W	Work
x_H^*	Liquid molar fractions of heavy key component
$x_{H,D}$	Distillate molar fraction of heavy key component
x_L^*	Liquid molar fractions of light key component
$x_{L,D}$	Distillate molar fraction of light key component
y_H^*	Vapor molar fractions of heavy key component
y_L^*	Vapor molar fractions of light key component
X	Price of steam
Y	Price of CW
Z	Price of electricity

Greek letters

ε	Iteration calculation step size
η	AC overhead vapor distribution factor
λ	PC top vapor distribution factor
ξ	Side-reboiler fraction

temperatures. Because the AC reboiler is driven by the PC top vapor in the prototype scheme, in the hybrid scheme, a side-reboiler is designed at the AC stripping section, which acts as a new heat receiver at suitable temperatures for the donator by shunting part of the reboiler duty. To better match the heat cascade, an optimization programming function based on pinch technology was developed as a shortcut for the determination of the column parameters. Simultaneously, rigorous simulations were employed to judge the profitability through comparisons of the 4-column schemes before and after the introduction of HP in terms of energy consumption and operational expenditure. To the authors' knowledge, the hybrid methanol distillation design has not yet been reported.

This work is organized as follows. The related theories are depicted in Section 2. In Section 3, a prototype scheme is derived from a typical 4-column setup running in Northern China. The energy consumption and operating cost of the hybrid schemes are expected to be lower than those of the prototype scheme. An economic evaluation of the payback period (PBP) for HP auxiliary equipment is necessary to determine the feasibility of the hybrid schemes. These contents are introduced in Sections 4 and 5. Finally, the conclusions are given in Section 6.

2. Theory

2.1. Pinch technology

Energy saving, in the way of reduction in the use of fossil fuel, has been under active consideration for many years as this leads to the strengthening of competitiveness by saving cost in operation [13]. Heat integration has been widely applied to oil refineries and chemical industries for process energy saving through synthesizing heat exchanger network (HEN) [14,15]. To achieve maximum energy recovery, Linnhoff's widely respected and accepted pinch technology for heat integration and HEN synthesis must be applied [16]. A comprehensive bibliography of the HEN design procedure can be reviewed in the literature [17,18]. In considering HEN synthesis, the pinch technology emphasizes that any heat leakage from a higher temperature zone above the pinch to a lower temperature region below it will cause an increase in both hot and cold utilities, namely a double penalty. Therefore, the main concern of pinch technology becomes preventing any heat transfer from crossing the pinch, to achieve maximum energy recovery. Following this philosophy, HEN should be designed separately above and below the pinch.

Given a list of hot streams (HSs), cold streams (CSs) and a minimum temperature difference $\Delta T_{\min}$, a conceptual temperature-enthalpy (T-H) curve of the heat integration system can be formulated using pinch technology [4]. Besides, a further grand composite curve (GCC) can be plotted to show the net heat flow leaving each internal temperature on T-H axes and to identify heating and cooling requirements at different temperature levels [16]. In this work, pinch technology is used to analyze heat cascade within the methanol distillation process and to synthesize HEN.

2.2. The column grand composite curve

The main goal of distillation process optimization is to reduce its energy consumption. The principal approaches are either improving the distillation equipment or strengthening heat integration [8]. For this purpose, in-depth analysis about the distribution of energy along tray in distillation column can provide useful information for column design and heat integration.

The column grand composite curve (CGCC) can be constructed from the column internal stream mass flows and enthalpies [19]. The T-H curve for a binary distillation column under the minimum thermodynamic conditions (MTCs) can be plotted by solving the coupled heat and mass balance equations for the reversible separation scheme. For multicomponent systems, a simplification proposed by Dhole and Linnhoff [20] uses the light key and heavy key components to approximate the binary situation, thereby reducing the problem to that of