Energy xxx (2014) 1–8

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Further optimization of a parallel double-effect organosilicon distillation scheme through exergy analysis

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ARTICLE INFO

Article history:
Received 12 October 2013
Received in revised form
1 March 2014
Accepted 6 March 2014
Available online xxx

Keywords:
Heat pump
Energy conservation
Exergy analysis
Organosilicon distillation

ABSTRACT

In our previous work, a significant improvement in organosilicon monomer distillation using parallel double-effect heat integration between a heavies removal column and six other columns, as well as heat integration between methyltrichlorosilane and dimethylchlorosilane columns, reduced the total exergy loss of the currently running counterpart by 40.41%. Further research regarding this optimized scheme demonstrated that it was necessary to reduce the higher operating pressure of the methyltrichlorosilane column, which is required for heat integration between the methyltrichlorosilane and dimethylchlorosilane columns. Therefore, in this contribution, a challenger scheme is presented with heat pumps introduced separately from the originally heat-coupled methyltrichlorosilane and dimethylchlorosilane columns in the above-mentioned optimized scheme, which is the prototype for this work. Both schemes are simulated using the same purity requirements used in running industrial units. The thermodynamic properties from the simulation are used to calculate the energy consumption and exergy loss of the two schemes. The results show that the heat pump option further reduces the flowsheet energy consumption and exergy loss by 27.35% and 10.98% relative to the prototype scheme. These results indicate that the heat pumps are superior to heat integration in the context of energy-savings during organosilicon monomer distillation.

1. Introduction

Organosilicon materials have been used in electric products, building, textiles, machinery, aerospace, medical, etc., since the early 1940s, which is when the industrial production of these materials began. Much attention has been paid to the outstanding properties of organosilicon materials under different conditions, which has led to specialized applications. Zhang et al. [1] reported a low-cost method for preparing amorphous Si–C (silicon–carbon) nanospheres as anodic materials in Li-ion batteries using methyltrichlorosilane. Lu et al. [2] successfully synthesized two series of novel luminescent hybrid material systems using a functional precursor from the hydrosilylation of methyldichlorosilane with 4-vinylpyridine. Zhan et al. [3] discovered that silicalite-1 modified with chlorosilanes was very effective for increasing the surface hydrophobicity of zeolite particles and improving their integration in a PDMS (α,ω-Polydimethylsiloxanediol) matrix. Zhao and Lu [4] studied the adsorption of MCM-41 (a siliceous mesoporous molecular sieve) modified using trimethylchlorosilane. When increasing the production scale, however, the energy consumption for the entire plant became remarkably high; 70% of this energy is expended during monomer refining distillation. Any improvement in the energy efficiency of the distillation system will be significant for the entire plant. Consequently, a new energy-efficiency-enhancing conceptual scheme was proposed; specifically, parallel double-effect heat integration or distributive heat integration, for the currently running nine-column organosilicon monomer distillation system we developed previously, whose flowsheet is described in the later section. In our previous paper, because the viability of heat integration between the heavies column with other columns was ascertained by the x–y diagram of heavies component and Me1 as well as heavies component and Me2 at different pressure, the operating pressure of the heavies column was increased to 360 kPa from 110 kPa to enhance the temperature of the top vapor, which was divided into six parts to heat the low removal column, the lights removal column, the MeH column, the azeotrope removal column, the Me3 column and the Me2 column simultaneously. Moreover, the Me1 column was integrated with the Me2 column by raising its pressure to 280 kPa from 110 kPa, whose feasibility was confirmed by the x–y diagram of Me1 and Me2.

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http://dx.doi.org/10.1016/j.energy.2014.03.027
0360-5442/

Please cite this article in press as: Sun J, et al., Further optimization of a parallel double-effect organosilicon distillation scheme through exergy analysis, Energy (2014), http://dx.doi.org/10.1016/j.energy.2014.03.027

List of symbols

Me1	methyltrichlorosilane
Me2	dimethylchlorosilane
Me3	trimethylchlorosilane
MeH	methyldichlorosilane
VC	vapor compression
VRC	vapor recompression
M	the mass of standard coal required to produce a specific quantity and form of energy
m	the quantity of high-temperature steam
H	enthalpy
e_0	the heat released from the combustion of 1 kg of standard coal
η	the operating efficiency of the boiler
T_0	ambient temperature
e	electrical power
Q_R	the heat duty of the reboiler
Q_C	the heat duty of the condenser
T_R	the temperature of the heating medium for the reboiler
T_C	the temperature of the cooling medium for the condenser
S	entropy
E_{Xloss}	exergy loss
LB	low-boiling-point component
HB	high-boiling-point component

Calculations showed that the optimized scheme reduced the total exergy loss of the currently running counterpart by 40.41%. However, as described above, the Me1 column must be operated at a higher pressure, which is required for heat integration between itself and the Me2 column. More importantly, the Me1 column still consumed a considerable amount of steam to meet the separation requirements [5]. All of these factors provide motivation for further improvements to the parallel double-effect heat integration scheme.

The heat pumps implemented extensively in today's industry are a very popular method for saving energy during distillation [6]; these devices can reduce the energy consumption of distillation by approximately 20%–50% under certain conditions [7]. Researchers agree that heat integration is superior to a heat pump as an energy-saving method for distillation in certain systems [8]. Nevertheless, this work will present an exception to this viewpoint. Compared to double-effect distillation, heat pumps can facilitate the reuse of the lower-temperature heat of the top stream by enhancing the stream pressure of the column tops instead of increasing the operating pressure of the entire column to achieve separation, safely avoiding the high operating pressure in the optimized scheme described above, referred to as "the prototype" in the following section. In this work, based on the parallel double-effect heat integration scheme, heat pumps are introduced to improve the scheme by simultaneously applying the heat pump and parallel double-effect heat integration to reduce the energy consumption and improve the energy efficiency of the nine-column organosilicon distillation. This new scheme will be referred to as "the challenger".

To clearly display the difference in the total energy consumption between the two optimized schemes, all types of energy consumption are converted to the mass of standard coal required to produce the same quantity and type of energy. Moreover, because the concept of exergy has been introduced to reflect the quality and efficiency of energy over the past several decades, an exergy analysis will be applied to compare the energy efficiency of the two counterparts.

2. Theories

2.1. Heat pump distillation and parallel double-effect distillation

2.1.1. Heat pump distillation

Heat pump distillation involves vapor compression, as well as thermal and mechanical recompression [7], to enhance the heating capability by escalating the temperature of the stream from the column top to heat the reboiler. This system can recover the potential heat of the low-temperature stream from the top of the column to reduce energy consumption. The energy consumption can be divided into two common columns used to integrate a heat pump with a distillation column: the VC column (vapor compression) and the VRC (vapor recompression column). For the VC, as shown in Fig. 1a, the working medium evaporated by the top vapor of column is compressed to increase the temperature, condensed within the reboiler and cooled with a throttle valve to reach a temperature below that of the condenser. However, the working fluid of the VRC is compressed to a higher temperature and is the column top vapor, which is condensed in the reboiler and refluxed partially to the column top, as shown in Fig. 1b [9].

2.1.2. Parallel double-effect distillation

For the conventional double-effect distillation, the top vapor with higher temperature of the higher-pressure column only heat one downstream column, where a large amount of heat in the top vapor cannot be fully utilized, when the higher-pressure column has a larger vapor load. Therefore, parallel double-effect distillation, derived from the famous thermal integrative pattern, is proposed in our previous report [5] that outperforms conventional double-effect distillation; the conventional system should feature three or more distillation columns, one of which operates at a pressure above that of the others to enhance its temperature of top vapor. Therefore, the top vapor of the higher-pressure column can be divided into two or more parts whose flow rates are determined by the reboiler duty of each lower-pressure column to heat the reboiler of the remaining lower-pressure columns. One typical scheme of parallel double-effect distillation in which one higher-pressure column heats two or more lower-pressure columns simultaneously is illustrated in Fig. 2.

2.2. Converting energy consumption to the mass of standard coal

The high-pressure steam frequently used to heat the reboiler during distillation can be produced by heating water under environmental conditions with a coal-fired boiler. Therefore, according to the fundamental thermodynamic relation, the mass of standard coal (M) required to produce a certain amount of high-pressure steam (m) can be obtained using the following formula:

$$M = \{m(h - h_0)\}/e_0\eta) \quad (1)$$

where h and h_0 are the enthalpy of steam at a certain temperature and pressure and that of water at the reference temperature T_0 (25 °C), e_0 is a constant equal to 29,307 kJ/kg representing the heat released from the combustion of 1 kg standard coal [10] and η