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Process and plant improvement using extended exergy analysis, a case study

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Abstract

In this paper, energy and exergy analyses of a distillation unit is conducted to study thermodynamic efficiency of the unit, performance evaluation and total annualized cost (TAC) optimization. A systematic procedure for analysis as well as optimization have been proposed and demonstrated by two case studies. The feed location, side stream withdrawal and operating conditions have been selected as variables for the optimization. Compared with the base case, alternative case withe side stream (SS) achieved a higher thermodynamic efficiency (14.47 %).

Keywords: Exergy analysis, Optimization, Distillation.

1. Introduction

Exergy analysis is an efficient technique for the design of more efficient thermal systems by reducing inefficiencies. Although many studies have been undertaken to conduct energy analyses of various thermodynamic systems and processes in petroleum and petrochemical industries, very limited work has been done on the exergy analysis of distillation processes. Al-Muslim et al**.** [1] conducted a thermodynamic analysis of crude oil distillation systems to study energy and exergy efficiencies for system analysis, performance evaluation and optimization. Previous works have shown that potentially, large savings could be obtained in the use of high quality energy [2], [3]**.** The use of irreversible thermodynamics is relatively new to the field of distillation, and is still under development.

In this study, a thermodynamic analysis of a distillation unit is presented. Maximum efficiency corresponding to minimum entropy production in the column is found. The ultimate goal of this study is to include aspects such as cost or economic (TAC) in order to find the optimum design.

2. Methodology

Figure 1 represents the proposed methodology's structure showing the inter-linking of the software tools used. The process is modeled using Aspen Plus^{TM} simulator. Mass and energy data from the Aspen Plus^{TM} model are transferred to MS-Excel© to compute the exergy of the streams and thermodynamic efficiency of the distillation unit under study. The successive quadratic programming algorithm (SQP) of Lang and Biegler [4], which is integrated in Aspen Plus^{TM} and has been adopted to the model requirements is used for economic optimization. The base case is improved by generating structural alternatives such as variation of feed stage and side stream withdrawal.

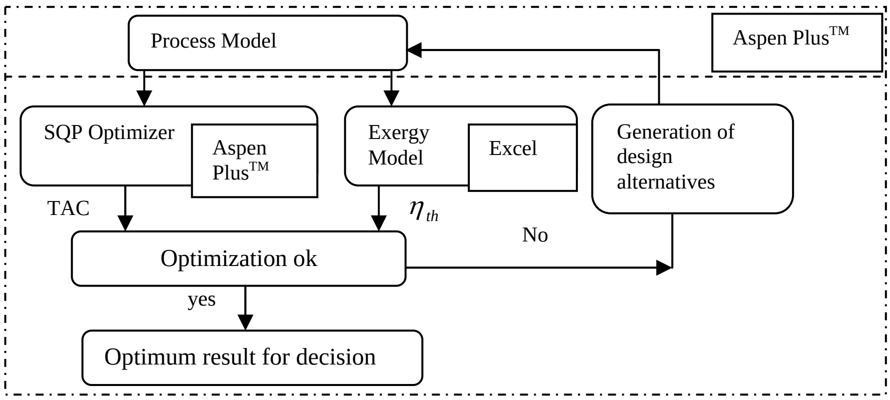

Figure 1. Methodology

3. Case study

A case study of a stripping column of Hydrocarbon recovery (HCR) plant (see figure 2) is used to show the procedure and demonstrate the methodology illustrated above. The column is part of the Hydrocarbon recovery (HCR) plant, which removes hydrocarbons and other components from the offgass of the DF (Distillation Fraction) plants. The feed stream to the stripping column enters normally the column on plate 16. The column operates with live steam injection into the base on tray 35 at temperature 140^{o}C and 3.75 bar.

From the physical limitations, some more constraints are usually enforced. For example, acetone recovery must be kept within a certain range of specification as shown below (mass %).
Distillate: x_{water}< 10 %, $x_{Acetone}$ > 50 %, Base: $x_{Acidity}$ < 3 %, $x_{Acetone}$ < 2 %.
The base case was modified by introducing a side stream at tray 30 and variation of feed location, see figure 3. This modification contributed to energy saving, and reducing the TAC.

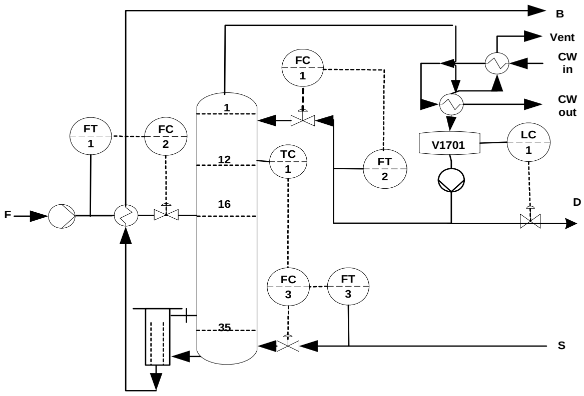

Figure 2. process flow sheet

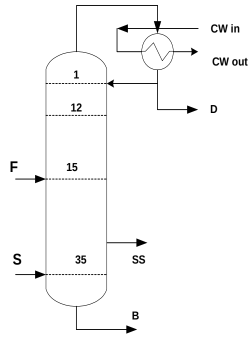

Figure 3. Structural alternative (SS)

3.1. Column balance

Figure 4 shows the balance regions of the distillation unit under study. For a steady state process, the energy and entropy balances (inner balance) region are.

$$\dot{M}_F \cdot h_F + \dot{M}_S \cdot h_S - \dot{M}_D \cdot h_D - \dot{M}_B \cdot h_B = \dot{Q}_{cond} \tag{1}$$

$$\Delta\dot{S}_{irr} = \dot{M}_D \cdot s_D + \dot{M}_B \cdot s_B + \frac{\dot{Q}_{cond}}{T_{cond}} - \dot{M}_F \cdot s_F - \dot{M}_S \cdot s_S \geq 0 \tag{2}$$

Where $\Delta\dot{S}_{irr}$ is the entropy production in the distillation unit. Exergy loss and entropy production in distillation are related to each other by [3].

$$\dot{E}_{loss}^{total} = T_o \cdot \Delta\dot{S}_{irr} \tag{3}$$

The exergy balance for the distillation unit (outer balance region) is.

$$\dot{E}_F + \dot{E}_S = \dot{E}_D + \dot{E}_B + \dot{E}_{cond} + \dot{E}_{loss}^{total} \tag{4}$$

The exergy loss on tray is calculated with exergy balance over the tray (see figure 5). The exergy loss over tray n, is calculated according to Revero (2005).

$$\dot{E}_{n,tray}^{loss} = \dot{N}_{n+1}^{V} \cdot e_{n+1}^{V} + \dot{N}_{n-1}^{L} \cdot e_{n-1}^{L} - \dot{N}_{n}^{V} \cdot e_{n}^{V} - \dot{N}_{n}^{L} \cdot e_{n}^{L} \tag{5}$$

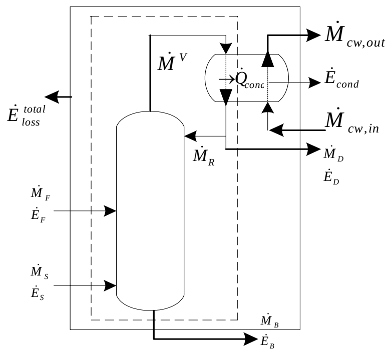

Figure 4. Exergy balance of distillation unit

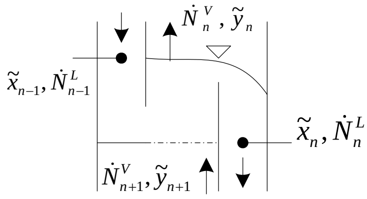

Figure 5. Component balance

3.2. Minimum work and thermodynamic efficiency

The minimum amount of work required for separation can be calculated as follows.

$$\dot{W}_{\min} = \dot{M}_D \cdot e_D^* + \dot{M}_B \cdot e_B^* - \dot{M}_F \cdot e_F^* - \dot{M}_S \cdot e_S^* \tag{6}$$

The thermodynamic efficiency of the column can be express as.

$$\eta_{th} = \frac{\dot{W}_{\min}}{\dot{W}_{\min} + \dot{E}_{loss}^{total}} \tag{7}$$

3.3. Economic Model

The cost effectiveness of operating a process plant can be evaluated by applying attributes like cost, return on investment and total annualized cost (TAC) [5]. TAC (Operational cost + Annualized capital investment cost) is considered in this paper. Annualized capital cost is based on the sum of the costs of column, condenser, tray and pump. Operating cost is estimated in terms of energy cost.

$$\dot{C}_{Energyy} = c_S \cdot \dot{M}_S \cdot (8000\,h/yr) + c_{cw}^* \cdot \dot{Q}_{cond} + C_{el}^* \cdot \dot{P}_{el} \tag{8}$$

$$\dot{C}_{TAC} = \dot{C}_{Energy} + \left(C_{cond} + C_{col} + C_{tray} + C_{pump}\right) \cdot \dot{d} \tag{9}$$

3.4. Results & discussions

The results of the simulation are summarized in table 1. Compared with the base case, minimum work is reduced in side stream case. Savings in TAC is evident in side stream case. In terms of the column performance and cost, the side stream solution should be preferred.

Table 1. Results of the case study

		Base case	Side stream case
$\dot{Q}_{cond}$	kW	276	266
$\dot{C}_{TACT}$	$/yr	281418	280613
$\dot{M}_{s}$	kg/h	603	590
$\dot{E}^{Loss}_{Total}$	MJ/h	1576	1532
$\dot{W}_{\min}$	MJ/h	268	257
η_{th}	%	14.30	14.47

Exergy loss is greatest at the base of the column, for both cases studied. This situation is illustrated in Figure 6. The side stream case achieved 102 MJ/h of exergy loss at tray 35 compared with base case with 109 MJ/h loss. The main contribution to the exergy loss comes from steam (too hot) and feed (too cold), so there is some potential for further improvement.

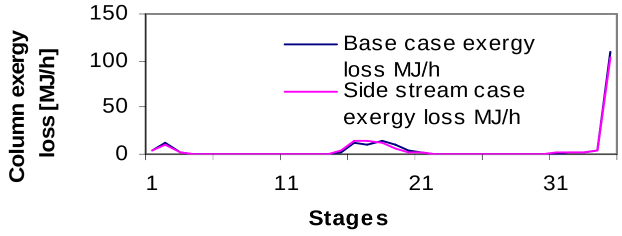

Figure 6. Exergy loss profiles in columns

4. Conclusions

The thermodynamic efficiency indicates that much exergy supplied by the steam is wasted. It is obvious that a large amount of energy is lost at the steam and feed trays. In future work a feed preheater, pump around and intermediate heat exchangers will be analyzed, also safety and operability aspects will be integrated.

Nomenclature

c	$/kg	specific cost	$\dot{P}$	kW	electrical power
c^*	$/(kW*yr)	cooling water cost	S	kJ/K	entropy
$\dot{C}$	$/yr	cost per year	s	kJ/(kg/k)	specific entropy
C^*	$/kWh	electricity cost	T	K	temperature
$\dot{d}$	1/yr	depreciation factor	$\dot{W}$	MJ/h	separation work
$\dot{E}$	MJ/h	exergy rate	$\dot{Q}$	kW	heat duty
e	MJ/kmol	specific exergy	$\tilde{x}_i$	kmol/kmol	liquid mole fraction
e^*	MJ/kg	specific exergy	x_i	kg/kg	liquid mass fraction
$\dot{M}$	kg/h	mass flow rate	$\tilde{y}_i$	kmol/kmol	vapor mole fraction
$\dot{N}$	kmol/h	mole flow rate	y_i	kg/kg	vapor mass fraction

subscript superscript

B	Bottom	cw	cooling water	el	electrical	R	reflux	L	liquid
col	Column	D	distillate	irr	irreversible	S	steam	V	vapour

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