Chinese Journal of Chemical Engineering 23 (2015) 1518–1522

Contents lists available at ScienceDirect

Chinese Journal of Chemical Engineering

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

Process Systems Engineering and Process Safety

Simultaneous optimization of heat-integrated crude oil distillation systems☆

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ARTICLE INFO

Article history:
Received 10 September 2014
Received in revised form 21 January 2015
Accepted 6 February 2015
Available online 27 March 2015

Keywords:
Crude oil distillation
Annual economic benefit
Energy optimization
Particle warm optimization
System engineering

ABSTRACT

Crude oil distillation is important in refining industry. Operating variables of distillation process have a critical effect on product output value and energy consumption. However, the objectives of minimum energy consumption and maximum product output value do not coordinate with each other and do not lead to the maximum economic benefit of a refinery. In this paper, a systematic optimization approach is proposed for the maximum annual economic benefit of an existing crude oil distillation system, considering product output value and energy consumption simultaneously. A shortcut model in Aspen Plus is used to describe the crude oil distillation and the pinch analysis is adopted to identify the target of energy recovery. The optimization is a nonlinear programming problem and solved by stochastic algorithm of particle warm optimization.

1. Introduction

Crude oil distillation plays an important role in refineries, affecting economic benefits and energy consumption. The distillation unit splits crude oil into a series of oil products with different values. The yield distribution of oil products affects product output value and energy consumption. For example, adding the heat taken from the top by changing the heat taken from the mid-pumparounds of the atmospheric column will increase the output of light constituents such as naphtha, which will increase the output value of the column and result in more energy consumption. Thus the optimization of crude oil unit should coordinate the increase in product output value and reduction of energy consumption simultaneously, maximizing the economic benefit.

Some advances in crude oil distillation process include improving heat exchanger network structure [1–3], investigating the effect of mixing different crude oils on product profit to increase economic profit [4,5], optimizing operating parameters of distillation unit to maximize product profit [6–9], and improving production program by solving nonlinear programming (NLP) problems [10,11]. Liebmann *et al.* put forward design procedures of a heat-integrated conventional crude oil distillation tower using pinch analysis [12]. Suphanit adjusted reflux, flow rate of steam stripping and other degrees of freedom to reduce operating cost considering the interaction of distillation column and heat exchange network [13]. Some improvements were made to Suphanit's approach and applied to retrofit design [14–17]. Most of previous studies focused on maximizing the product profit and minimizing the energy consumption separately, which are related to economic benefit of a refinery. However, considering the two targets separately may not give the maximum economic benefit. Besides, boiling point temperatures of refining products were fixed at a predetermined value in these optimizations. In fact, the boiling point temperature of a refining product varies in a permissible range, within which the quality of the product is satisfactory. Therefore, product yield distribution of a crude oil distillation column is different when optimizing the operating parameters affecting both product output value and energy consumption. In this study, we optimize operating parameters including distributions of product yield and flow rates of stripping steams to maximize the annual economic benefit considering the product output value and energy consumption simultaneously by a systematic approach based on the SCFrac shortcut model of Aspen Plus and the pinch analysis. The optimization is a NLP problem and solved by stochastic algorithm of particle warm optimization (PSO) algorithm [18]. A case study is used to illustrate the application.

2. Process Description

Fig. 1 shows a general flow sheet of the initial distillation in a refinery. Crude oil enters the preheat train, which consists of heat exchangers associated with various downstream equipment in the system. The preheat train raises the temperature of crude significantly and reduces the overall energy consumption. The heated crude enters the primary furnace, where a large portion of it evaporates. Then the vapor–liquid mixture goes to the atmospheric distillation tower

☆ Supported by the National Natural Science Foundation of China (21176178) and the State Key Laboratory of Chemical Engineering (SKL-ChE-13B02).
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http://dx.doi.org/10.1016/j.cjche.2015.03.008
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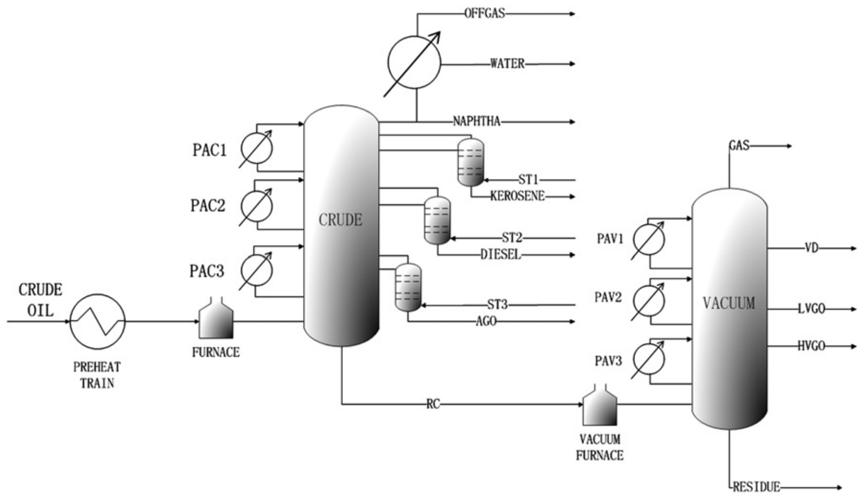

Fig. 1. Aspen model of atmospheric and vacuum distillation units.

named CRUDE. The potion with boiling point lower than 350 °C is distillated from CRUDE as products, while the atmospheric residue RC is send to the vacuum distillation named VACUUM to recover additional distillates and gas oils.

In this study, all operation conditions and values of operating variable are based on an existing refinery in China. After preheated to about 370 °C at 145 kPa in the atmospheric furnace, the crude oil entered the flash zone of atmospheric column at Stage 29, which contained 31 theoretical stages. The pressure of the column was maintained at 131 kPa at the top and at 147 kPa at the bottom. The temperature of the top condenser was kept at 47 °C. A steam stream was fed at the bottom of atmospheric column. Three pumparounds were located between Stages 3 and 1, between Stages 12 and 10, and between Stages 21 and 19. The top distillate product was naphtha, and the side products from 3 steam strippers (S1, S2, S3) were kerosene, diesel and atmospheric gas oil (AGO), which were drawn from Stages 10, 13 and 24 in sequence.

The residual oil from the bottom of atmospheric column was heated to 394 °C in the vacuum furnace and entered the flash zone of vacuum column, which had 14 theoretical stages with pressure maintained at 2.7 kPa at the top and at 3.9 kPa at the bottom. There were 3 pumparounds, PAV1 located between Stages 2 and 1, PAV2 located between Stages 7 and 6, and PAV3 located between Stages 9 and 8. The side products, vacuum diesel (VD), light vacuum gas oil (LVGO), and heavy vacuum gas oil (HVGO), were drawn from Stages 2, 7 and 9, respectively. The bottom product was the residue. In the distillation system, naphtha, kerosene, diesel, AGO, and vacuum diesel were direct products, while LVGO, HVGO and the residue went to downstream units.

3. Crude Oil Distillation Model

3.1. Shortcut model

In a design and retrofit problem of crude oil distillation systems, shortcut models [15] are more suitable for optimization and can be solved more quickly than strict models, especially when multiple variables are considered simultaneously. In this paper, SCFrac shortcut model in Aspen Plus [19] is used to simulate the crude oil distillation. The SCFrac model is based on the following assumptions: (1) a complex column can be divided into a series of simple column sections, as shown in Fig. 2; (2) liquid flows between sections are negligible; and (3) all steam flows to the top of the column and is withdrawn with overhead product. SCFrac model decomposes a complex tower with *N* products into *N*-1 simple towers sequentially numbered from the top to the bottom. SCFrac model requires the following conditions: (1) pressure of side products, (2) estimated initial amount of side product withdrawn, and (3) amount of stripping steam of all products in addition to overhead product [19]. By specifying the column pressure, the estimated

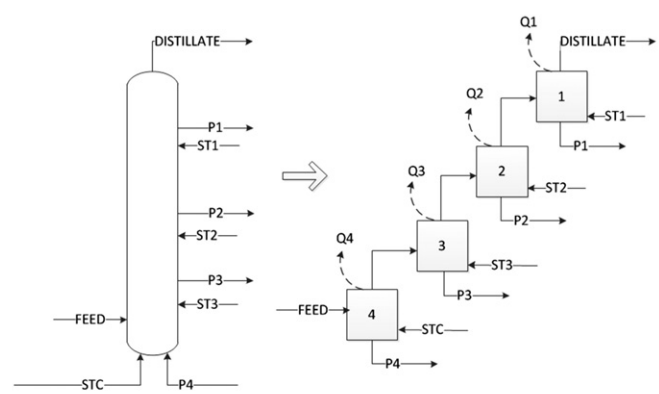

Fig. 2. SCFrac model in Aspen Plus.

product flow, the number of theoretical stage, the steam flow rate, and the value range of product property (D86 95% point), the SCFrac can give relatively accurate results including product status and heat duties of each condenser, furnace, and pumparound.

3.2. Energy consumption calculation

The pinch analysis method has been proposed to calculate energy recovery without knowing the exact structure of a heat exchanger network [20], which is adopted here to obtain theoretical hot (required furnace heat) and cold (required cooling duty) utility consumption. We take the minimum temperature difference of 15 °C, used in the Chinese refinery. The crude oil feed is the only cold stream, while products and pumparounds are hot streams.

4. Optimization

4.1. Optimization variables

In the SCFrac model, the variables we optimize include the flow rate of four stripping steams (atmospheric column bottom stripping steam F_{STC} and three side stripping steams F_{ST1}, F_{ST2}, and F_{ST3}) and the D86