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Crude oil distillation with superheated water steam: parametrical sensitivity and optimization

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Abstract

Stability of crude oil distillation units was analyzed with mathematical models developed using Aspen Hysys. Parametrical sensitivities of light fractions yields, heat duties and steam load of column trays to perturbations of superheated steam flow rate were estimated. Objective function based on the light products yields and energy consumption for distillation was formed. The maxima of the objective function were calculated depending on operational parameters and flow rate of water steam.

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Keywords: Crude oil distillation unit; superheated water steam; parametrical sensitivity; optimization; objective function.

1. Introduction

Industrial separation units are by far the most dominating energy consumers. Energy consumption of the separation trains takes up to 80 percent of the process operating costs¹.

The main directions of intensification are enhancing recovery of lighter fractions and reducing energy consumption for fractionation².

Water steam usage in rectification process is an effective and inexpensive way for oil refining efficiency

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increase^{3,4}.

Steam injection allows hydrocarbons to evaporate at temperatures lower than their boiling points⁵.

Using of superheated steam or neutral gas prevents decomposition of insufficient heat-resistant compounds because of reducing separation temperature of hydrocarbon mixtures^{6,7}.

Water superheated steam is used to create a vapor steam⁶ below the feed section that is especially useful when it is difficult or impossible to equip column with steam device to provide necessary upward vapor flow in the stripper section⁸.

Furthermore, water steam is explosion-proof and fireproof. It does not require additional heat exchange equipment, the flow rate is simple to control.

However, the use of water steam can cause some adverse effects which depend on the relative amount of water steam and column operating parameters. Negative effects such as increase in vapor load in column, increase in energy consumption for obtaining superheated steam and its later condensation, formation of water–hydrocarbon azeotropes are possible^{9,10}.

Possible condensation of water in the column should be considered because it can be a reason of operational failures.

In order to maximize oil refining efficiency and minimize the negative features of water steam use, stability analysis and optimization are needed at different flow rates and operational parameters of the superheated steam.

Usually such problems are solved by using mathematical models. The paper² presents rigorous simulation and optimization framework of both the distillation columns and the heat exchanger network simultaneously to maximize the efficiency of existing equipment. In the paper¹¹, possible energy savings up to 21% were demonstrated by means of simulation of crude oil separation using PRO/II from Simsci-Essor.

Mechanisms of steam distillation are directly described in several studies¹²⁻¹⁶.

Advantage of simulation of steam distillation process with artificial neural network (ANN) was shown in¹⁷⁻²⁰.

2. Experimental

2.1. Crude oil distillation flowsheets with superheated steam

Mathematical models of two distillation units were developed. These units have one prefractionation column and the atmospheric distillation column with superheated water steam supply. One of them has partially integrated flows (fig. 1).

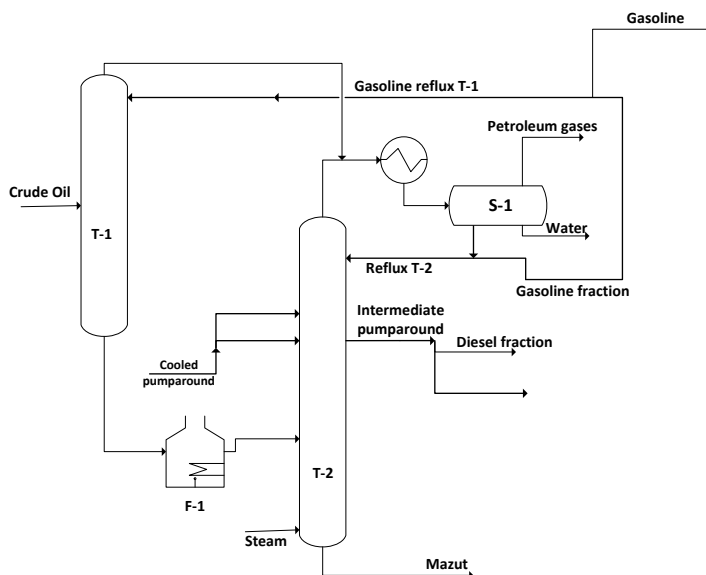


Fig. 1. Flowsheet of distillation unit with partially integrated flows

Apparatus: T-1 – prefractionation column; T-2 – atmospheric column; F-1 – furnace; S-1 – separator

2.2. Possible negative effects of superheated steam supply

Instability of systems with heating steam supply can be caused by:

- Water - hydrocarbon azeotropes formation,
- Possible water condensation in the column,
- Superheated water steam flow rate fluctuations,
- Steam load fluctuation on the trays of the column.

The conditions of azeotropic mixtures formation were theoretically investigated in the distillation column.

Preliminary calculations showed that conditions of azeotropic formation and water condensation are excluded under water steam supply up to 3 wt.% (of crude oil).

2.3. Estimation of parametrical sensitivity

Impact of superheated water steam flow rate fluctuations and vapor load fluctuations on the unit stability was estimated by parametrical sensitivity analysis.

Appropriate stability analysis algorithm with mathematical models was proposed in²¹.

In this paper the same algorithm was used with the crude oil units simulated in Aspen Hysys.

Superheated steam flow rate at the bottom of the atmospheric column was adopted as perturbing parameter.

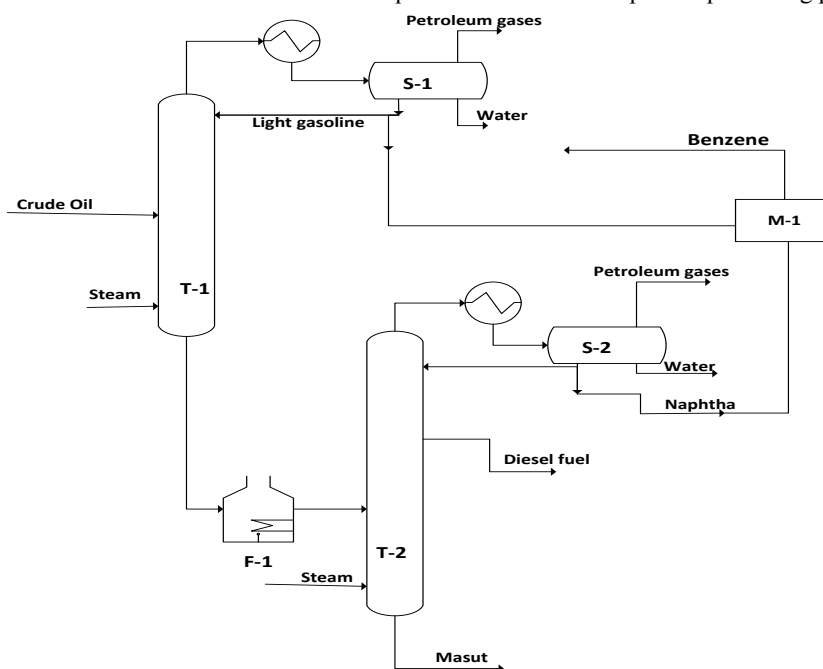


Fig. 2. Flowsheet of distillation unit without integrated flows

Apparatus: T-1 – pre-fractionation column; T-2 – atmospheric column; F-1 – furnace; S-1, S-2 – separators, M-1 - flow mixer

This parameter was varied from 0.8 to 2.0 wt. %.

The yield of diesel fraction, total yield of gasoline fractions, heat duty on the condenser of the main column, vapor column load were accepted as the target parameters.

The largest parametrical sensitivity coefficient was obtained for the flowsheet with partially integrated flows (steam flow rate 1.2 wt. % of crude oil), it was sensitivity coefficient of the condenser heat duty. In general, this scheme has higher sensitivity to steam flow rate perturbation, which requires more accurate control.

The extreme behavior of the parametrical sensitivity coefficients to small perturbation of steam flow rates was

observed for both distillation units. However, small values of these coefficients ensure stable unit operation under these perturbations.

2.4. Optimization

Optimization criterion (objective function) based on the product yield and energy consumption for steam production and condensation was formed as a function of parameters and steam flow rate with restrictions on the products quality.

$$U = \frac{\sum \Delta(G_{\text{gasoline}} + G_{\text{diesel}})}{\sum \Delta Q} = f(G_{\text{SWS}}, T_{\text{SWS}}, P_{\text{SWS}}) \rightarrow \max (1)$$

$T_{\text{EBP}}(\text{gasoline}) \leq 150 - 155^{\circ}\text{C}$, $T_{95 \text{ vol.\%}}(\text{diesel}) \leq 360 - 370^{\circ}\text{C}$,

where U – objective function, $\sum \Delta(G_{\text{gasoline}} + G_{\text{diesel}})$ – increase of summary gasoline and diesel fractions yield,

$\sum \Delta Q$ – total energy consumption, G_{SWS} – superheated water steam flow rate, kg/h,

T_{SWS} – steam temperature, $^{\circ}\text{C}$, P_{SWS} – steam pressure, kPa.

Temperature and flow rate were adopted as the main parameters because there are no possibilities for steam pressure variation.

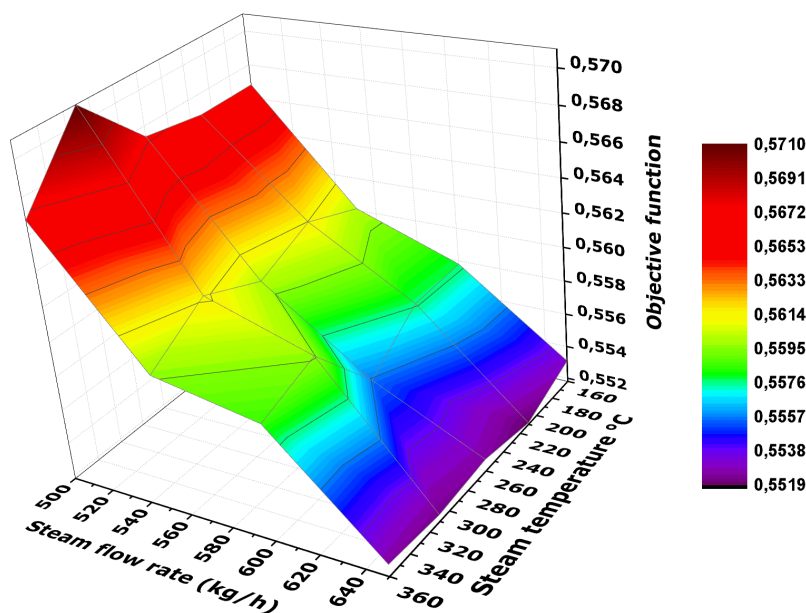


Fig. 3. Objective function versus temperature and flow rate of superheated steam for the distillation unit with partially integrated flows

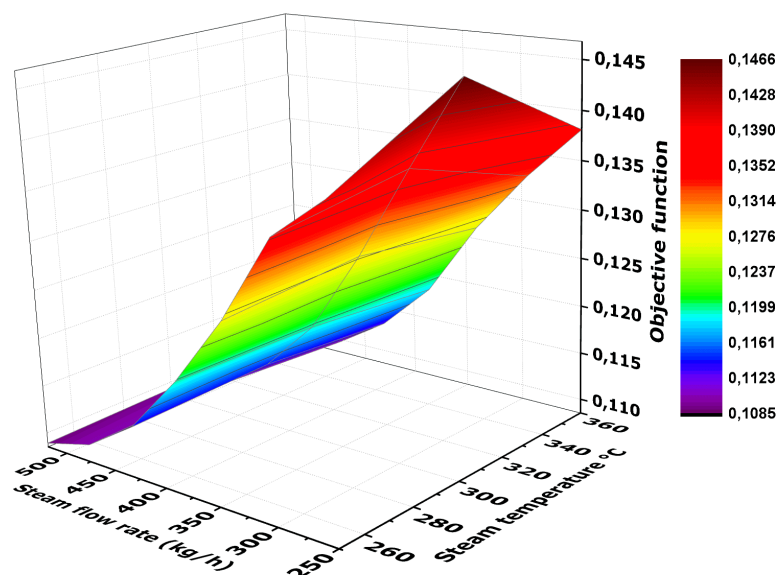


Fig. 4. Objective function versus temperature and flow rate of superheated steam for the distillation unit without integrated flows

Extremes (maxima) of the objective function corresponding to the optimal parameters of the heating steam are shown in Fig. 3, 4.

For the unit with partially integrated flows (fig. 1, 3):

- Temperature of the superheated steam is 310°C,
- Steam flow rate for the atmospheric column bottom is 1.2 wt. % (of crude oil).

For the unit without integrated flows (fig. 2, 4):

- Temperature of the superheated steam is 310°C,
- Steam flow rate for the atmospheric column bottom is 1.4 wt. % (of crude oil).

Steam pressure is 420 kPa in both cases.

3. Conclusion

The main advantages and disadvantages of water steam usage in crude oil separation were considered.

Stability analysis detected low parametrical sensitivity to perturbations of superheated water steam flow rate both for the unit with partially integrated flows and for the unit without integration.

Objective function was proposed, and procedure was optimized, optimal operational parameters of superheated steam were obtained for both units.

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