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GENERAL ALGORITHM FOR EFFICIENCY EVALUATION OF MULTI-COLUMN DISTILLATION FLOWSHEETS

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Abstract

The paper shows the development and application of a general algorithm for efficiency evaluation (AEE) of distillation sequences. The algorithm provided consideration of energy efficiency, flowsheet structure, and product specifications. In Aspen HYSYS™, we developed two "first principle" models of crude oil distillation units with and without heat integration. We have applied the AEE to compare the effectiveness of their performance for different types of oil. The effectiveness was higher for heat integrated unit, so its model was adopted as basic. Six alternative retrofit flowsheet models were developed for the purposes of preliminary optimization. Preliminary optimization was a combination of predesign optimization of unit flowsheet structure and apparatus design to create the optimal crude oil distillation unit and to provide the process flexibility in respect of feed flowrate and oil quality. Parametrical optimization was performed for all configurations of flowsheet structure. Maximum feed flowrates and the product yields were defined for all flowsheet structures. Relative total investments for retrofits of the basic flowsheet were estimated. They consider the cost of distillation columns, the internal device, pumps, heat exchangers, piping. AEE application to all retrofit flowsheets allows designing effective and relatively inexpensive refinery unit.

Keywords: *crude oil distillation unit; multi-column distillation sequences; general algorithm for efficiency evaluation; preliminary optimization; parametrical optimization; thermodynamic efficiency.*

1. Introduction

Distillation technologies and oil fractionation is not an exception. Energy consumption in the fractionation units determines the energy efficiency of a refinery in whole. The feed rate of the refineries, as a rule, exceeds one million ton per year. According to the data [1] average feed rate of a refinery in the Russian Federation is 8.72 million tons per year.

Numerous studies are conducted in order to increase the energy efficiency of oil fractionation since the even slight reduction in energy consumption delivers sufficient benefits. Increase in efficiency of the fractionation units executes both in the way of efficient utilization of external heat and in high recovery of light oil distillates.

Complex oil composition and complexity of a flowsheet structure along with heat integration and recovery require both preliminary optimization on the design stage and optimization during a unit performance [2].

Optimization based on the simulation is executed with the use of technologic, thermodynamic or economic criteria. The aim of thermodynamic analysis is to minimize energy consumption by means of optimal flowsheet development.

The authors [3] noted that the energy consumption for the distillation column is proportional to the minimum number of transfer units and the minimal reboiler duty. They proposed the original methods to calculate these values based on thermodynamic analysis for the initial design stage. The authors [4] performed an algorithm for the optimal design of thermally coupled distillation sequences. The criterion of optimality was the minimal reboiler duty corresponding to maximal thermodynamic efficiency.

A thermodynamic analysis is widely used to evaluate and minimize irreversibility in the distillation systems, for the decrease in the operation costs and ecological expenses. In paper [5], the author has reviewed conventional methods and case studies of thermodynamic analysis for binary and multicomponent systems and for refinery as well. Authors [6] performed the exergy analysis of single- and two-stage crude oil distillations, showed the sufficiently lower exergy lost for the two-stage flowsheet.

However, the energy efficiency of a unit performance depends considerably on a heat recovery for which rigorous simulation of the whole flowsheet is required. Economic criteria are formulated in terms of investments and operation cost.

In the paper [7], alternatives of representation were examined for economic optimization of a single distillation column. The objective function – the total annualized cost (TAC) was the sum of equipment and heat transfer fluid costs. The algorithm requires sufficient CPU time and faces a convergent problem. Authors [8] performed the hybrid algorithm, which used the results of simulation the distillation flowsheets in Aspen HYSYS™ to minimize TAC. TAC is the sum of investments and operation costs. Investments are the sum of vessels cost, reboilers and condensers cost. Operation costs are the sum of the energy dependent of condensers' and reboilers' load. The algorithm allows optimizing the flowsheets of simple structure with a limited set of equipment neglecting heat recovery and column piping.

The main drawback of the approaches mentioned above is neglect of heat recovery and column piping that limits the ability to calculate the effectiveness of the whole unit. Technologic criteria, as a rule, are expressed by the product specifications and recovery efficiency.

In this paper, we developed the general algorithm for efficiency evaluation and showed its application to choose an optimal mode and flowsheet structure of oil fractionation unit.

2. Thermodynamic efficiency of oil fractionation units

Thermodynamic efficiency criteria reflect the relation between external and utilized heat flow. Thermodynamic efficiency can be calculated as:

$$\eta_T = \frac{q_0 - q_k}{q_0} * 100\% \qquad (1),$$

Thermodynamic efficiency criterion reflects both heats utilized for distillation and heat recovery rate in a unit. Consequently, the criterion implies the flowsheet structure.

Product specifications and recovery affect the criterion value as well, since the increase in recovery requires an increase in reflux flow, hence increase in condensers and reboilers loads. The part of recovered heat decreases that results in a decrease in the thermodynamic efficiency criterion.

In Aspen HYSYS™, we developed two "first principle" models of crude oil distillation units with and without heat integration in order to find optimal flowsheet structure.

Simplified flowsheet structure without heat integration is shown in Fig. 1. Optimization of operation mode was carried out for different types of crude oil.

Thermodynamic efficiency of the flowsheet without heat integration does not exceed 50% because of low heat recovery.

The fractionation unit shown in Fig. 2 is of the more complex structure with an atmospheric column equipped with two stripping and two intermediate pump rounds. The heat of all intermediate and product flows is utilized in heat recovery. The model was verified for all types of oil, for different product specifications and meteorological conditions [9]. Average thermodynamic efficiency was about 70%, for this reason, this structure was taken as basic. Developed "first principle" model of the unit includes all equipment, e.g. columns, separators, vessels, heat exchangers, pumps. The sizing and hydraulic calculation for internals (valve trays) of the columns were carried out as well. The possibility to set the value of ambient temperature on the air coolers' inlet was included into the model as far as the temperature affects substantially over vapor loads, separators' performance and heat exchange. A detailed description of the flowsheet and product set are performed in [2].

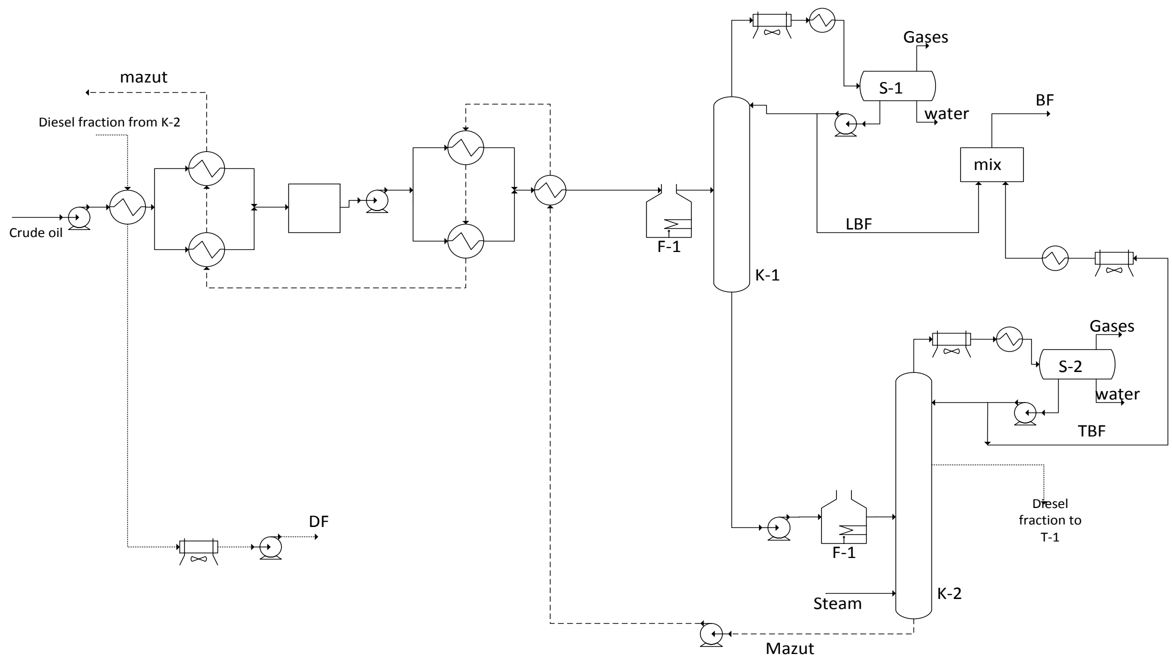

Fig. 1. Structure of crude oil distillation unit without heat integration

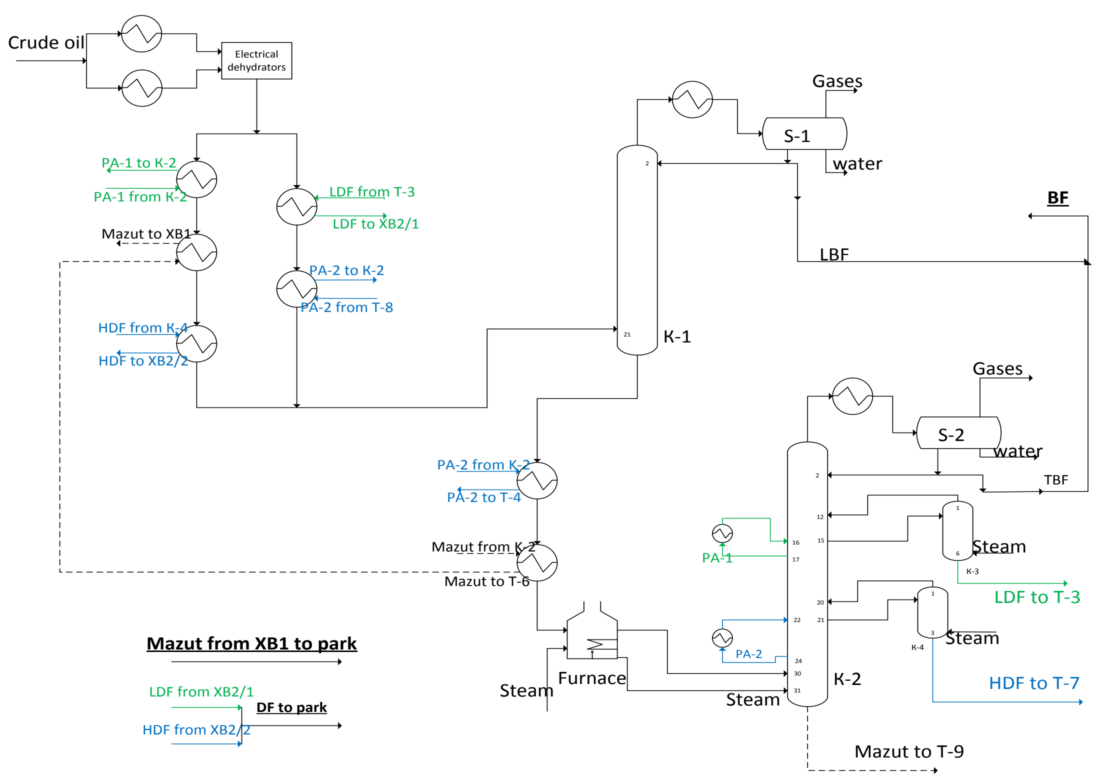

Fig. 2. Basic distillation unit with heat integration

3. Alternatives for retrofit

Performance of the basic unit was studied on the model in a wide range of feed load between 500 000 and 900 000 tons per year. Stage increase in load was used along with detection of “pinch points” and parametrical (technologic) optimization on each stage.

Based on the obtained results, we proposed six alternatives to retrofit:

1. The process flow diagram (PFD) equipped with an additional tray column, working in parallel with the main column K2 (Fig.3).
2. The PFD equipped with an additional packing column, working in parallel with the main column K2.
3. The PFD equipped with a main tray column K2 of a greater diameter.
4. The PFD equipped with a main packing column K2 of a greater diameter.
5. The PFD with an additional side-draw from the main tray column K2 equipped with a stripping (Fig.4).
6. The PFD with an additional side-draw from the main packing column K2 equipped with a stripping.

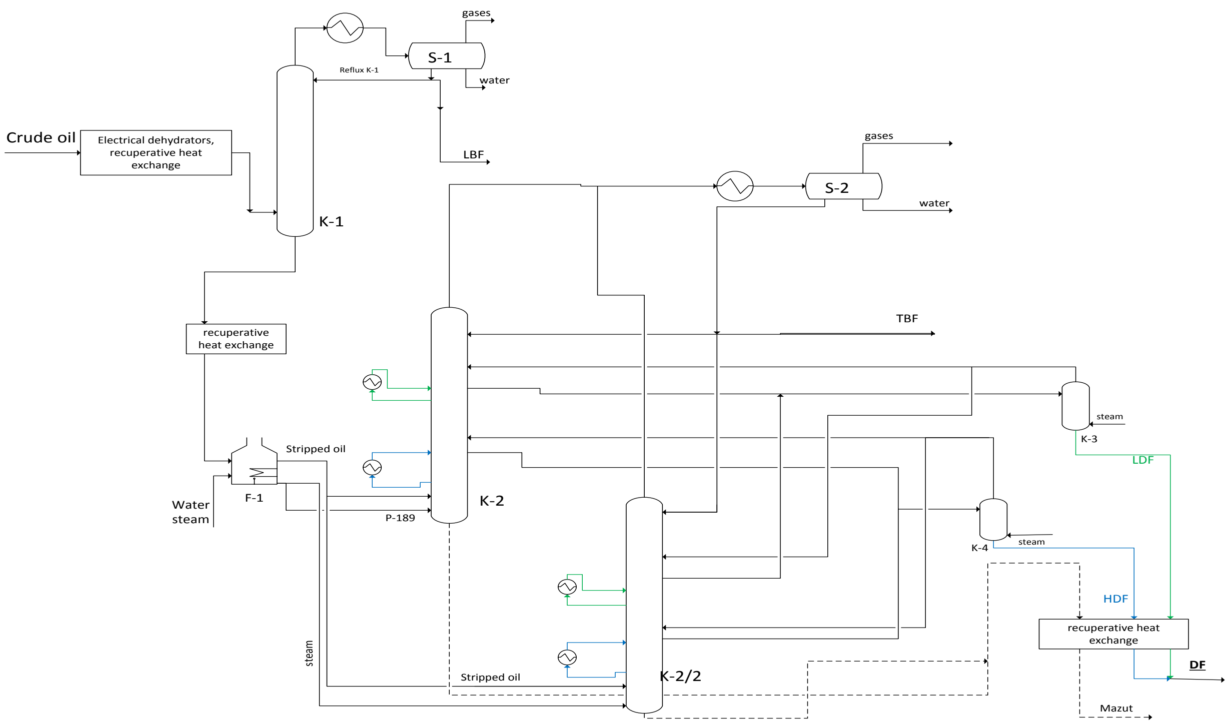

Fig. 3. The PFD equipped with an additional tray column, working in parallel with the main column K2 Alternatives of retrofit number 1, 2

4. Algorithm implementation

4.1. Parametrical optimization

The aim of parametrical optimization was a maximum yield of light distillates under sustainable operating and facing product specification. The conditions of overheated steam to columns and stripping were considered during optimization [10]. We used the algorithms previously tested and performed in [2, 9, 10].

4.2. Economic and thermodynamic optimization

For economic optimization, we estimated the sums of relative capital investments and operating costs above the basic flowsheet costs. Investments included the cost of additional equipment, cost of the unit construction and installation. Additionally, the annual operation cost and increase in the value of the product were calculated. Calculations were referred to the economic performance of the basic flowsheet.

The surface of the thermodynamic efficiency criterion in the space of economic parameters is shown in Fig. 5. Maximum of the criterion corresponds to the most effective alternative. Flowsheet numbering in Fig. 5 corresponds to the mentioned above numbering (Chapter 3).

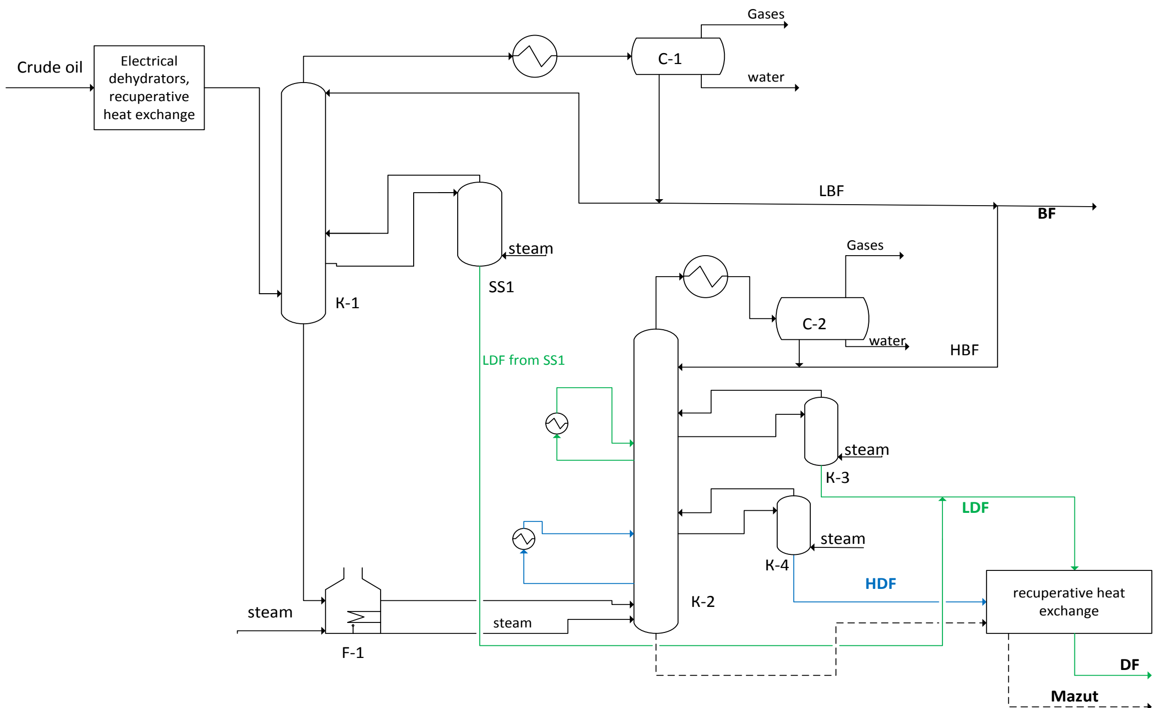

Fig. 4. The simplified scheme of the crude oil distillation unit with pre-fractionator and extra stripping (SS1). Alternatives of retrofit number 5, 6

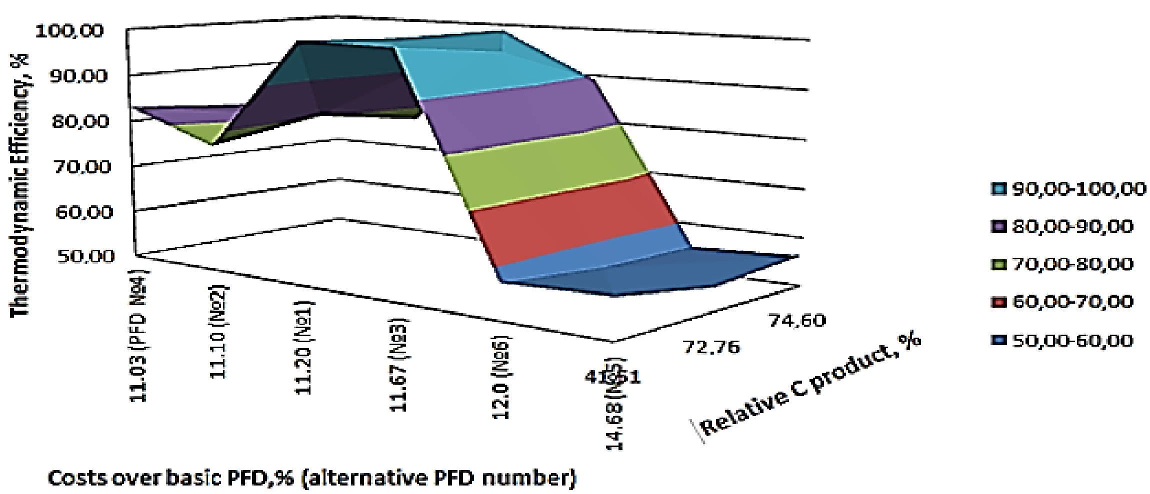

Fig. 5. Thermodynamic efficiency criterion in the space of economic parameters

5. Conclusion

The general algorithm for efficiency evaluation of multi-column distillation flowsheets was developed on the basis of designed thermodynamic, economic, technological optimization criteria using the results of the simulation. This hybrid algorithm for efficiency evaluation (AEE) was applied to select the optimal distillation sequence with heat integration and recuperative heat exchange from the proposed alternative flowsheets. The alternatives for retrofit were selected to provide the process flexibility in respect of flowrate of crude oil (load) and oil quality. The optimal operation modes were defined with consideration of the product quality.

The best distillation sequence for the design is characterized by relatively low total cost with maximum light product yields. Operating mode optimization of this flowsheet makes it possible to obtain energy efficiency higher than 90% without loss of product quality.

Symbols

η_T *thermodynamic efficiency, %;*

q_0 *total external heat flow, kWt;*

q_k *heat flow withdrawn by heat exchangers and air coolers and unutilized for heating feed or intermediate streams, kWt.*

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