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Pre-design optimization of crude oil distillation flowsheet

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Abstract

Several first principle models of crude oil distillation units were developed in Aspen Plus^{TM} for purposes of pre-design optimization of flowsheet structure and apparatus design and choice of the optimal variant of distillation to provide the process flexibility in respect to flowrate of crude oil and oil quality. The developed models consider air temperature and type of crude oil. The two-column flowsheet of crude oil distillation is adopted as basic. The sum of the capital investments and operation costs per year was estimated for the basic flowsheet. Stepwise increasing of crude oil flowrate is used to determine "weak points" of the flowsheet and estimate maximum oil flowrate. Parametrical optimization was performed for each step. The alternative upgrading flowsheets were developed to increase operation effectiveness in a wide range of crude oil flowrates. The optimization criterion was developed to evaluate the relative efficiency of the alternative distillation unit flowsheets. The optimization criterion was a ratio of average annual revenue from the sale of petroleum products to the total costs (capital investments and operational costs) with restrictions on the product quality. The way of re-equipment of the column internals was chosen as a preferable variant.

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Keywords: Crude oil distillation unit; pre-design optimization; flowsheet structure optimization; apparatus design optimization; operation mode optimization; first principle model; parametrical optimization; optimization criterion; process flexibility.

1. Introduction

Distillation is the most common process in the global industry. Much energy consumed in chemical and petrochemical industry is needed for distillation, for example, for heating of the feed streams, vapor condensation for reflux, heat input to reboiler or bottom of the column, superheated water steam production, etc. All these reasons explain demand for energy and resource-efficient distillation flowsheets.

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In changing economic situation it is necessary to provide flexibility of projected technological flowsheets toward feed fluctuations and unstable crude oil composition.

Load of crude oil can vary widely due to oil prices fluctuations, fiscal policy – changes in customs duties and excise taxes on oil and oil products, market conjuncture. In addition to these factors the feed type and changing market demands for various petroleum products lead to feed (crude oil) load changes at oil refining units.

These factors require pre-design analysis and optimization of crude oil distillation units.

Pre-design optimization of the projected technological units is possible in several ways:

- Flowsheet structure optimization;
- Apparatus design optimization;
- Operation mode optimization;
- Combination of the above mentioned ways.

Ways to optimize the flowsheet structure or apparatus design are significantly more effective compared with operation mode optimization. Optimization of the process flowsheet is possible at the design stage using mathematical models of the processes.

Development and optimization of energy and resource-efficient multicomponent distillation flowsheets at the design stage allow maximizing product yield and minimizing energy consumption and capital costs.

Different algorithms for performance, distillation column design and operation mode optimization are compared; the purpose of these optimization algorithms is to minimize capital and operating costs[1].

The procedure of optimization of thermally coupled distillation sequences for the separation of multicomponent mixtures presented in the paper[2] allows designing the flowsheets with high thermodynamic efficiency and decrease in energy consumption in comparison with the conventional distillation schemes.

A simple heuristic method for the synthesis of the optimal sequences for multicomponent separation which can significantly reduce the cost of the designed distillation units is also proposed[3].

To solve the problems of structural and parametrical optimization of the multicomponent distillation processes it is advisable to use mathematical models developed in CAD systems (computer-aided design).

Many researches[2,4] illustrate undeniable effectiveness of using modern CAD systems such as Aspen Plus^{TM} to solve many engineering problems of design and optimization.

2. Pre-design optimization of crude oil distillation

The efficiency of distillation units is largely determined by the efficiency of distillation columns, but it is advisable to perform optimization for all the flowsheets taking into account heat exchangers, vessels, and pumping equipment.

The purpose of the work is to perform pre-design optimization of unit flowsheet structure and apparatus design and choose the optimal variant of distillation flowsheet to provide the process flexibility in respect of flowrate of crude oil (load) and oil quality.

Several first principle models of crude oil distillation units were developed in Aspen PlusTM[5,6] to achieve these purposes; the units differ in structure and equipment composition, and column internals (trays or packing).

2.1. Oil distillation basic model development

Two-column flowsheet of crude oil distillation is adopted as basic (fig. 1). Crude oil is pumped from the reservoir to the heat exchangers where it is heated by the vapor from the top of the column K1 (the prefractionator) and K2 (the main atmospheric column), then it enters the electrical dehydrators. After desalting and dewatering the oil stream passes the next block of the recuperative heat exchangers where it is heated by the product flows (the diesel fractions from the strippers K3, K4) and the intermediate pumparounds of the column K2. The heated oil is fed to the K1, the stripped oil leaves the bottom of the column K1, then it is heated by the intermediate pumparound and the bottom residue of K2, then it is pumped through the furnace to the column K2. The column K2 is a complex atmospheric distillation column equipped with two strippers K3, K4, and it has two intermediate pumparounds. All columns K1 - K4 are equipped with the traperiform valve trays. Hydrocarbon gases are separated from the tops of the K1 and the K2 vapors in the separators C1 and C2, after cooling and partial condensation in the heat exchangers.

The superheated water steams are supplied at the bottoms of K2, K3, K4. The product streams are cooled in the water and air coolers before pumping to the park.

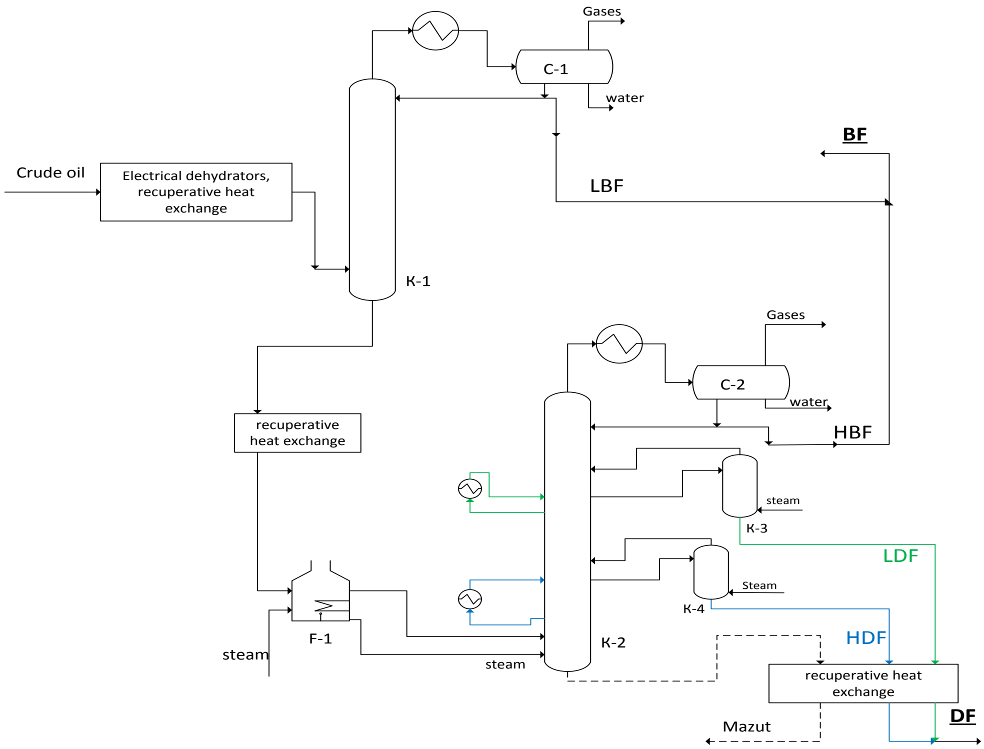


Fig. 1. Simplified basic distillation unit scheme.

Apparatus: K-1 – prefractionation column, K-2 – atmospheric column, K-3, K-4 – stripping columns, C-1, C-2 – separators, F-1 – furnace; Material streams: LBF, HBF, BF – light, heavy benzene fractions, mixture – benzene; LDF, HDF, DF – light, heavy diesel fractions, mixture – diesel.

The product streams: LBF – light benzene fraction (from the top of K1), HBF – heavy benzene fractions (from the top of K2), BF – benzene (mixture of LBF and HBF); LDF – light diesel fraction (from the bottom of K3), HDF – heavy diesel fraction (from the bottom of K4), DF – diesel (mixture of LDF and HDF).

The mathematical model of the basic flowsheet developed by the authors is the first principle model. The model takes into account all the main equipment – the distillation columns, separators, pumps, recuperative heat exchangers (fig. 2). The model considers the design features of the column internals (valve trays) and allows calculating hydraulics such as maximum flooding, section pressure drops, tray details and column geometry, etc. (fig. 3). A set of specifications is used to control the column K2 (fig. 4).

The model considers air temperature for robust calculation of the air coolers because the steam loads on the distillation trays, separators and recuperative heat exchangers operations are dependent on environment temperature.

According to GOST R 51858 - 2002, oil is classified into five types in accordance with its density. But the maximum load fluctuations are possible because of different content of light fractions in crude oil especially during summer season in the operational mode of the maximum diesel production. The authors carried out oil classification into three types in accordance with its content of light distillates. X – is light fractions content in crude oil. For heavy oil type X was assumed in the range of $59 \le X < 61$ liq.vol. %; for middle type X is in the range of $61 \le X \le 63$ liq.vol. %;

for light oil the range is $63<X\leq 65$ liq.vol. %.

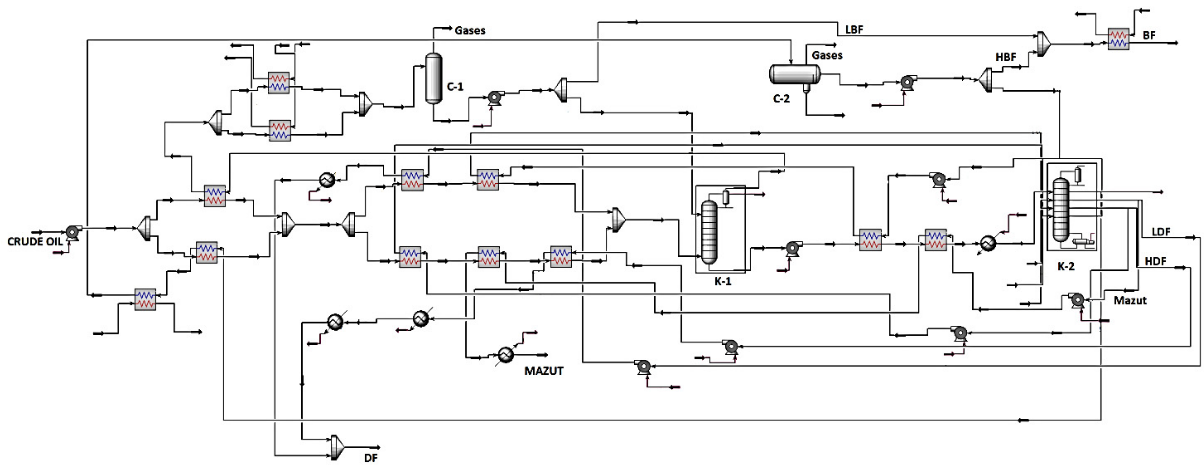


Fig. 2. The basic flowsheet of crude oil distillation in Hysys.

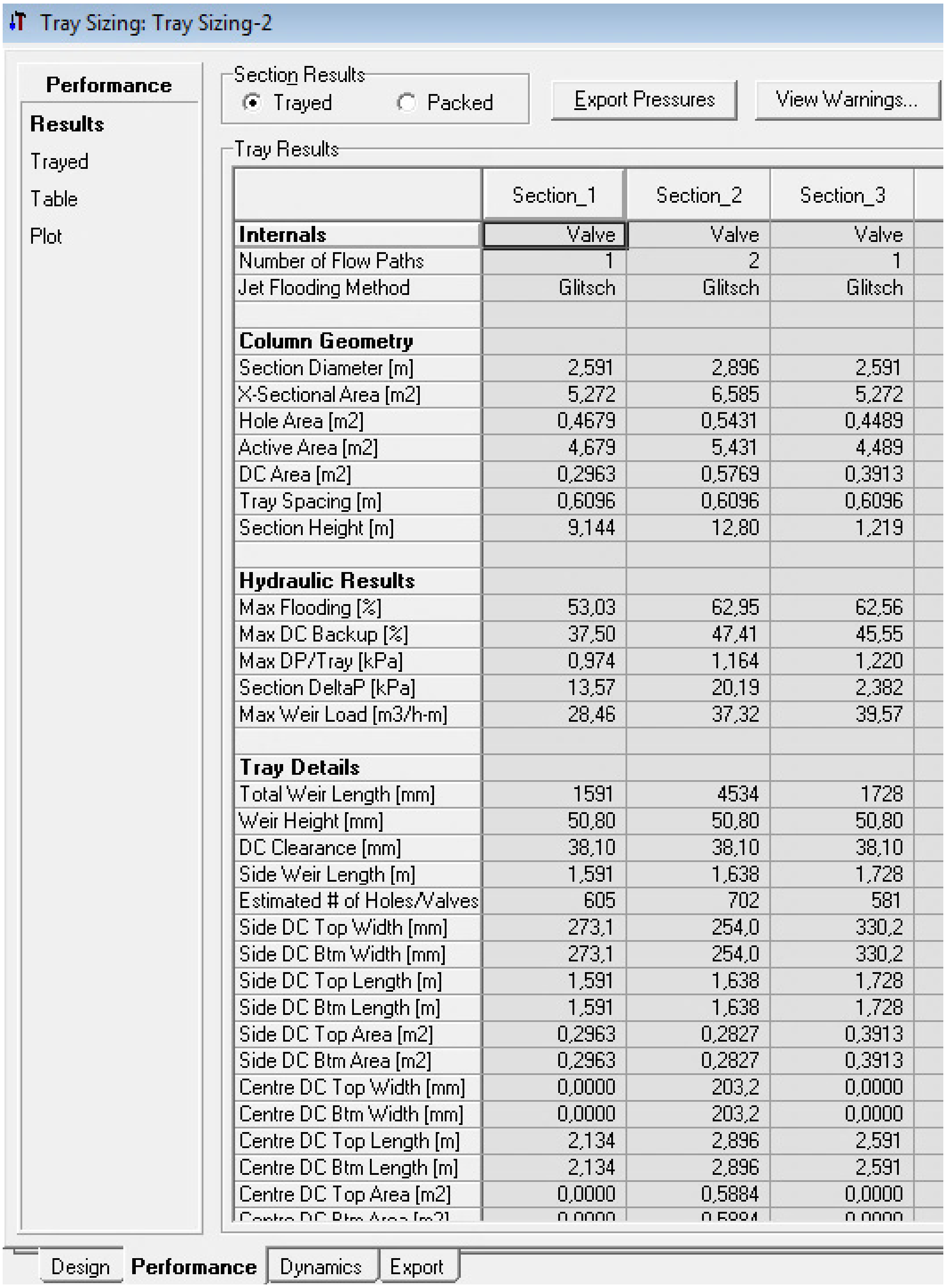
Consideration of air temperature and crude oil type is the most important advantage of the mathematical model of crude oil distillation developed by the authors.

2.2. Parametrical optimization of the flowsheet and upgrading variants

Distillation unit operation (basic flowsheet) was investigated in a wide range of crude oil loads (500 – 900 thousand tons per year) using the developed mathematical model.

The investigation was carried out by stepwise increasing of crude oil flowrate to identify "weak points" of the flowsheet at each step.

Parametrical optimization was developed for the summer operation mode because of the maximum vapor and liquid loads on the trays of the distillation columns. The algorithms of the parametrical optimization are described[7,8].



Tray Sizing: Tray Sizing-2

Performance

Results

Trayed

Table

Plot

Section Results: Trayed / Packed

Export Pressures

View Warnings...

Tray Results

	Section_1	Section_2	Section_3
Internals	Valve	Valve	Valve
Number of Flow Paths	1	2	1
Jet Flooding Method	Glitsch	Glitsch	Glitsch
Column Geometry			
Section Diameter [m]	2,591	2,896	2,591
X-Sectional Area [m2]	5,272	6,585	5,272
Hole Area [m2]	0,4679	0,5431	0,4489
Active Area [m2]	4,679	5,431	4,489
DC Area [m2]	0,2963	0,5769	0,3913
Tray Spacing [m]	0,6096	0,6096	0,6096
Section Height [m]	9,144	12,80	1,219
Hydraulic Results			
Max Flooding [%]	53,03	62,95	62,56
Max DC Backup [%]	37,50	47,41	45,55
Max DP/Tray [kPa]	0,974	1,164	1,220
Section DeltaP [kPa]	13,57	20,19	2,382
Max Weir Load [m3/h-m]	28,46	37,32	39,57
Tray Details			
Total Weir Length [mm]	1591	4534	1728
Weir Height [mm]	50,80	50,80	50,80
DC Clearance [mm]	38,10	38,10	38,10
Side Weir Length [m]	1,591	1,638	1,728
Estimated # of Holes/Valves	605	702	581
Side DC Top Width [mm]	273,1	254,0	330,2
Side DC Btm Width [mm]	273,1	254,0	330,2
Side DC Top Length [m]	1,591	1,638	1,728
Side DC Btm Length [m]	1,591	1,638	1,728
Side DC Top Area [m2]	0,2963	0,2827	0,3913
Side DC Btm Area [m2]	0,2963	0,2827	0,3913
Centre DC Top Width [mm]	0,0000	203,2	0,0000
Centre DC Btm Width [mm]	0,0000	203,2	0,0000
Centre DC Top Length [m]	2,134	2,896	2,591
Centre DC Btm Length [m]	2,134	2,896	2,591
Centre DC Top Area [m2]	0,0000	0,5884	0,0000
Centre DC Btm Area [m2]	0,0000	0,5884	0,0000

Design | Performance | Dynamics | Export

Fig. 3. The results of tray hydraulics calculation in Hysys.

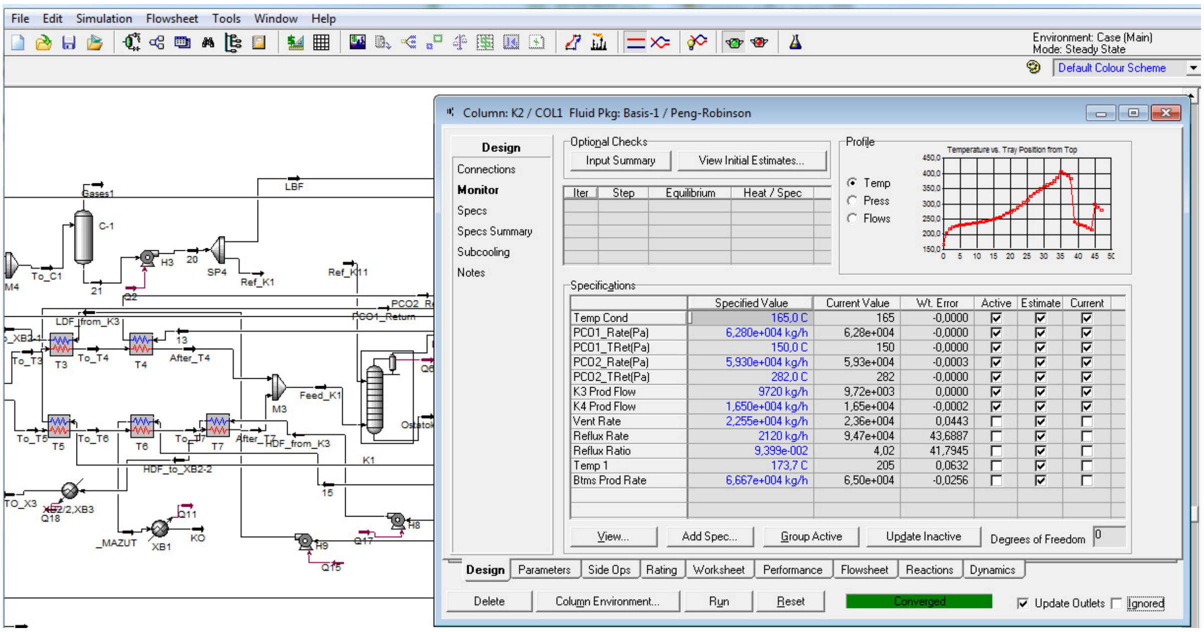


Fig. 4. An example of specifications of the main column K2 in Hysys.

Maximum crude oil flowrate was determined for the basic flowsheet of the unit under conditions of maximum light products yield and restrictions on the product quality. Table 1 illustrates "weak points" of the basic distillation unit.

Table 1 shows that the main atmospheric column K2 is the limitative apparatus, because of this maximum crude oil flowrate is 500 thousand tons per year. Furthermore, increasing crude oil flowrate requires changing of the recuperative heat exchange structure.

Table 1. The maximum crude oil flowrates for the equipment of the basic crude oil distillation unit.

№	Type of equipment	Maximum crude oil flowrate, thousand tons per year
1	Prefractionation column K1	900
2	Atmospheric column K2	500
3	Furnaces	900
4	Heat exchangers	800
5	Pumps	600

Accordingly, the variants of upgrading were developed to increase operation effectiveness for a wide range of crude oil flowrates:

1. The crude oil distillation unit with the two parallel atmospheric distillation columns (the main K2 and additional tray column);
2. The crude oil distillation unit with the two parallel atmospheric distillation columns (the main K2 and additional packed column);
3. The crude oil distillation unit with the tray column of larger diameter instead of the main column K2;
4. The crude oil distillation unit with a packed column of larger diameter instead of the main column K2;
5. The crude oil distillation unit with the prefractionator – the tray column K1 equipped with the extra stripping column (fig. 5);
6. The crude oil distillation unit with the prefractionator – the packed column K1 equipped with the extra stripping column;
7. The crude oil distillation unit where the trays of the main column K1 are partially replaced by packing with the vertical contact grids (PVG) and all trays of K2 are replaced on PVG[9];

8. The crude oil distillation unit with the K1 and K2 columns equipped with the column internals of company SULZER, including the valve trays, inlet devices, gas and liquid distributors (for K2) of SULZER[10].

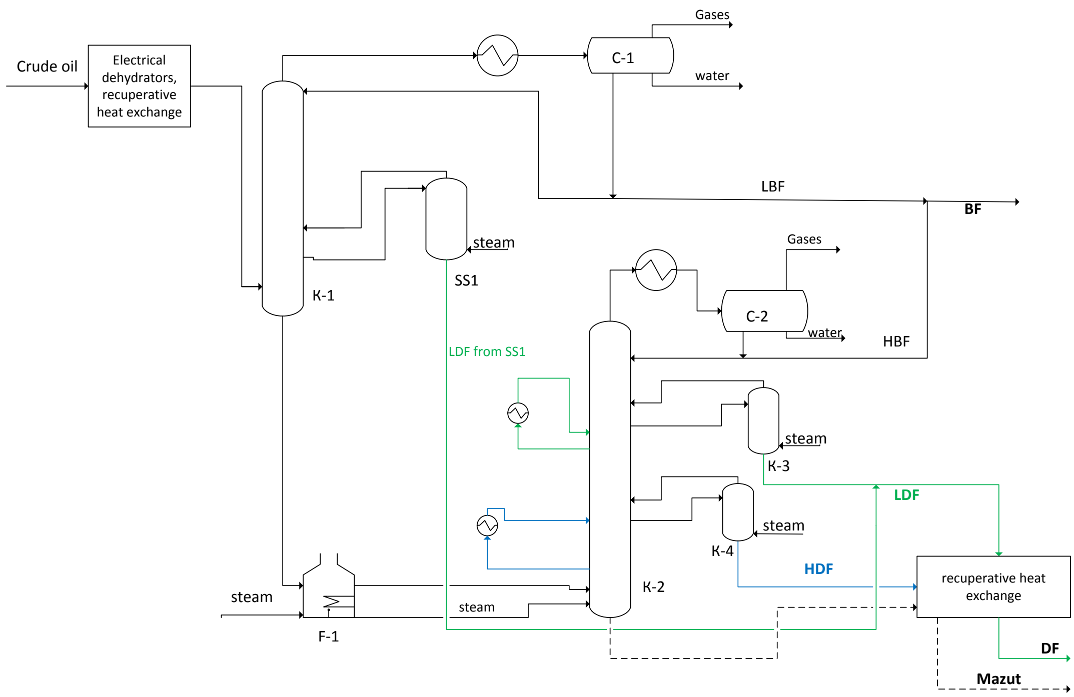


Fig. 5. The simplified scheme of crude oil distillation unit with the prefractionation column K1 equipped with the extra stripping column (SS1).

2.3. Optimization criterion

Optimization criterion is a ratio of average annual revenue from the sale of petroleum products to the total costs (capital investments and operational costs) with restrictions on the product quality.

$$U = \frac{\sum C_{product}}{\sum (Z_{capital} + Z_{operation})} \rightarrow \max, \tag{1}$$

where U – optimization criterion;

$\sum C_{product}$ - total annual revenue from products sale, million rubles a year;

$Z_{capital}$ - capital costs ($Z_{capital}$ were calculated over the costs on the basic flowsheet), million rubles a year;

$Z_{operation}$ - operation costs, million rubles a year.

The sum of the capital and operation costs during a year for the basic flowsheet was estimated preliminarily. The number of operational hours per year for the equipment is 8000.

The fundamental mathematical models were developed for each of eight upgrading variants, and optimization procedure was performed in accordance with the proposed criterion (1).

Special mathematical correlations for the transport properties of hydrocarbon systems were used for simulation of the packed columns (variants 2, 4, 6). The calculations were performed for the conventional packed types such as the ceramic Raschig rings.

The upgrading variants 7, 8 are expected to save basic sizes of the distillation columns and location / construction of unions.

Estimation of the total capital costs for the implementation of each proposed variant of upgrade includes:

- Costs for the purchase of additional equipment;
- Costs for construction and installation works.

3. Discussion

Fig. 6 illustrates the comparison of the capital costs, total annual operating costs, and summary costs of alternative oil distillation flowsheets. The comparison was developed in the percentage over the basic flowsheet. Saving the basic equipment in the variants of upgrading 7 and 8 allows significantly reducing capital costs. Besides, the flowsheets 7, 8 are characterized by minimum operation costs. These reasons increase optimization criterion (1) (fig. 7).

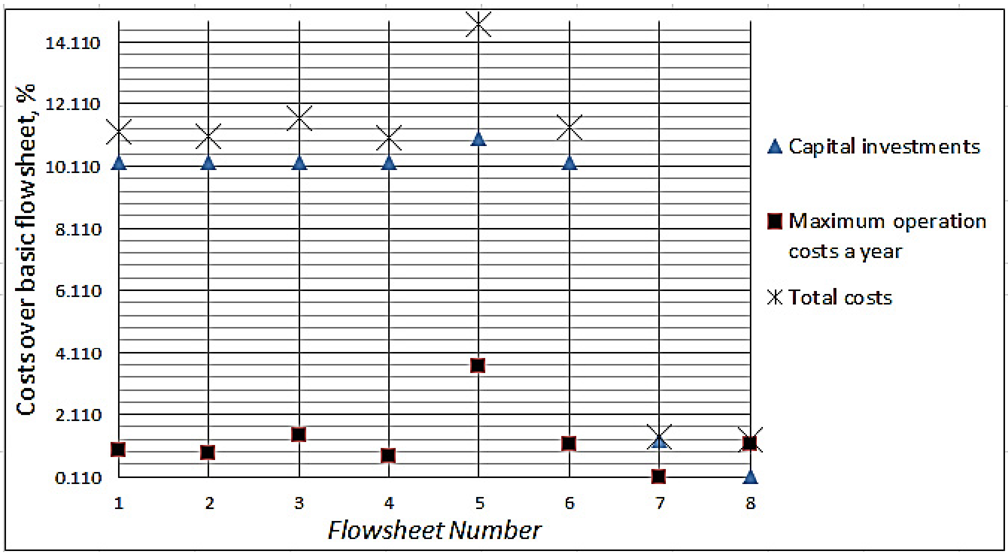


Fig. 6. The analysis of capital investments and annual operating costs over the total costs of the basic crude oil distillation unit.

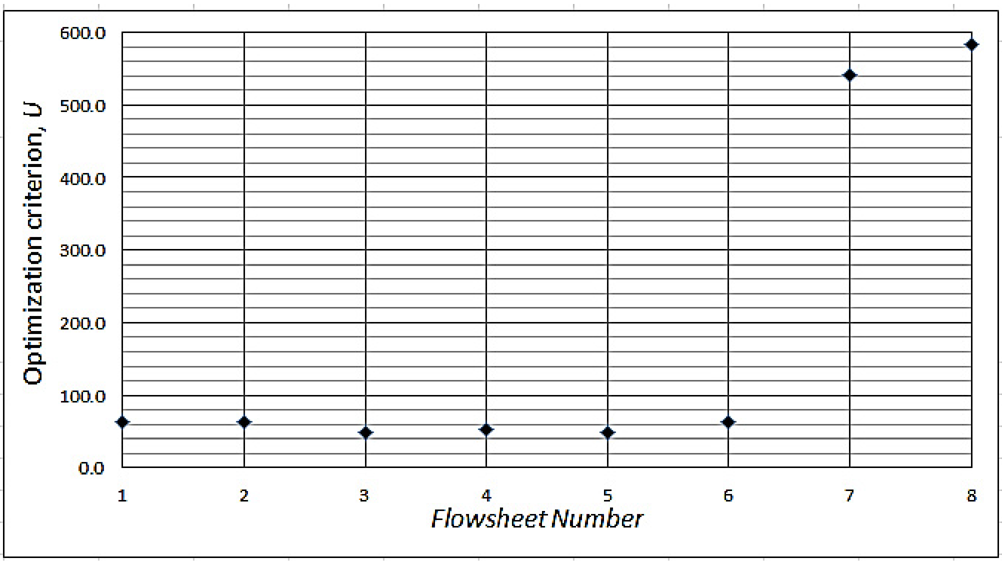


Fig. 7. The optimization criterion.

The analysis of the results allowed evaluating the relative efficiency of the alternative distillation unit flowsheets and choosing the best flowsheet design.

The way of re-equipment with modern column internals is preferable – it was illustrated by upgrading variants 7 and 8 which are characterized by minimum capital investments and relatively low operating costs to achieve the required feed flowrate, maximum light product yields with restrictions on the product quality.

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