Increasing the Efficiency of Mass and Heat Exchanger Networks.

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The most effective practical solution to heat exchanger network synthesis problems is a group of pinch methods [1-5]. The basis of all versions is an analysis of the composite curves by means of a temperature-enthalpy diagram (TED). The TED allows for the easy determination of the maximum integral heat exchange and minimum utility duties.

A more difficult problem for pinch methods is the design of a practical scheme for heat exchangers. The designs obtained by this method consist of many small exchangers and intermediate heaters and coolers. The combinatorial methods [6] are more flexible in specifying stream matches than pinch methods and may synthesize networks in which more heat is exchanged by a smaller number of heat exchangers as compared with networks synthesized by pinch methods.

For complex chemical and technological systems, consisting of several sub-systems (separation, heat exchange, reactor sub-systems, etc.), the problem of the synthesis of optimal heat systems is a sub-problem that is repeatedly solved while searching for the optimum of the general criterion — the minimization of the cost of the system.

In this case the use of combinatorial and pinch methods to obtain the exact solution is difficult due to the fact that they are not sufficiently fast. Moreover, such issues as the synthesis of heat exchanger networks using standard heat exchangers chosen from a catalogue, as well as ones with variable heat transfer coefficients, have not been studied well.

Heuristic methods with thermodynamic heuristics can be used for the solution of the sub-problem of the syntheses of heat exchanger networks [7]. The main heuristic rule is formulated as follows:

- Among possible tree vertices one should choose a vertex in which the further network development produces the maximum possible heat exchange (Qmax). The maximum possible heat exchange is determined by the TED (Qmax).
- Among possible tree vertices one should choose a vertex corresponding to maximum exergy efficiency. (The use of exergy efficiency as a heuristic allows the driving force of the heat exchange process to be kept high during heat exchange system synthesis).

A specific comparison of the methods has been done on the problem of an aromatic plant [1].

CASE STUDY 1

Table 1.Initial data for synthesis of heat exchange networks [1]

Flow No	W, kW/ ^oC	T_{in}, ^oC	T_{out}, ^oC
Cold streams			
1	100	100	300
2	70	35	164
3	350	85	138
4	60	60	170
5	200	140	300
Hot streams			
1	100	327	40
2	160	220	160
3	60	220	60
4	400	160	45

Minimum temperature difference (Δt_{min}) is 10 ^oC; heat transfer coefficient 0.5 kW/m^2 ^oC; heat exchanger cost is £700$F^{0,83}$; normative coefficient 0.2983 yr^{-1}; cooling (water) is £7 kW/year; steam is £70 kW/yr; steam temperature is 350 ^oC; initial temperature of water is 25 ^oC; final temperature of water is 35 ^oC.

The exact solution for this problem exists. The annual cost is £2,143,131 a year (Fig.1) compared to £2,182,979 a year for a network synthesized by the pinch method and £2,147,657 a year for a network synthesized by the combinatorial method with the evaluation functions.

Analysis of the results shows that increasing the heat transfer surface in a heat exchanger (2C, 3H) from 646 to 840 m^2 increases the heat load from 4867 to 5049 kW, and Δt_{min} decreases to 7°C.

When the third heater is removed, the annual cost is reduced to £2,139,372 a year. At the same time, synthesis at Δt_{min}=7 for all heat exchangers did not result in any decrease in the reduced annual costs.

The synthesis should have been carried out by varying Δt_{min}, as this value is not a global constant but depends on the corresponding streams and their position in the heat exchanger network.

If combinatorial or pinch methods are used, the definition of the optimal Δt_{min} for each heat exchanger is not possible due to a sharp increase in the number of synthesis variants. Using heuristic methods, Δt_{min} can be changed in the synthesis processes, for instance by means of random dependence.

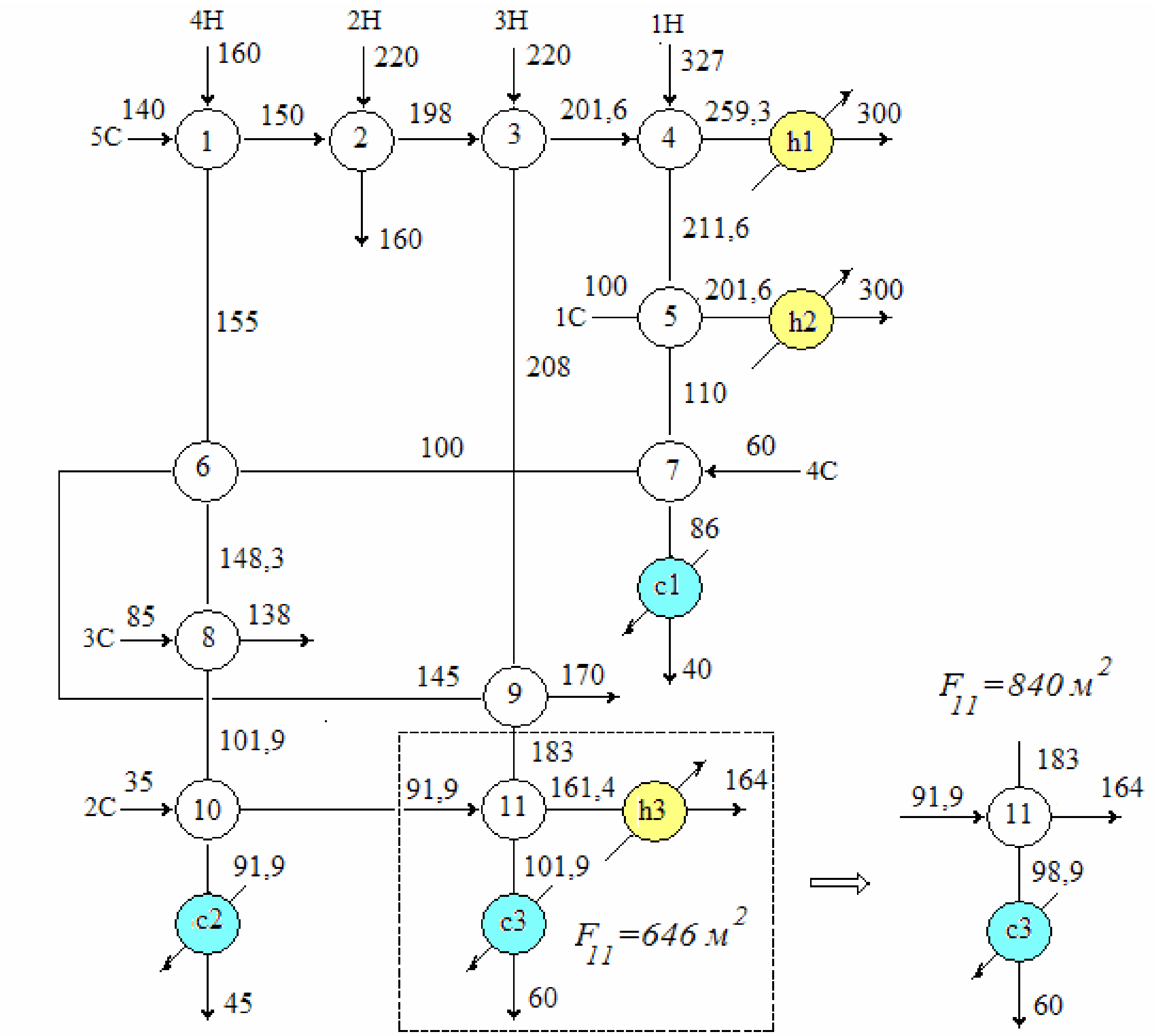

Fig 1. Results of synthesis of heat exchange networks

One of the problems arising for synthesis of optimal heat exchanger networks is the requirement of choosing standard heat exchangers from catalogues and industry standards. In principle, this problem can be solved using constant heat transfer coefficients, and the heat exchangers can be chosen after the structure of a synthesized network and temperatures have been defined. However, the considerable effect of Δt_{min} on the synthesis results forces us to choose standard heat exchangers immediately in the course of synthesis. This problem was solved as follows. After the *i-th* pair of streams has been chosen, a heat exchanger is found in the catalogue with surface area F_c on the basis of the set conditional pressure and admissible linear speed of the streams.

The heat transfer coefficient and required theoretical area of the heat exchange surface were calculated for the chosen heat exchanger:

$$F_{\mathrm{T}} = \frac{q}{k\Delta t_{av}}$$

The number of the same type heat exchangers in a heat exchange module makes

$$n_{\mathrm{T}} = \mathrm{entier}\left(F_{\mathrm{T}} / F_{\mathrm{c}}\right) + 1.$$

If just one stream reaches the target temperature, there is no need to recalculate the temperatures of the streams at the heat exchanger's outlet (the availability of a bypass line in the actual network is assumed since the actual surface is more or equal to the calculated one). If both streams fail to reach the target temperatures, the temperature of hot and cold flows and the actual amount of transferred heat q is defined for the actual surface $F_{\mathrm{r}}=n_{\mathrm{T}}F_{\mathrm{c}}$ with the help of checking calculation made for the heat exchanger model.

In this approach, Δt_{min} is not constant and depends on a standard heat exchanger used. The number of bypass lines, which cause the system to increase in cost, is decreased in the actual network. This method allows us to synthesize the schemes with positive results.

Many refineries were built before efficient methods of syntheses appeared. These refineries have larger heat networks and are not as efficient. The reconstruction of older refineries to take advantage of these efficiencies can be profitable if the changes are small and result significant cost savings. If the potential savings are large enough, but huge changes are required, it may be reasonable to build new facilities. However, partial reconstruction is possible, which can be carried out at the same time as scheduled maintenance.

We consider the heat exchanger network for a crude oil distillation unit with a capacity of six millions tons per annum(Fig.2)

CASE STUDY 2

Annual cost of unit duty of hot utility	5000 (ruble Mcal $\cdot$ yr^{-1}).
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Exchanger capital cost (ruble)	$48500 \cdot (area(m^2))^{0,6}$.
Average heat transfer coefficient	150 kcal/(m^2 $\cdot$ hour $\cdot$ ^{o}C)
Normative coefficient	0,2983 yr^{-1}

The stream parameters are introduced in table 2

Table 2 The stream parameters of the heat exchange network. (crude oil distillation unit).

№	Stream type	Flow rate kg/hour	Heat capacity kcal/kg °C	T in, °C	T out, °C
Cold streams					
1	Crude oil	335608.8	0.5258	11	121
2	Crude oil	338190.4	0.5170	11	102
3	Desalinized oil	305221.8	0.6166	100	225
4	Desalinized oil	175782.2	0.6236	100	240
5	Desalinized oil	182174.2	0.6236	100	240
6	Reduce fuel oil	14912.9	0.5111	70	96
7	Gasoline	98692.3	0.6591	47	146
8	Topped oil	291500.0	0.7342	246.5	372
9	Topped oil	291500.0	0.7342	246.5	372
10	Petroleum cut 62-105 °C		0.7003	116	116
Hot streams					
1	II circulating reflux	289634.4	0.6582	256	98
2	I circulating reflux	277364.4	0.6116	107	76
3	I circulating reflux	118870.4	0.6116	107	76
4	Diesel fuel	144527.3	0.5983	178	68
5	Diesel fuel	144531.2	0.6986	256	198
6	Black oil	134994.2	0.6273	355	75
7	Black oil	144134.4	0.6273	355	75
8	Kerosene	62116.2	0.5909	95	48

Summary heat exchangers cost is 48,500 $\sum_i F_i^{0,6}$ =12.971 million rubles. The heat recovery is $0.947 \cdot 10^8$ kcal/hour. The annual cost is 285.5 million rubles.

From TED (Fig.3) it follows that the degree of heat recovery is 91.2%. Therefore, it is theoretically possible to have 91Mcal/hour heat recovery.

The problem of the synthesis of heat exchanger network was solved by means of a heuristic method at variation $\Delta t_{\min}$..

$$\Delta t_{\min} = 30\,^{\circ}\mathrm{C} \pm \gamma \cdot (\Delta t^{u}_{\min} - \Delta t^{d}_{\min}),$$

where γ -pseudorandom sequence; $\Delta t^{u}_{\min}, \Delta t^{d}_{\min}$ - upper and lower limit of the minimum temperature difference.

The network synthesized by heuristic method is shown in Fig. 4.

The heat of recovery is $1.036 \cdot 10^8$ kcal/hour. The annual cost is 243.3 million rubles.

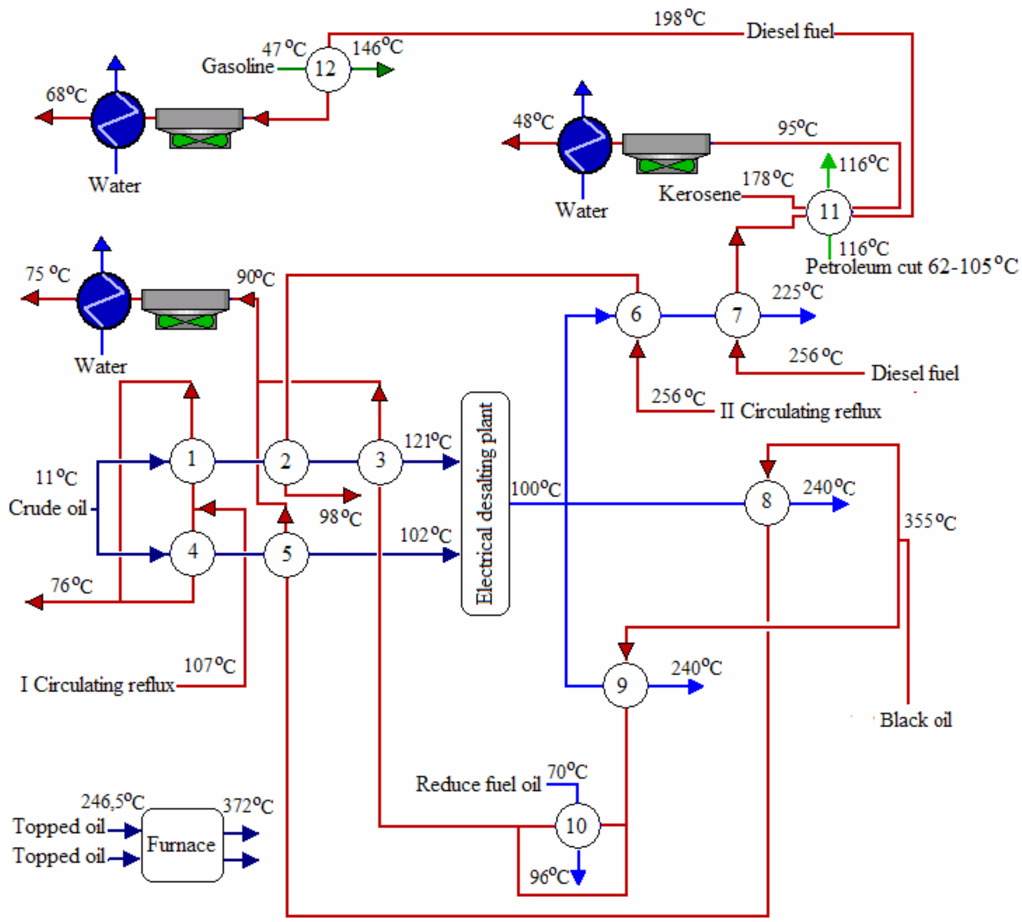

Fig 2. Heat exchanger network of crude oil distillation unit

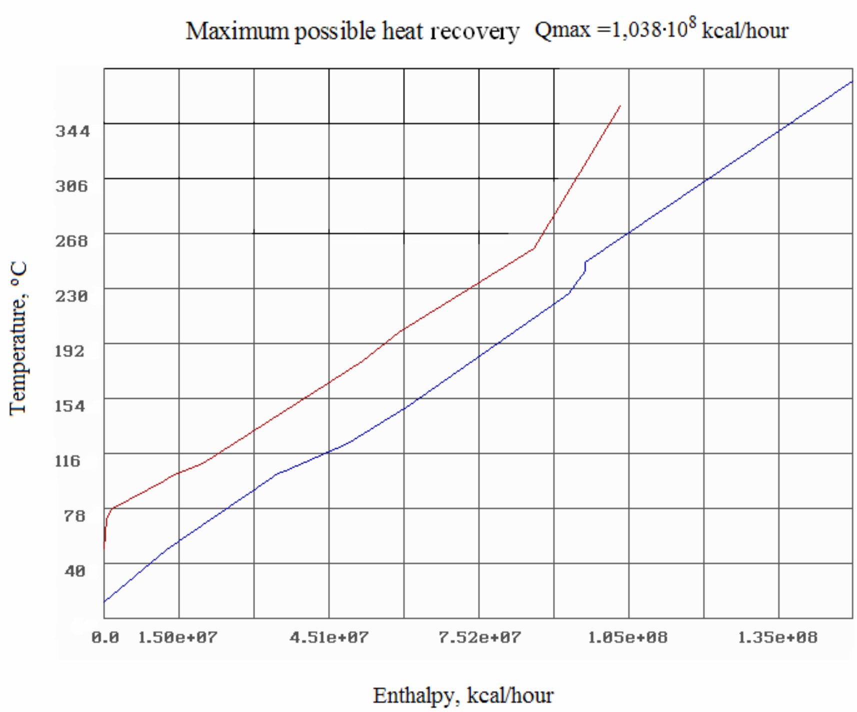

Fig.3 Temperature-enthalpy diagram for streams of crude oil distillation unit.

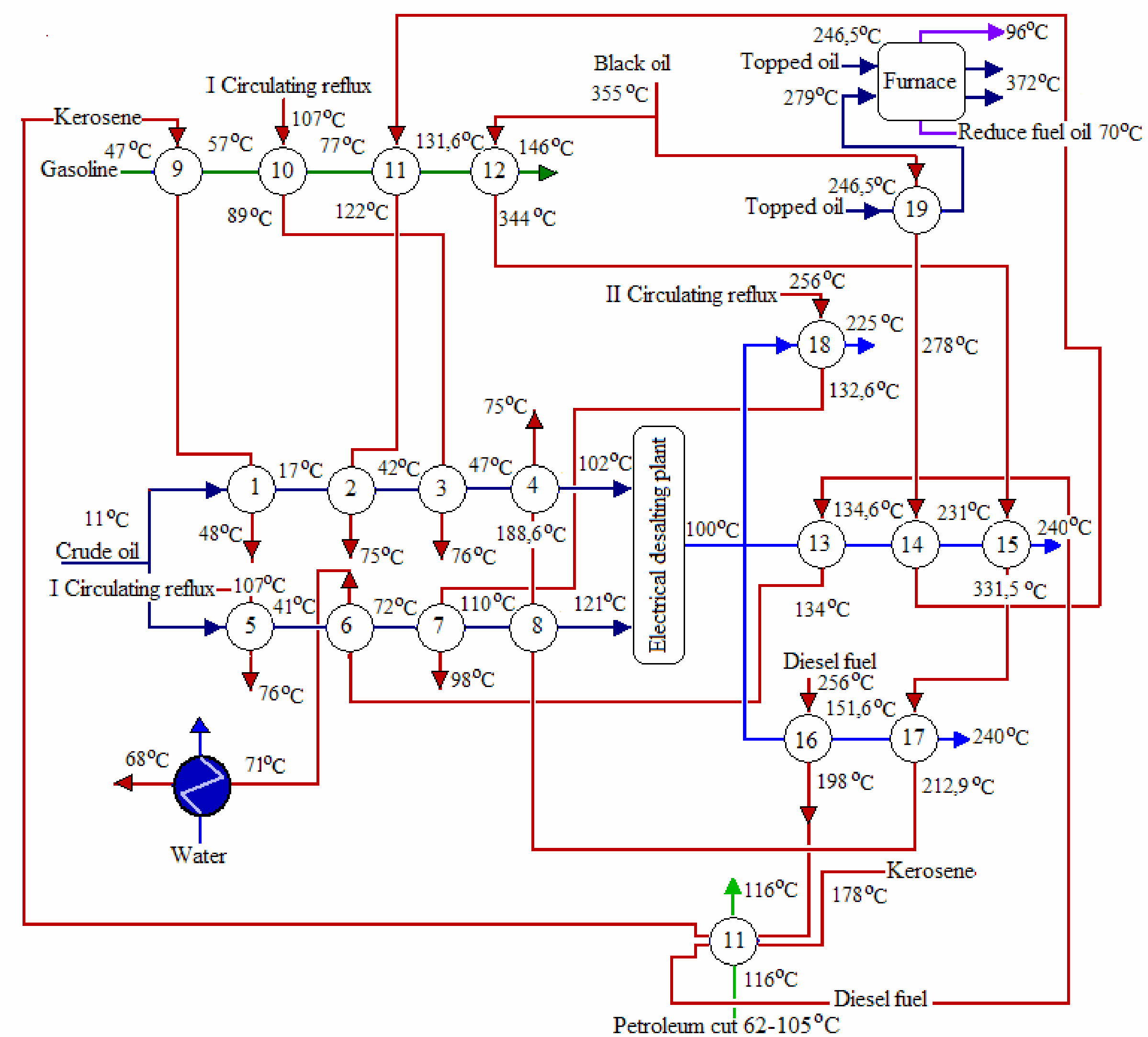

Fig 4. Optimal heat exchanger network of crude oil distillation unit.

Although the cost of the synthesized heat exchanger network is far less than the current system, huge changes are required for it. Therefore, it is advisable to carry out only a partial reconstruction.

The comparison of the synthesized and current heat exchanger networks shows that the reduction in the cost is achieved by the increase in the temperature of the topped oil entering the furnace. It is preferable to use a stream with a high temperature for heating the topped oil, for instance the black oil stream (stream No. 6). The parameters of the black oil stream will change as a result of the change in heat.

If we fixed heat exchange between black oil and topped oil, the problem has to be resolved for streams, which were heated by black oil. The streams, which exchange heat with utilities, have to include in the resolved problem.

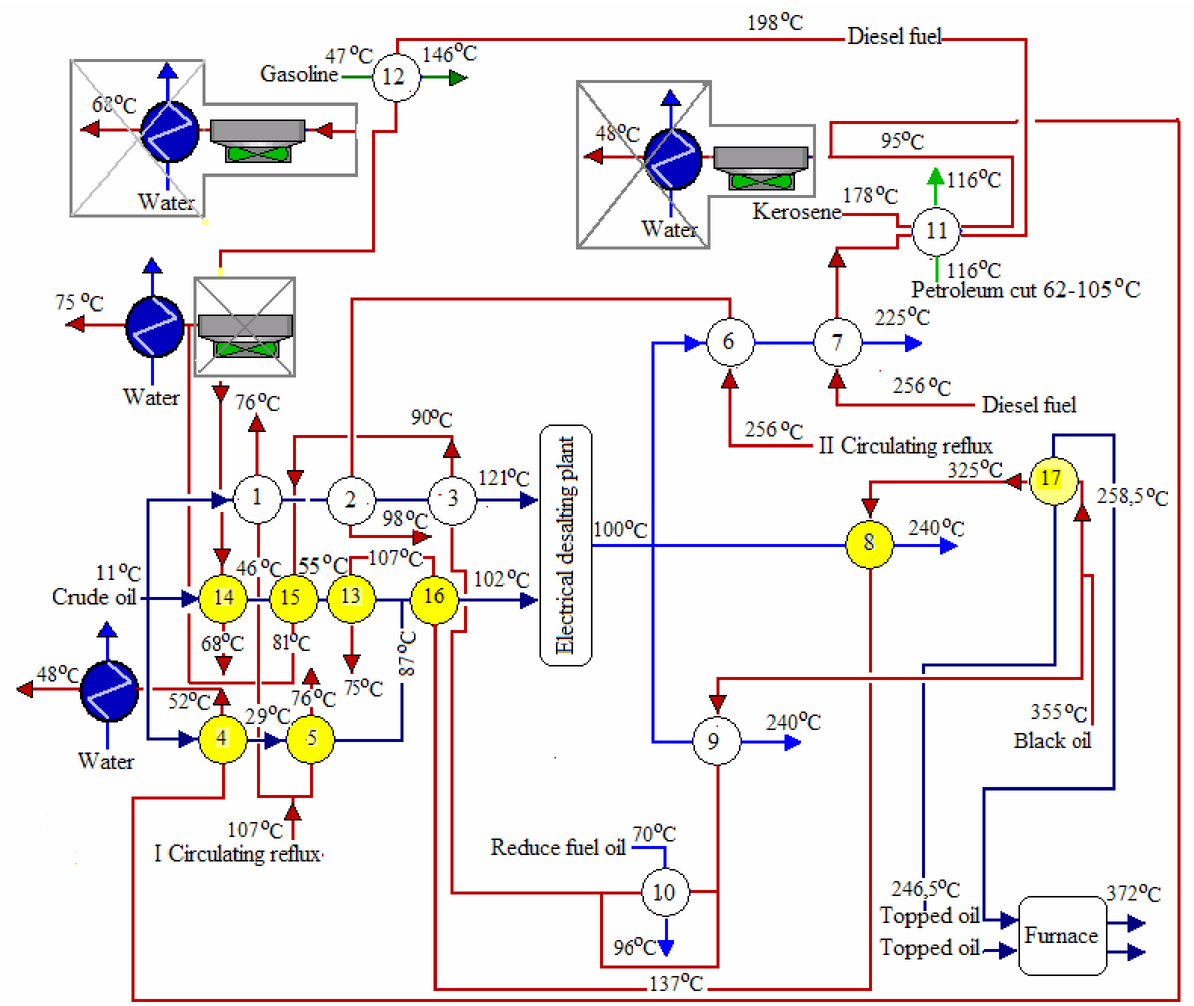

Fig.5 The heat exchanger network after partial reconstruction.

(On drawing by colour newly installed exchangers are marked)

The results from the TED are that the maximum possible heat recovery is 34.29 Mcal/hour, and the pinch point is 97 degrees. The annual cost of the heat exchange network after reconstruction is 270.5 million rubles. The savings from the partial reconstruction are 15 million rubles per annum.

It should be pointed out that instead of heating the topped oil in heat exchanger No. 17 it is possible to heat the desalinized oil (stream No 5) in heat exchanger No. 8 to 262 °C and therefore reduce the heat demand in the reboiler of topping oil distillation column.

As noted above, the synthesis of the heat network is a subsystem of more complex systems, for instance systems of separation. The Problem of the synthesis of heat integrated separation systems is part of the search for of the minimum annual cost:

$$\min_{\substack{p_1,\dots,p_{N-1} \\ s\subset S}} \left(C_S + C_H\right),$$

N – number of components, p – entry pressure in the column; C_S - annual cost of separation system; C_H -annual cost of heat exchanger network.

For many technological processes, the cost of the energy vastly exceeds the investment in equipment.

In this case, the lower boundary of an annual cost of heat exchanger network may be calculated with a simplified formula:

$$C_H^* = C_{cu} + C_{hu},$$

where C_{cu} - annual cost of unit duty of cold utility; C_{hu} - annual cost of unit duty of hot utility.

Values C_{cu} and C_{hu} are defined from TED..

The synthesis of heat integrated separation system may be realized by means of a two-level Method.

The problem of searching for the minimum is solved on the first level

$$\min_{\substack{p_1,\ldots,p_{N-1} \\ s \subset S}} \left(C_S + C_H^* \right)$$

If number component mixture less six, the optimum scheme for separation may be found in a simple enumeration of possibilities. Otherwise, the part of components united in pseudo components[8].

On the second level, the heat exchanger network synthesis is carried out by searching for the minimum C_H by means of a heuristic method using standard heat exchangers from catalogues.

The described method for the synthesis of the heat-integrated systems of separation was organized for a gas-fractionation plant. The synthesized heat integrated separation system turned out to be 30% less expensive than the same without recuperation of heat.

In the synthesized system of separation, auxiliary energy carriers were necessary for use in the column for the separation of butane and isobutane. Heat recovery may be increased using a heat pump. The possibility of using a heat pump for the butane and isobutane separation column is considered in the following example.

CASE STUDY 3

Feed: 28т/hour.

Ratio iC4:nC4 inflow feed 18:82.

Pressure: 10 bar,

The temperature of the bottom and top of the column: 80 and 61°C, respectively.

The amount vaporized liquid in the reboiler: 133т/hour (heat power 9400 Mcal/hour);

The amount of condensed vapor in the cooler: 9000Mcal/hour.

The general power for four electric motors: 360 KW.

Annual cost of vapor: 51.5 million rubles per annum.

Total annual cost: 55.5 million rubles per annum.

The preliminary calculations show that the decompression of the low product(n-butane) was the most expedient. The liquid from the boiler (133 т/hour) cooled from 80°C to 32°C because of the reduction in the pressure to 3 bar and entry into the heat exchanger, where it is changed by heat and vapor (the temperature of the liquid is 61°C). The surplus vapor (17 т/hour) of the column moves into air coolers. The condensed vapor in the heat exchanger mixes with the condensate from the air coolers. The evaporated flow of normal butane is compressed in the compressor to a pressure of 10 bar and returns to the bottom of the column.(Fig.6)

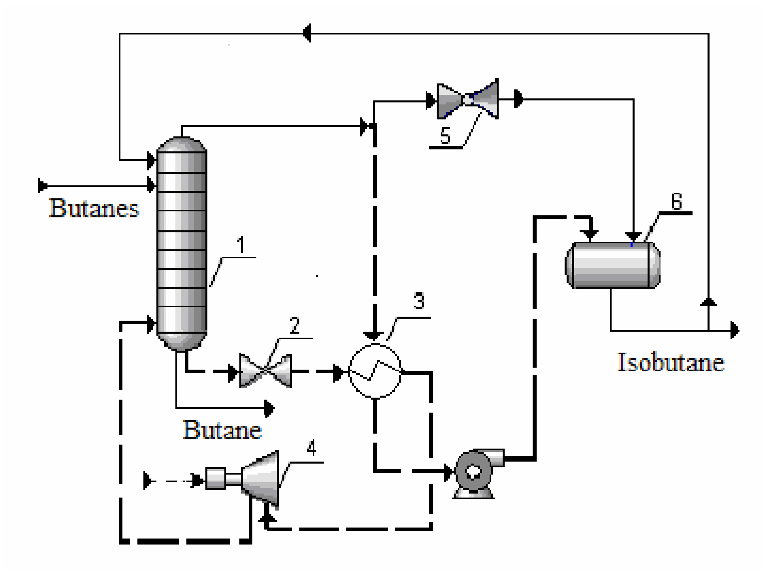

Fig.6 The scheme of the column for separation butanes with a heat pump.

1- column; 2-throttle;3- heat exchanger; 4 - compressor; 5 - air cooler; 6-reflux volume.

For the normal operation of the described scheme, the isobutane stream upon output from heat pump cannot have a steam phase, but the normal butane stream cannot have a fluid phase.

The intention of the above scheme is not to consume heating vapor. The reduction of costs for heating vapor is 51.5 million rubles per annum. The additional cost for electric power is 19.5 million rubles per annum. The resulting reduction in costs is 32 million rubles per annum.

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