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ORGANIZATION OF PRODUCTION

Modernizing Furnace Systems at Oil Refineries for Multifunctionality

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Abstract—At oil refineries, furnaces account for much of the energy expenditure. Energy efficiency may be improved by means of an integrated system that contains a furnace and a unit for heating the incoming gas with energy recovered from the smokestack gases. By exergetic analysis and efficiency assessment of the energy distribution in the system (on the basis of the zeroth law of thermodynamics), a multifunctional approach to effective integration of the furnace subsystem and the energy subsystem is proposed. That results in greater stability of the integrated system; provides the energy required for all the technological operations, as well as additional inexpensive electrical power; and helps curb thermal pollution of the environment. This approach may be adopted in modernizing existing systems or creating new systems.

Keywords: furnaces, energy recuperation, energy conservation, exergy, exergy losses, exergetic efficiency, energy fluctuations, zeroth law of thermodynamics, modeling, polygeneration, multifunctionality, oil refineries

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An oil refinery is a complex set of shops, machines, and systems with automatic control. Its product range is broad and includes, in particular, gasoline, kerosene, fuel oil, diesel fuel, and coke [1]. The overall efficiency of a refinery is determined by the optimal structure and topology (interrelationship) of the components, on the one hand, and by the efficiency of its individual components, on the other.

In selecting the production characteristics, current trends in the industry must be taken into account: shortages of locally generated energy with transition to new technological standards; and pressure to intensify production and to protect the environment. Heating furnaces consume the most energy at oil refineries (Fig. 1): more than 65% of total energy needs [2].

Of this total, energy sources amount to 34%: locally generated steam (4%); electrical energy (6.1%); and some thermal energy in the form of steam (24.5%). The remainder (66%) consists of boiler and furnace fuel: gas from oil processing (44.5%); liquid fuel (15.7%), and natural gas (5.1%). In Fig. 2, we show the balance of electrical energy for the enterprise in Fig. 1 [2].

In-plant generation of electric power is increasing, according to [2]. That stabilizes the power supply and

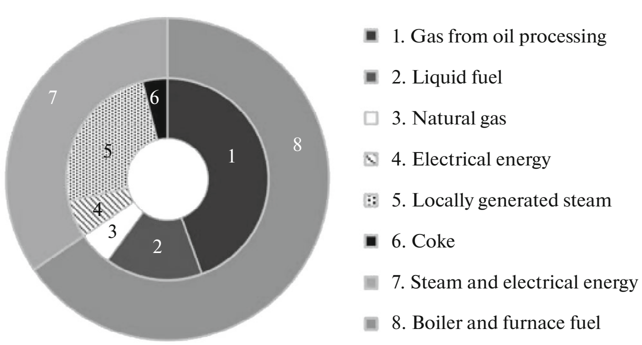

Fig. 1. Example of an oil refinery's energy balance.

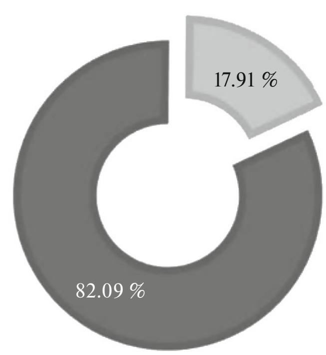

Fig. 2. Electrical energy balance for the enterprise in Fig. 1 (2016) [2]: 82.09% purchased power; 17.91% locally generated electric power.

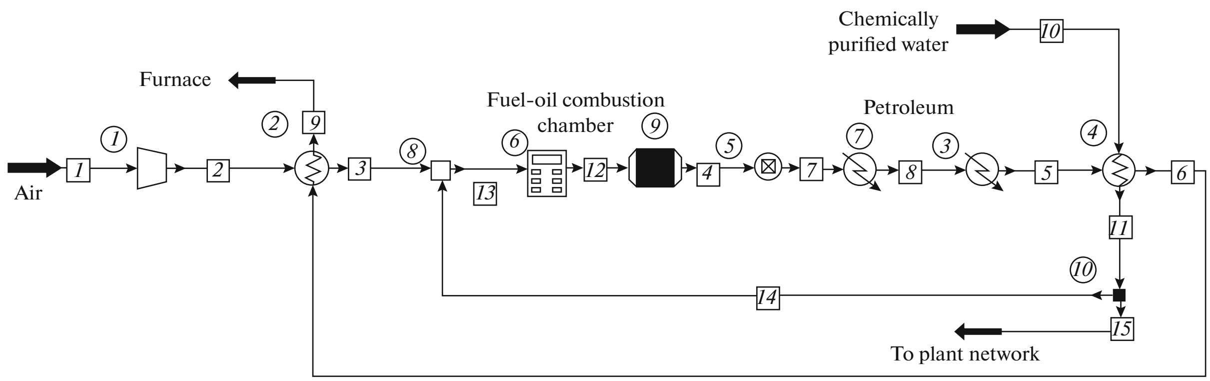

Fig. 3. Basic furnace system. The furnace burns fuel oil.

improves energy security. Thus, today's oil refineries confront a tangle of technological challenges: multifunctional approaches based on cogeneration and polygeneration may prove useful here. Two paths are possible:

(1) extensive solutions: the use of some of the boiler and furnace fuel from the energy balance to generate electric power in the Brayton cycle (the gas-turbine cycle) or the Rankin cycle (the steam-turbine cycle);

(2) intensive solutions: thorough utilization of the residual heat in waste fluxes on the basis of special equipment integrated into the refinery's structure.

Extensive measures are relatively obvious and need no detailed discussion here. Intensive measures, by contrast, call for careful analysis of the energy efficiency throughout the enterprise so as to integrate power-generating modules into the existing structure and to select the structure, working media, and operating conditions of such modules. There are many practical examples of intensive solutions based on the Rankin cycle with low-boiling working media (the organic Rankin cycle, ORC) [3].

For example, the use of a Rankin cycle based on *n*-butane to reclaim heat from the rectification columns (the stripping column C1 and the basic rectification column C2) in the atmospheric distillation of petroleum was discussed in [4].

However, it is obvious from the energy balance in Fig. 1 that the power-generating module will have the greatest effect if integrated into the refinery's furnace system. Therefore, we investigate a system consisting of a furnace and a plate-type recuperator for heat transfer from the smokestack gases to the air that is fed to the furnace. The furnace fuel is the fuel-oil fraction from petroleum.

In Fig. 3, we show the basic furnace system. On that basis, the system parameters are calculated by means of CHEMCAD software.

The supplies to the furnace are fuel oil (combustion chamber 6), air (flux 1), and steam (flux 11). The fuel is burned in a radiant chamber, and the smokestack gases heat the petroleum (heat exchanger 3). Then the smokestack gases are sent to a convective chamber, where steam is generated from chemically purified water for use in fuel-oil combustion (heat exchanger 4) and for plant needs. Then the smokestack gases are recycled (flux 6) to the recuperator for air heating. The Gibbs reactor (unit 9) permits calculation of the smokestack-gas composition, since high-temperature dissociation is taken into account.

In the first stage of the research, the energy efficiency of the furnace system is assessed by exergetic thermodynamic analysis. In writing the exergy balance, the loss of useful energy in each component must be taken into account. On that basis, the efficiency of the components may be compared.

The method of exergetic analysis was outlined in [5]. By determining the exergy, the reversible work in mass transfer to attain equilibrium with the environment may be measured. The environment generally consists of biosphere components: the atmosphere, the hydrosphere, and the lithosphere. In contrast to the thermal balance, the exergetic balance takes account not only of the quantity of energy but also of its quality, which changes as a result of the loss of utility of the fluxes. Consequently, exergetic thermodynamic analysis is the best method of assessing the energy efficiency of the system.

In the exergy of a technological flux, as a rule, we may identify two components: physical and chemical. The sum of the physical and chemical exergy is the thermal exergy, expressed in terms of the characteristic enthalpy H, the entropy S, and the chemical potentials μ of the fluxes

$$E_i = H_i - H_0 - T_0(S_i - S_0) - \sum_{j=1}^{N} x_j(\mu_j - \mu_0) \quad (1)$$

or in differential form

$$e_i = (T_i - T_0)dS + vdp + \sum_{j=1}^{N} (\mu_j - \mu_0)dx_j. \quad (2)$$

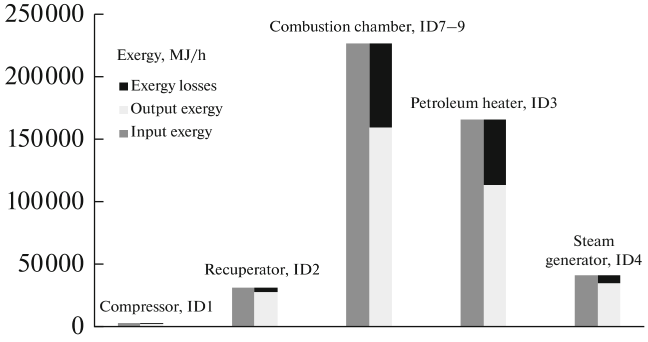

Fig. 4. Calculated exergy balance of the furnace system.

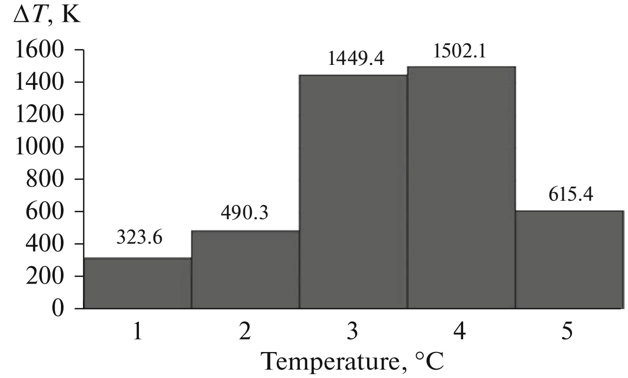

Fig. 5. Distribution of the mean energy levels in the furnace system.

The efficiency of the system is characterized in absolute form by the exergy losses, determined from the exergy balance; or in relative form by the exergetic efficiency

$$\eta_{ex} = \sum_i E_{\text{out},i} / E_{\text{in,i}}. \quad (3)$$

Such exergetic analysis is incorporated in the Exergy Unit program, which is part of commercial CHEMCAD software [6]. This software may be used for exergetic analysis of the furnace system.

In Fig. 4, we show the calculation results.

As we see in Fig. 4, the exergy losses are greatest in the furnaces combustion chamber (unavoidable losses) and in heating the petroleum (partially preventable losses). These greatly exceed the other exergy losses.

Table 1 presents the overall exergy balance of the furnace system and the exergetic efficiency of the system.

In the second stage of the research, we require the theoretical apparatus for well-founded choice of optimal design approaches. We employ the framework proposed in [7]. Essentially, the optimal organization of the system is established by optimal energy distribution between its elements: the distribution of mean energy levels of the conversion processes is analyzed, in the same scale (for 1 mole or 1 kmole). The optimal distribution of mean energy levels in the system corresponds to minimal inconsistency of the mean energy levels. To simplify the analysis, we consider a generalized source and a generalized sink. With minimal inconsistency of the mean energy levels, the system tends to a stable state, according to the zeroth law of thermodynamics.

The mean energy levels are calculated from the formula [8]

$$\Delta T_{\text{en}i} = \varepsilon_i \Delta T_{\text{lo}i} \left(1 - \frac{R}{C_{pi}} \ln \frac{p_{\text{in}i}}{p_{\text{f}i}}\right). \quad (4)$$

Here ε_i is the mole fraction of the flux to the mixer or beyond the separator; p_f is the final pressure in the gas-dynamic process; p_in is its initial pressure; R is the molar gas constant; $C_{\text{p}i}$ is the molar specific heat at constant pressure; and ΔT_lo is the mean logarithmic temperature level.

In Fig. 5, we show the distribution of the mean energy levels according to Eq. (4).

We see in Fig. 5 that the first three levels to which energy is supplied may be combined into a generalized source, while the last two may be combined into a generalized sink.

The generalized fluctuation may be written in the form [7]

Table 1. Overall exergy balance and exergetic efficiency of the furnace system

Input exergy, MJ/h		Output exergy, MJ/h		Exergy losses, MJ/h
Air	456.66	Smokestack gases	14018.60	93643.92
Fuel oil	203597.30	Steam (for functional uses)	4275.75	
Raw materials	14243.63	Raw materials	72713.04	
Chemically purified water	450.28	Exergy of hypothetical heat sink	37350.36	
Electric power	3253.81			
Total	222001.68	Total	128357.75	
Exergetic efficiency, %				57.82

Table 2. Power balance of multifunctional system

Power generated, kW		Power consumed, kW	
Rankin-cycle turbine	3081.27	Rankin-cycle pump	157.86
		Air compressor	903.84
		Net power generated	2019.57
Total	3081.27	Total	3081.27

$$\Delta T_{\text{en}} = \sqrt{\frac{\sum_{i}^{L} \alpha_i \Delta T_{\text{en}i}}{L}}, \quad (5)$$

where $\Delta T_{\text{en}i}$ is the mean energy level of process i; L is the number of processes combined in the generalized source (sink); and $\alpha_i = C_{vi}/R$ is a dimensionless coefficient.

On the basis of Eq. (5), we obtain the mean energy levels of the generalized source and sink: 1776 and 2099 K, respectively. Analysis reveals mismatch between the generalized energy fluctuations: the fluctuations of the generalized sink (levels 4 and 5) exceed those of the generalized source (levels 1–3) by more than 20%.

We now consider possible adjustment of the energy levels so as optimize the system. It follows from technological considerations that the position of the first level cannot be changed since the initial air temperature is the ambient temperature, while the output pressure must simply compensate the hydraulic losses in the system, which are constant. The discrepancy between the generalized energy fluctuations of the source and sink may be decreased by changing the system's structure: by replacing system components and by adding or removing components. That permits decrease in energy fluctuations of the generalized sink (levels 4 and 5). Accordingly, the system will approach its optimal distribution, since the generalized energy fluctuations depend on the number of transformations L (among other things), according to Eq. (5).

Generally, the positions of the middle energy levels are interrelated. Therefore, we must consider the overall effect. The simplest approach to improving system efficiency is to decrease the consumption of chemically purified water supplied to the furnace's convective chamber, without changing its consumption in the combustion process.

Calculations show that, if the consumption of chemically purified water is decreased from the conventional value (6765 kg/h) to the minimum value for fuel-oil combustion (1535 kg/h), the energy efficiency of the system will be increased from 57.8 to 62.2%. In that case, however, the structure of the system is unchanged, and there is no gain in multifunctionality. The energy level of the generalized sink may be lowered by profound recuperation of heat from the smokestack gases after generation of the required steam in fuel-oil combustion.

The organic Rankin cycle with a low-boiling working medium may be used for profound utilization of the heat from the smokestack gases with electric power generation. The introduction of an additional energy module calls for reconstruction of the furnace system so as to create a multifunctional system.

In accordance with these recommendations, we propose a system in which an energy module is integrated with the furnace system so as to generate power by the Rankin cycle. The basic system structure for elaboration in CHEMCAD software is shown in Fig. 6.

Neopentane is chosen as the working medium in the Rankin cycle, on the basis of the data in [9, 10]. Its boiling point is a third of that for isopentane.

Overall, a benefit of pentanes as working media is that they may be used with natural coolants (well water, air) in the Rankin cycle. That is expedient in practice.

The Exergy Unit program permits calculation of the multifunctional system's exergy balance characteristics (Fig. 7). According to the calculations, the exergetic efficiency of the system is 43%. Table 2 presents the power balance of the multifunctional system integrating the furnace and the energy module based on a Rankin cycle.

Note that comparison of the exergetic efficiency of the multifunctional system with that of the initial furnace system is incorrect. Remember that the initial furnace system cannot operate without electric power from a centralized source or generated locally. Therefore, the exergetic efficiency of the multifunctional system must be compared with a system in which separate technological and energy modules are present.

The exergetic efficiency of the system containing the technological and energy modules will be equal to the product of their individual efficiency values. According to the most optimistic estimate, the exergetic efficiency of that system is 28% (adopting the maximum exergetic efficiency of the energy module, which is 46%).

Thus, intensification of furnace systems at oil refineries is a promising trend. Given the number of furnaces at oil refineries, we may expect considerable energy savings—in particular, reduced consumption of electric power—especially as it is relatively simple to combine smokestack-gas fluxes with the same compo-

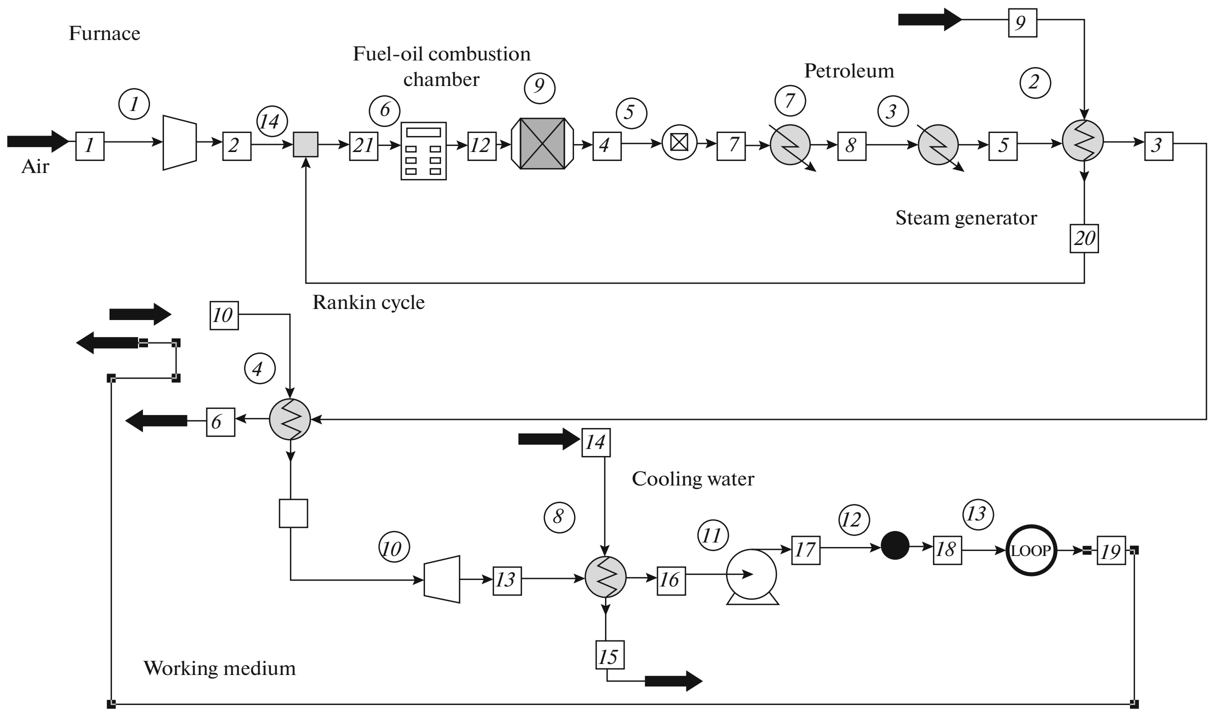

Fig. 6. Multifunctional system obtained by integration of the technological and energy modules.

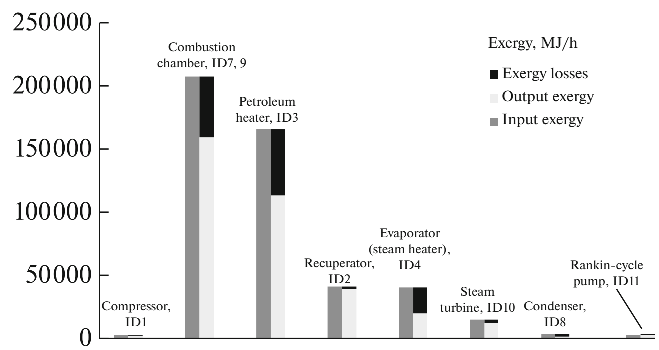

Fig. 7. Exergetic analysis of the multifunctional system.

sition and parameters from multiple furnaces. In that case, an energy module based on the Rankin cycle may serve the whole oil refinery.

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