Thermodynamic analysis of the hydrocarbons processing plants fuel supply systems efficiency

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Abstract. Hydrocarbon processing plants (HPP) are the key elements of the fuel and energy complex of the Russian Federation. At the same time, they are characterized by the increased energy consumption of the production and have a negative impact on the environment. The energy and resource saving technologies implementation necessity at the industry enterprises is declared at the state level and is a complex scientific problem. HPP energy efficiency improvement high potential is concentrated in the fuel systems modernization. The paper presents the fuel system analysis results, besides the fuel system relationships with the facility process system, its energy complex and external power supply systems were established. The energy consumption mix analysis of the HPP main production facilities for all types of fuel was carried out. Internal generation hydrocarbon fuel, namely refinery gas and mazut were established to be mainly applied as fuel. Refinery fuel gas of the internal generation was found out to have a variable blend composition. HPP fuel efficiency thermodynamic analysis was conducted to determine the fuel exergy absolute and specific consumption. Moreover, the HPP fuel systems efficiency improvement most promising areas were identified. On the basis of the conducted studies, a block scheme of the internal power supply source combined with the combustible secondary energy resources (SER) utilization system was developed. The feasibility study of the proposed scheme application expediency was conducted.

Key-words: oil and gas complex, hydrocarbons processing plants, thermodynamic analysis, exergy, fuel system

1. Introduction
Oil and gas complex is hydrocarbons extractive, transporting and processing objects being the strategic sector of the Russian Federation economy providing the federal budget to a large extent (43% in 2015). Besides, the mentioned objects are the basis of the Russian fuel and energy complex (FEC) as a whole. The energy resources (ER) annual balance presented in table 1 demonstrates that most of the exports and internal consumption falls on the hydrocarbons, namely oil, gas condensate, natural gas and their processing products [1]. The need to improve the energy efficiency of the Russian industrial sector including oil and gas complex (OGC) companies is declared at the state level [2, 3]. OGC facilities are characterized by the products increased energy consumption being from 2 to 3 times higher than the world average and making the domestic commercial output practically uncompetitive on the world market [4]. Currently, the industry rapid development and modernization is conducted, however, the share of the main and auxiliary obsolete and disabled equipment remains high. In addition, it should be noted that the issues of the energy and resource saving, environmental damage reducing, SER and manufacturing wastes complex utilization remain unsolved [5].
Table 1. The annual balance of the Russian Federation energy resources [3].

| Resources, million t. c.e. | Fossil fuel | Hydrocarbon processing products | Combustible secondary ER | Electric energy | Heat energy |
|---------------------------|-------------|---------------------------------|--------------------------|----------------|------------|
|                           | Oil, gas condensate | Natural gas | Coal |                       |             |            |
| Extraction (production)   | 752.4       | 741.8   | 251.9 | 454.1                   | 13.7        | 366.6      | 188.9      |
| Export                    | 320.4       | 201.1   | 116.7 | 212.8                   | -           | 2.8        | -          |
| Consumption for converting into other fuels | 0.9         | 301.2   | 81.3  | 11.7                    | 7.4         | 1.1        | -          |
| For processing into other fuels | 373.1   | 10.3    | 28.2  | 7.6                     | -           | -          | -          |
| For producing the non-fuels | 44.4   | 37.4    | 0.2   | 24.1                    | -           | -          | -          |
| As a material for non-fuels | 0.2       | 12.5    | 0.1   | 13.1                    | 0.01        | -          | -          |
| For the final consumption | 0.4        | 173.2   | 14.9  | 186.0                   | 6.3         | 329.0      | 172.5      |
| Losses at the consumption and transportation stages | 8.5         | 7.6     | -     | -                       | -           | 36.7       | 16.4       |

Oil refining industry is OGC essential link defining the hydrocarbons application efficiency, as well as being characterized by the problems inherent to the whole complex, despite the efficiency improvement existing potential. For example, the HPP fuel systems, which is due to the significant amount of combustible SER not currently being used, and also to the industrial oil-containing effluents and low–potential hydrocarbon gases involving possibility into the energy and processing balance. HPP rational fuel system synthesis with its operation modes optimization in conjunction with the facility energy complex (EC), its process system (PS) and fuel and energy resources (FER) providing external sources is a promising area of the fuel efficiency improvement, manufacturing energy consumption reduction and energy costs share decrease of the products final cost. Thermodynamic analysis exergy method can be used as the HPP actual situation analysis effective method with the facility fuel systems optimal schemes synthesis methodology further development. When conducting the analysis, the FER efficiency by the main systems, plants, units is defined; the application potential of SER, manufacturing wastes (effluents and gas emissions) is estimated; the largest energy losses sources and their elimination ways are determined. The given method application will make it possible to assess the HPP fuel system performance objectively, to develop the evidence-based actions aimed at the facility energy and resource efficiency improving, total fuel consumption and environmental damage reducing.

2. Problem statement

HPP fuel system structure and operating modes optimization is a complex scientific and engineering problem, which solution is possible only under the system approach [6], the facility thermodynamic analysis being one of the given approach significant stages.

The exergy method is widely used for analysing various industrial and energy facilities, power and heat and processing equipment. However, for such complex and multifunctional systems as HPP its application is limited by a number of factors. Firstly, it is such enterprises specificity not allowing to develop the exergy analysis universal methodology. Secondly, the time-varying internal and external factors influence degree consideration, such as the processed raw material composition, units processing conditions, ecologic and climatic factors etc. remains extremely difficult and unstudied. Taking into account these features, the scientific foundations and universal methodology development of carrying out the HPP exergy analysis is a relevant and promising research area.

The exergy analysis with the system and engineering and economic approaches elements which was performed taking into consideration the research subject specificity will make it possible to define the facility energy efficiency improving most promising areas, HPP fuel system optimal schemes and to propose science based engineering solutions.
3. Theory

3.1. HPP fuel consumption structure

HPP fuel system possesses a complex and multifunctional structure which main objective is to ensure the reliable and uninterrupted fuel supply interacting with all major industrial processes and their elements through the fuel generation and consumption continuous processes (figure 1).

![Cluster diagram of the HPP fuel system interrelations with the EC subsystems and FER external source.](image)

The hydrocarbon liquid and gaseous fuel of the internal generation or obtained from external power supply systems are usually used as a HPP fuel. Gas processing plants (GPP) are characterized by the primary use of natural gas from the commercial output and partly (for the leading enterprises) off-spec gas mixtures of variable composition. Oil refineries (OR) have more complicated fuel consumption structure consisting of gaseous fuel, liquid fuel and solid fuel (table 3). The internal fuel resources include refinery gases, mazut, coke (conversion fuel). The internal gas main sources are crude oil distillation plants (hydrocarbon gas C2-C4 0.23% into gas, liquefied gas C2-C4 1.13% into oil), catalytic reforming units, gas fractionation plants (GFP), as well as thermal and catalytic cracking units. Mazut is generated in the crude distillation units and catalytic cracking ones. The matrix model (table 2) sufficiently reflects the relationship of fuel fluxes and HPP industrial processes.

| Industrial processes | Commercial gas | Gas of internal generation | Mazut | Coke |
|----------------------|----------------|---------------------------|-------|------|
| Primary distillation |
| Thermal cracking     |
| Catalytic cracking   |
| Catalytic reforming  |
| Hydro treating       |
| Isomerization        |
| Mild hydrocracking   |
| Sulfuric acid production |
| Flare facilities     |
| GFP                  |

The fuel various types consumption approximate structure at the domestic refineries on the basis of the standard indicators of the plants power consumption is given in table 3.

Table 3. The fuel annual consumption of the refineries industrial processes.

| Industrial processes | Fuel consumption, % |
|----------------------|----------------------|
Based on the obtained data analysis, it can be concluded that the fuel of the internal generation is mainly consumed, the rest of the fuel is compensated by the natural gas from the outside source. However, despite the relatively small share of the purchased natural gas in the total fuel consumption, this parameter plays an important role in the enterprise fuel balance. Natural gas is pumped into the fuel system to maintain the required pressure, besides its consumption significantly increases during the plants commissioning and scheduled overhauling due to the internal fuel production decrease. It should be noted that there is a tendency to increase the natural gas share (commercial gas for refineries) in the total fuel consumption with the processing imperfection and main and auxiliary equipment simultaneous obsolescence.

When using the refinery gases as the HP3 main fuel to maintain the preset operational parameters, it is necessary to take into account that they are characterized by the uneven production and variable composition changing dynamically depending on the composition of the processed raw materials, plants processing conditions and climate conditions. The average composition of gas used as a fuel at the main processing plants is shown in Table 4.

### Table 4. The fuel gas average annual composition of the main HPP industrial processes.

| Industrial process | CH$_4$ | C$_2$H$_6$ | C$_3$H$_8$ | n-C$_4$H$_{10}$ | i-C$_4$H$_{10}$ | C$_6$H$_{12}$ | C$_8$ | H$_2$ | H$_2$S |
|--------------------|--------|------------|------------|-----------------|----------------|-------------|------|-----|------|
| Primary distillation| 18.7   | 8.2        | 13.9       | 2.4             | 2.1            | 0.9         | 0.0  | 53.5| 0.3  |
| Thermal cracking   | 25.0   | 9.7        | 25.5       | 6.1             | 4.4            | 1.3         | 0.0  | 27.3| 0.7  |
| Catalytic cracking | 18.7   | 11.2       | 11.0       | 3.1             | 1.5            | 1.0         | 0.0  | 53.4| 0.1  |
| Catalytic reforming| 12.5   | 14.9       | 19.1       | 4.3             | 3.8            | 1.2         | 0.0  | 43.7| 0.5  |
| Isomerization      | 13.5   | 8.3        | 17.1       | 4.0             | 3.2            | 0.9         | 0.0  | 52.7| 0.3  |
| Hydro treating     | 19.1   | 16.8       | 10.4       | 1.9             | 2.4            | 2.8         | 0.0  | 46.5| 0.1  |
| Mild hydrocracking | 16.7   | 26.8       | 21.4       | 4.6             | 4.5            | 1.7         | 0.0  | 24.3| 0.0  |
| Sulfuric acid production| 8.2   | 10.3       | 30.0       | 8.1             | 6.2            | 1.4         | 0.0  | 35.1| 0.7  |

The fuel gas composition variable behavior results in the fuel-consuming equipment operating modes effective regulation need, namely furnaces, evaporators, power equipment, etc., the absence of which will cause the fuel consumption specific indicators increase (in comparison with the normative indicators), processing conditions disturbance, equipment stoppage. The conducted joint analysis results of the data in tables 1-4 confirm that the exergy analysis application is necessary for creating the scientific foundations and structure optimization methodology of the HPP fuel system, its operating modes.

### 3.2. HPP fuel system thermodynamic analysis
The HPP thermodynamic performance indicators are compiled in the form of the exergy efficiency ($\eta_{ex}$) defined for the facility PS and EC various elements as the exergies sum at the outlet ($\sum ex_{out}$) and inlet ($\sum ex_{in}$), as well as the system losses sum [7]:

$$\eta_{ex} = \frac{\sum ex_{out}}{\sum ex_{in}} = 1 - \frac{\sum ex_{l}}{\sum ex_{ex}} \quad (1)$$

$$\sum ex_{l} = \sum D = \sum ex_{out} - \sum ex_{in} \geq 0 \quad (2)$$

The supply and removal processes of electrical (mechanical) energy (E), heat (Q) and process flow energies (J) are generally performed in the HPP elements. Practically all the HPP process flows contain combustible components. The substance flow exergy in general terms is represented by the sum of the following values:

$$ex_{j} = ex_{pot} + ex_{kin} + ex_{phys} + ex_{chem} \quad (3)$$

where $ex_{pot}$, $ex_{kin}$ is the substance potential and kinetic energy exergy, correspondingly (which is not taken into account within the operating objectives framework);

$ex_{phys}$, $ex_{chem}$ is the physical and chemical exergy, correspondingly.

The physical exergy is defined by the equation:

$$ex_{phys} = H - H_{0} - T_{0} \cdot (s - s_{0}) \quad (4)$$

where $H, H_{0}$ is the system and environment enthalpy, correspondingly, $T_{0}$ is the ambient temperature;

$s, s_{0}$ is the system and environment specific enthalpy, correspondingly.

In case of HPP, the chemical exergy is rightly considered as the fuel exergy. The concentration and reaction exergies defining methods cannot be applied in this case, and specially developed methods [8] based on the use of the fuel calorific value, taking into consideration its moisture content, are applied for calculating the fuel exergy. It is expedient, since the fuels combustion exergy and heat are closely approximated values:

$$ex_{chem.l} = 0.975 \cdot Q_{op}^{f} \quad (5)$$

$$ex_{chem.g} = 0.95 \cdot Q_{op}^{f} \quad (6)$$

$$ex_{chem.s} = Q_{op}^{f} \cdot (1 - d_{f}) \quad (7)$$

where $ex_{chem.l}, ex_{chem.g}, ex_{chem.s}$ is the chemical exergy of the liquid, gaseous and solid fuel, correspondingly.

Since the fuel exergy value in most cases differs from the low operation calorific value $Q_{op}^{f}$ by 2-3% [9], the following assumption can be accepted:

$$ex_{chem.f} = Q_{op}^{f} \quad (8)$$

The exergy losses $\sum D$ are divided into two groups:

- internal exergy losses $D_{i}$ related to the irreversibility of the processes within the element or system;
- external exergy losses $D_{e}$ related to the HPP elements and systems interaction conditions with the environment and external sources, and receivers of energy and working substance (at the chemical transformations).
The exergy balance of HPP with the consumption of thermal, electric energy and partly the fuel component from the external sources has the following form:

\[ ex_j + ex_o + ex_i + ex_f + ex_w = ex_R + ex_c + ex_o + \sum D \]  

(9)

where \( ex_j, ex_o, ex_i, ex_f, ex_w, ex_R, ex_c, ex_o \) is the exergy of the feedstock, heat and electric energy, fuel, water, production, effluents, wastes; \( \sum D \) is the material and energy flows exergy losses.

For the fuel system the exergy balance is described by the equation:

\[ ex_{\text{pf}} + ex_{\text{ff}} + ex_{\text{sf}} + ex_{\text{pf}} = ex_{\text{pf}} + ex_{\text{r}} + ex_{\text{ff}} + ex_{\text{r}} + \sum D \]  

(10)

where \( ex_{\text{pf}}, ex_{\text{ff}}, ex_{\text{sf}}, ex_{\text{io}}, ex_{\text{rf}}, ex_{\text{ff}}, ex_{\text{r}}, \sum D \) is the exergy of the inlet and outlet process flows, fuel of the internal generation (refinery gases, mazut, coke), external fuel, PS combustible wastes, heat and electric energy generation fuel, wastes (including unused industrial sewage containing combustible components, low-potential gases; \( \sum D \) is the exergy losses during gas consumption processes.

HPP fuel system optimization by the thermodynamic losses criterion is to minimize the amount of \( (ex_c + ex_o + \sum D) \rightarrow \min \). It is important to note that the optimal variant corresponds not only to the minimum of losses \( ex_o + \sum D \) and wastes \( ex_c \), but also to the FER minimum consumption from the outside sources including the reduction of the fuel consumption (internal and external generation): \( (ex_o + ex_i + ex_f + \sum D) \rightarrow \min \), to HPP industrial processes combustion wastes exergy maximum use.

During HPP fuel system thermodynamic analysis, the consumed fuel exergy (1)-(5) was calculated for all the main industrial processes of the facility. The percentage of the fuel exergy absolute and specific consumption by the HPP industrial processes is presented in table 5.

### Table 5. HPP fuel exergy consumption distribution.

| Industrial processes         | Fuel exergy absolute consumption, % | Fuel exergy specific consumption, % |
|-----------------------------|-------------------------------------|-------------------------------------|
| Primary distillation        | 36.4                                | 5.7                                 |
| Thermal cracking            | 13.2                                | 11.6                                |
| Catalytic cracking          | 6.8                                 | 11.0                                |
| Catalytic reforming         | 19.5                                | 20.9                                |
| Hydro treating              | 12.4                                | 1.7                                 |
| Isomerization               | 0.4                                 | 6.1                                 |
| Sulfuric acid production    | 4.9                                 | 35.6                                |
| Mild hydrocracking          | 4.5                                 | 7.3                                 |
| Gas flare facilities        | 1.8                                 |                                    |

The feedstock primary processing facilities are characterized by the fuel exergy maximal absolute consumption due to the facilities high performance and consequently the absolute fuel consumption highest level. In turn, the feedstock recycling (deep conversion) processes and sulfuric acid energy consuming production have the highest level of the fuel exergy specific consumption. It can be concluded that the fuel exergy consumption by the HPP main industrial processes is uneven and that fuel exergy absolute and specific consumption indicators diverge greatly. Table 5 shows that the units of the oil primary distillation, sulfur production and catalytic reforming possess the fuel system efficiency improvement greatest potential.

As a result of the conducted thermodynamic analysis, the fuel system energy efficiency improvement main directions were established to be related to the process flows potential application, manufacturing combustible wastes involvement into the fuel balance, consumption reduction of FER from the external sources and internal energy resources generation.
The ER generating individual system based on the combustible wastes and effluents fire detoxification unit in the thermal utilization block (figure 2) is an example making possible to implement the above mentioned activities.

Figure 2. The scheme of the internal energy supply source integrated with EC and PS of the refineries:

GTU is the gas turbine unit; WHB is the waste heat boiler; STP is the steam turbine plant; PC is the process customer of the heat energy; HE is the grid heat exchanger; HC is the heating customer; WT is the water treatment; TUB is the thermal utilization block; 1 is the fuel gas; 2 is the air; 3 is the high temperature fuel gases; 4 is the electric energy; 5-7 is the water vapor (5 is to the steam turbine, 6 is from the steam turbine to processing, 7 is from the steam turbine to the hot water converter); 8,9 are the heating load and HTW; 10 is the condensed water; 11 is the demineralized water; 12 is the water into the industrial domestic consumption system; 13 is the process flow; 14 is the exhaust gases for drying; 15 is the manufacturing wastes (effluents and hydrocarbon gases); 16 is the dried exhaust gases; 17 is the dry wastes.

The proposed power supply source on the basis of gas turbine units is integrated with PS processes and installations, water supply systems, and the thermal utilization unit makes it possible to neutralize wastes contained at the OGC facilities such as hydrocarbon gases, industrial oil effluents, etc. Electric and heat energy combined generation occurs in the combined-cycle gas turbine plants (CGTP) combining gas turbine and steam turbine units (GTU and STU). High-temperature exhaust gases of the processing plants and TUBs are supplied to the steam WHB, the extraction steam serves as the CGTP working body.

The scheme block structure makes it possible to adapt it perfectly to any specific processing facility topology. For example, for integration with refineries the scheme can be supplemented with mazut, bitumen, tar gasification block (10) allowing using the gasification gases as TUB fuel and resulting in the heat energy generation significant increase. Such facilities introduction at the HPP will make it possible to use the industrial oil-containing effluents exergy effectively, to reduce the production harmful impact on the environment through the thermal wastes utilization, to decrease the FER consumption from the external sources by substituting them with the internal generation energy resources.

4. Numerical experiments results
The main and auxiliary equipment optimal selection for the internal power supply sources of HPP depends on the processed feedstock chemical composition, facility life cycle structure and stage and is performed on the basis of the developed theoretical approaches [6]. The conducted analysis revealed that the scheme of the internal power supply based on CGTP-TPP containing the following equipment: 2 turbines SGT-400 (Cyclone) Alstome; 2 boilers WHB-18; 1 turbine P-1.5-2.6/0.6 was the most effective. The main indicators of the investment project efficiency of the represented hardware implementation in the energy complex structure are the following:

Power:
- electric, MW 26.3
The given data indicate the expediency of introducing the energy supply internal sources into the HPP EC structure on the basis of CGTP-TPP with industrial wastes utilization in the TUB.

5. Conclusions

- Based on the fuel HPP system conducted analysis, its relations with all subsystems of EC, PS and FER external systems were defined. All fuel types consumption structure at the plant was determined and analysed. The share of the internal fuel (refinery gases, liquid fuel, coke) in the total energy consumption was calculated. The fuel composition consumed at the main HPP industrial processes was analysed.
- On the basis of the HPP fuel system efficiency thermodynamic analysis, the fuel exergy absolute and specific consumption by the main industrial processes of the plant was determined. A block scheme of the internal power supply source making it possible to generate the heat and electric energy and to use effectively the exergy of industrial wastes, namely industrial oil-containing effluents and low-potential combustible gases is proposed.
- The main equipment optimal configuration of HPP internal power supply source was chosen. The investment projects effectiveness integral indicators calculation allows to make a conclusion about the economic feasibility of introducing the internal source of combined heat and power generation with the wastes thermal utilization block, the integral effect constitutes to $46.5 million (in ten years), a payback period is no more than 5.5 years.

6. References

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