Methods of object-focused design and analysis of energy complexes for gas processing enterprises

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Abstract. The article describes some solutions to problems related to analysis and design of energy complex for gas processing facilities via object-focused design methods. The authors propose a hierarchy for classes and objects of the facilities and review properties and methods of such objects by using formation and analysis of power engineering balance of raw gas condensate processing facility as an example. The article contains results of quantitative simulation of “compressor” and “engine”-class objects that can be used for commercial gas drying and compressing as well as sulfur production. The authors provide analysis of operation modes of compressor units and gas blowers utilized at such facilities and provide general correlations between process parameters and external energy resources consumption. The article contains analysis of correlation between specific generation and consumption of hydrocarbon gases used as fuel for process and energy complexes and external energy supply system of gas processing facilities. The concepts and methods developed by authors can be used in object-based design to analyze the efficiency and degree of optimization of energy complex structure within the framework of variable process equipment layout and dynamically changing object properties at all hierarchic levels.

1. Introduction

Analysis of operational activities of gas and gas condensate processing enterprises (GGCPE) [1–4] revealed the necessity of systemic and, at the same time, individual approach to improvement of energy complex (EC) of such facilities. Based on the results of such analysis, we can outline the following general properties of facilities EC that may vary in process equipment layout and time of their operation (Table 1):

- EC structure and energy resource (ER) consumption and generation modes determine the volume, pressure and composition of raw hydrocarbons (RHC), list of goods produced by facilities and structural parameters of process complex (PC) of GGCPE;
- technological factors as well as ecological, climate, engineering and economical conditions change throughout the operational cycle of GGCPE that is specific for each gas condensate deposit starting from its construction and until its decommissioning;
- consumption of electric and heat energy (steam) from external energy supply (EES) systems is relatively low with heat supplied mostly from facilities’ own sources by utilizing secondary energy sources; this may help to construct a dynamically developing EC based on equipment integrated with based and auxiliary facilities of the PC;
• the primary contribution to total ER consumption is made by fuel gas comprised from production flows of various composition; at the same time, secondary facilities dedicated to waste decontamination have greater energy potential that can be used for ER generation, thus, allowing to significantly decrease their consumption from EES.

Table 1. Structure of consumption of ER at GGCPE.

| GGCPE                                              | Specific consumption (t e. f. / 10^3 m^3 RHC) | Consumption of ER (%) | electrical energy | thermal energy | fuel |
|----------------------------------------------------|-----------------------------------------------|-----------------------|-------------------|----------------|------|
| Astrakhan Gas Processing Plant (AGPP)              | 0.255–0.258                                   |                       | 9.5               | 7.5            | 46.1 |
| Orenburg GPP (OGPP)                               | 0.044–0.045                                   |                       | 20.1              | 3.9            | 23.5 |
| Sosnogorsky GPP                                  | 0.035–0.037                                   |                       | 12.0              | 12.3           | 3.4  |
| Novo-Urengoy Plant for Gas Condensate Preparation for Transport | 0.012–0.013                                   |                       | 16.9              | 0.7            | 23.5 |
| Surgut Plant for Gas Condensate Stabilization     | 0.039–0.040                                   |                       | 23.1              | 0              | 32.7 |
| Vuktyl Gas Field Office                          | 0.040–0.041                                   |                       | 10.0              | 2.4            | 15.2 |

* BP and AP basic and auxiliary productions

As the above mentioned parameters of GGCPE EC may vary, its construction and optimization of its structural and operational parameters in accordance with production goal and PC topology can be most successfully performed via object-based design (OBD) methods based on the principles of type-design practice, hierarchy, data abstraction and modularity. Generally, OBD can be described as design method that combines object-based decomposition of GGCPE EC with a system of representation for its logical, physical, static and dynamic models comprising the so-called object model of development [5].

2. Object-based decomposition of GGCPE

Hierarchical systems including GGCPE consist of several subsystems combined and organized in various ways; object-based decomposition represents such subsystems as objects of various classes with hierarchic relations. Here we have to clarify the meaning of some terms used to describe the object-based technology. For the purpose of our study, we do not mean classes and object developed by programmers. The application domain of EC design sees a development of a more abstract classification of GGCPE that produce goods, generate and consume ER that correlates with external resource and energy supply systems and account for impact of ecological, climatic, engineering and economical factors.

Objects with clear borders (enterprise, systems, productions, plants, unit, equipment) and distinctive qualitative and quantitative parameters are marked as unique objects during GGCPE decomposition. Object status is characterized by a list of its properties (statistically defined within a class) and their current (usually, dynamically changing) values. Structure and behavior of similar objects is defined
within the structure of their common class representing many of their significant qualities. During actual implementation of OBD method for design, analysis and creation of GGCPE EC, the classes are static while objects can be created and excluded from hierarchic structure of GGCPE throughout its operational cycle.

Class hierarchy is characterized by “general / specific” structural type while object hierarchy is characterized by ‘whole / part’ type. Figure 1 depicts the variation of such hierarchies for a GGCPE of arbitrary topology.

![Diagram](image-url)

1 – elements of the GGCPE; 1 – GGCPE; 2.1 – Gas Processing Plant (GPP); 3 – Process Complex (PC); 4 – Energy Complex (EC); 5 – systems of the EC: 5.1 – Fuel System (FS), 5.2 – Electrical Power System (EPS), 5.3 – Heat-Power System (HPS), ..., 5.s – Process Water Supply System (PWSS), Waste Disposal System (WDS), other systems; 6 – Productions of the PC (6.1, ..., 6.j – pre-productions and processing of HRM, productions of conditioning and storage of hydrocarbon processing products); 7 – plants of the PC; 8 – equipment’s of the PC and EC

**Figure 1.** Hierarchy of classes and objects of EC GGCPE.

Structure of classes 3 – 5 is based on the following general and specific properties: functional features and intended purpose within GGCPE (3 – PC, 4 – EC, 5 – EC system); EC system affiliation with various abstraction of ER generation and consumption processes (5.1 – fuel system – FS, 5.2 – electrical power system (EPS), 5.3 – heat power system (HPS), 5.4 – process water supply system (PWSS), 5.5 – water disposal system (WDS), 5.6 to 5.s – other production systems of EC). When class 5 is formed, in addition to specific properties of particular GGCPE EC, the method accounts for pre-established general factors that determine the conceptual scheme of EC development and its interactions with EES sources [3, 4, 6].

Internal structure of class 8 (equipment) is formed from general properties of classes 8.1 to 8.k – furnaces, boilers, engines, heat exchangers and other equipment – together with their processing methods. In turn, classes 8.1 to 8.k include properties of objects united into classes with a lower hierarchic level compared to classes 8.1 to 8.k. For example, if there are class 8.1 objects – “furnaces”, then classes 8.1.1 to 8.2.n provide a detailed description of properties of such equipment that may differ in intended purpose (reaction-furnace, heater, evaporator) and constructive characteristics (radiative, radiative-convective, cylindrical, chamber and etc.). In the case of class 8.2 – “engines”, 8.21 to 8.2.r stand for the following object classes: “steam turbine”, “gas turbine”, “electric drive”, “combustion engine”, “steam-driven screw-rotor machine” and other types of engines with corresponding properties. Other GGCPE equipment that consumes or generates energy is classified the same way. Hierarchy depicted on Figure 1 represents a unified structure of classes and objects and their interactions for different variations of GGCPE EC and PC, processes of ER generation and consumption and raw hydrocarbon processing into finished goods.
3. Properties, methods and object models

As we already noted, class is a multitude of objects having a common structure and a list of distinctive properties. For example, a list of object properties for class 2.1 – “Gas Processing Plant (GPP)” – includes the name of enterprise (string-type parameter), annual and daily load schedules (1-D arrays), composition of raw materials taken from local deposit, geographic and climatic data (special type entries), list of produced goods and project data such as the volume of various types of produced goods as well as production and functional structure data, i.e. object class indicators: class 3 – “EC”, class 4 – “productions of PC”. The list of properties for class 8 objects (“equipments”) include structural and operation parameters of corresponding equipment as well as data related to consumed, generated and processed power and product flows (included as indicators to objects classified as “power flow” and “product flow”).

OBD method establishes two types of relations between objects of various classes – bonds and aggregation. These relations are implemented as object methods that support intended utilities of OBD method, i.e.: energy and production balance calculation, calculation of efficiency parameters for various hierarchic levels, confirmatory, structural and engineering and economical calculations, variable equipment combining performed in order to find the most optimal structure of EC and optimize its operation modes. Mathematical description of relations between objects forms the basis for such methods. There are two type of mathematical description implemented – iconographic (diagrams and flow graphs) and symbolic models (analytical correlations obtained via experimental analysis) [7].

Graphical models for all types of balances (diagrams) are produced via SADT-method (structured analysis and design techniques) [8] and describe the processes of RHС processing to finished goods, ER generation and consumption, water consumption and disposal and waste recycling. Basic functional model of EC and PC is energy and production balance with its organization chart provided on Figure 2.

![Figure 2. Organizational diagram for calculating the energy and technological balance of the object.](image)

In the case of “upstream” design, all calculations of developed models are performed starting from lowest level, i.e. material and fuel and energy balances for class 8 objects – “equipment”.

On Figure 2, each calculated element is designated with a corresponding ID number A0 to A5. The elements are bonded with each other via ICOM arcs (input – I, output – O, control – C, management tools – M). C and M arcs are not shown on Figure 2 while input and output arcs contain the following information on object properties.

1.0.0 – general properties including parameters of elements A0 to A5 (list of RHС and intermediate flow components, degree of RHС components conversion to finished product, process units operation
modes, climatic data, specific ER and water consumption and generation parameters for units with continuous and periodic production cycles, nominal and actual operation time, other element parameters; $I_{0.0} = \{I_{0.1}, I_{1.1}, I_{2.1}, I_{3.1}, I_{4.1}, I_{5.1}\}$.

$O_{0.0}$ – general output variables for all elements (production flows of obtained finished goods and intermediate products, amount of heat and electric energy consumed and generated by facility internal sources, amount of fuel gas taken from facility network for PC equipment loads and energy generation for EC, partial and complex ER consumption and generation efficiency parameters for EC and PC systems); $O_{0.0} = \{O_{0.1}, O_{1.1}, O_{2.1}, O_{3.1}, O_{4.1}, O_{5.1}\}$.

Input arcs of elements $A1$ to $A5$, that contain information on normalized product flows defining ER consumption or generation as well as water consumption and disposal, are a part of arc $O_{0.1}$: $I_{1.2} = f(O_{0.1})$; $I_{2.2} = f(O_{0.1})$; $I_{3.2} = f(O_{0.1})$; $I_{4.2} = f(O_{0.1})$; $I_{5.2} = f(O_{0.1})$. Calculation of fuel balance is performed after heat, water disposal (including wastewater recycling during thermal decontamination process) and electric energy balances (defining fuel consumption for electric energy generation) are calculated. This is reflected in implicative order of input arcs for element $A3$: $I_{3.3} = f(O_{2.1})$; $I_{3.4} = f(O_{5.1})$; $I_{3.5} = f(O_{1.1})$. In turn, electrical energy balance of element $A1$ is calculated on the basis of output data obtained after calculation of balances of other ER and water consumption and disposal: $I_{1.3} = f(O_{2.1}, O_{3.1}, O_{4.1}, O_{5.1})$.

Organization charts for separate elements $A0$–$A5$ are generated after the general organization chart. The information content of such charts is comprised from symbolic mathematical models that represent functional models of EC and PC class objects. Integration of all mathematical models of energy-technological and materials balance calculations is implemented via a software product that is used for further analysis and optimization of ER and water consumption and water disposal for GGCPE with a preset production facilities topology and variable input parameters [9].

Calculation methods for class 8.1 to 8.5 objects (PC and EC equipment) are implemented in several software products that are capable of providing analysis of internal structure and parameters of corresponding object and evaluate the impact of its construction and operational parameters on output operational parameters correlating with other objects. Information content of calculation modules is represented by object’s output variables function of input parameters and variables distributed over a space and capable of changing in time.

4. Design of optimal states for EC and PC class objects
Optimization of EC and PC class objects state (optimization of their operational and structural parameters) is performed via software developed using OBD methods. The software utilizes both partial criteria and multi-criteria efficiency index [7] that combines two groups of parameters put into order via hierarchy analysis method [10]:

- efficiency of production and economical activities of GGCPE (profits and efficiency as a business asset);
- resource and energy efficiency (maximal circularity of ER consumption cycle, degree utilization of secondary ER, hot wastes and wastewater utilization for ER generation, ecological safety, reliability of ER supply).

Results of numerical simulations of operational modes for blowers equipment utilized at sulfur production and facilities of finished gas compressing (classes 5 and 6 on Figure 1) obtained via author-developed software are provided on Figure 3.

Blower class is represented by gas blowers and compressors while engine class (blower drives) is represented by steam turbines and electric motors. The following process properties of objects is: sulfur production equipment load coefficient ($k_{w}$), degree of hydrogen sulfide conversion, amount of energy supplied to connected drive, current rates for electric and heat energy. Both partial criteria (specific costs of ER [E] measured in units of fuel equivalent per 1000 m$^3$ of finished gas product, as shown on Figure 3) and multi-criteria efficiency index have been used as efficiency parameters. Application of OBD methods helped us express the general correlation between ER consumption from external energy supply (in normalized units) for the aforementioned class of GPP as the following polynomial:
where \( Y = Y_S/(Y_{S_{\text{max}}} - Y_{S_{\text{min}}}) \) is normalized value of annual operational costs of ER; \( Y_S, Y_{S_{\text{max}}}, Y_{S_{\text{min}}} \) are current, maximal and minimal values of annual operational costs, respectively, in million rubles, for the calculated range of changing product and economic factors accounting for object’s operational cycle dynamics; \( A, B, C, D \) are coefficients found from empirical equations:

\[
A = -6.9175 + 8.2628 k_U; \quad B = 0.5323 - 0.5723 k_U;
\]

\[
C = -0.0094 + 0.0099 k_U; \quad D = -0.0002 + 0.0005 k_U - 0.0003 k_U^2.
\]

\( N_{\text{opt}} \) is the power of electric drive superchargers (actual and optimal); \( F \) is the line of variation of the optimum power; \( k_U \) is the load factor of sulfur production equipment.

**Figure 3.** Optimization of the power of the electric drive \((N, \text{MW})\) according the specific energy intensity of the processed gas condensate raw materials.

Analysis of optimization results based on specific energy consumption of processing RHC (Figure 3), normalized operational costs of ER (1) and multi-criteria parameters accounting for engineering and economical properties of objects have shown that for actual operating conditions of analyzed GPP the share of connected blower with electric motors must be 1.3 to 1.7 times higher compared to the share of blowers currently connected to operating lines of analyzed GGCPE that corresponds only to normal / designed value of production equipment load coefficient \([N_{\text{opt}} = (1.3...1.7) N_{/}]\).

Obtained data helped us to formulate the EC development strategy for a particular GGCPE that includes creation of internal ER sources integrated with PC equipment.

In the case of class 5 objects for fuel systems of GGCPE EC (class 5.1), we established correlations between PC and EES against the background of variable process and climatic factors. Their quantitative assessment revealed a quadratic dependency from facility output (that, in turn, depends on the object’s operation period), hydrogen sulfide and carbon dioxide concentration in RHC and phase composition of RHC. For class 2.1 objects (AGPP and OGPP types), a two-parameter model of EES fuel consumption for GGCPE within “specific fuel consumption \([h]\) – relative production output \([V_{RHC}\)] – hydrogen sulfide concentration in RHC \([C_{\text{H2S}}]\)” coordinate space can be expressed as follows:
\[ b = 0.2537 \times 0.0088C_{H_2S} + 0.0005C_{H_2S}^2 - V_{RHC} (0.2433 - 0.0167C_{H_2S} + 0.0011C_{H_2S}^2) + \\
+ V_{RHC}^2 (0.124 - 0.016C_{H_2S} + 0.0007C_{H_2S}^2). \] (2)

Fuel generation and consumption of class 2.1 object (AGPP type) can be described by the following general dependency:

\[ B_i = a_{3i}(C_{H_2S}) + a_{2i}(C_{H_2S})V_{RHC}, \] (3)

where \( a_{3i}(C_{H_2S}) \) and \( a_{2i}(C_{H_2S}) \) are one-parameter function for objects of corresponding \( i \)-th class (Table 2).

**Table 2. Dependencies for the definition of functions \( a_{3i}(C_{H_2S}) \), \( a_{2i}(C_{H_2S}) \).**

| Class | Object [Process] | \( a_{3i} \) | \( a_{2i} \) |
|-------|-----------------|-------------|-------------|
| 3, 7, 8 | PC; plants of the PC; [generation of hydrocarbon gases] | -83.886 + 0.1628C_{H_2S} | 1203.4 - 37.322C_{H_2S} + 0.7548C_{H_2S}^2 |
| 5.1 | FS; [consumption of fuel gas from the commodity network gas] | 454.54 - 4.787C_{H_2S} + 0.2415C_{H_2S}^2 | 1137.7 - 35.274C_{H_2S} |
| 3, 5.1, 8 | PC; FS; equipment’s of the PC; [consumption of fuel gas] | 25.548 - 2.1562C_{H_2S} | 1363.2 - 29.084C_{H_2S} + 0.815C_{H_2S}^2 |
| 4, 5.1, 8 | EC; FS; equipment’s of the EC; [consumption of fuel gas] | 294.08 + 5.5005C_{H_2S} | 990.7 - 45.499C_{H_2S} |

Fuel consumption for energy generation by EES supplying heat and electric energy to class 2.1 GGCPE can also be described by dependency (3) where \( a_{3i} \) and \( a_{2i} \) parameters for AGPP and OGP-type objects can be expressed as follows:

\[ a_1 = 5.7077 + 0.2394C_{H_2S}, \quad a_2 = 379.71 - 5.5332C_{H_2S}. \]

We have calculated the gradient of specific system fuel consumption depending on concentration of acidic components and production output for analyzed objects (class 2.1 – GPP): \( \Delta b = (0.52 \ldots 0.81) / (-1\%V_{RHC}) \), where the lower limit corresponds to 7% concentration of acidic component while the higher limit corresponds to 25% concentration. This allowed to perform prospective planning of decreased production output of fuel system depending on RHC parameter (specific fuel consumption increased by 0.52 to 0.81% per 1% of production output decrease).

Utilization of OBD-based optimization calculation techniques and corresponding software for GGCPE with ER consumption characteristics provided in Table 1 helped us perform a systemic assessment of potential increment of energy efficiency and determine the most prospective means of EC structure optimization (accounting for operational process features, climatic factors and engineering and economical characteristics of EES) [3, 7]: creation of EC systems with maximal utilization of low pressure process gases, combustible wastes and wastewater integrated into PC structure; development of internal energy generating complexes based on combined cycle technology; development of optimal power engineering systems operating in accordance with consumption modes of process equipment at every stage of GGCPE operational cycle; thorough heat recycling via process flow regeneration systems; optimization of cooling systems including air cooler unit, circulating water supply systems and process...
heat exchangers; utilization of low potential heat for cold generation within absorption heat transformers and steam ejector cooling units; development of maximally circulating water supply systems with wastewater recycling.

5. Conclusion
We have proposed a method of analysis and upgrade of energy complexes of raw gas condensate preprocessing and processing facilities based on principles and methods of object-based design. We have developed a general hierarchic structure of facilities that decompose its process and energy elements to classes and objects, as well as methods and models of general properties calculation allowing to analyse efficiency of facility operation modes, optimize structure of energy supply systems and develop a strategy of upgrading power engineering complexes amidst variable process topology at various hierarchic levels. We have performed optimization of electric and heat consuming equipment – electric drives of process blowers or sulphur production units and finished gas compression unit and found out general correlations between elements of fuel system of sulphurous raw gas condensate facilities and external energy supply systems.

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