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Satbayev University

ХАБАРЛАРЫ

ИЗВЕСТИЯ

НАЦИОНАЛЬНОЙ АКАДЕМИИ НАУК РЕСПУБЛИКИ КАЗАХСТАН
Satbayev University

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AUTOMATIC CONTROL SYSTEM OF A GAS-PUMPING UNIT

Abstract. Currently, the main type of intracontinental gas transport in all countries of the world is pipeline. The rapid development of pipeline transportation of gas is explained by the fact that pumping it through pipelines is more economical than delivery by other means of transport. The article deals with the problem of regulating the combustion temperature of fuel in the combustion chamber of a gas pumping unit. The gas pumping unit as a control object belongs to the class of nonlinear, multidimensional and high-speed objects. In order to properly conduct the technological process of gas transportation, the operational personnel of the compressor station must have reliable information about the state of the control object, about the regime and technological parameters characterizing the state of the process. In order to obtain information by actual measurements of parameters and calculations, a model for calculating the flame temperature has been developed in the MATLAB application software package. This model, being a system of logical relations that describe the real object, regulates the starting temperature by performing all the operations that were specified in the block calculation block diagram. During the simulation of this model, several values of the adjusted temperature were obtained. The calculated determination of the flame temperature of a particular mixture is quite a difficult task, since in addition to the composition of the mixture, the initial temperature and pressure strongly affect the temperature. An increase in the temperature and pressure of the initial components leads to an increase in the flame temperature. Heat exchange with the environment and dissociation reactions, on the contrary, reduce the flame temperature. The paper develops the structure of the automatic control system of the gas pumping unit, which is based on the balanced ratios between the energy indicators required for gas transportation and fuel costs for the creation of the turbine working fluid.

Key words: gas pumping unit (GPU), heat of combustion, dissociation, turbine power, automatic control system.

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ГАЗ ТАСЫМАЛДАУШЫ АГРЕГАТТЫ АВТОМАТТЫ БАСҚАРУ ЖҮЙЕСІ

Аннотация. Қазіргі таңда құрлық ішінде әлемнің барлық мемлекеттерінде негізгі газ тасымалдау құбырлар арқылы жүргізіледі. Құбырлар арқылы газды тасымалдаудың қарқынды дамуы оның басқа тасымалдау түрлеріне қарағанда экономикалық тұрғыдан тиімділігі. Мақалада газ айдау қондырғысының жану камерасындағы отынның жану температурасын реттеу мәселесі қарастырылады. Газ айдау қондырғысы басқару объектісі ретінде сызықты емес, көп өлшемді және жылдам әрекет ететін объектілер класына жатады. Газ тасымалдаудың технологиялық процесін дұрыс жүргізу үшін компрессорлық станцияның жедел персоналында басқару объектісінің жай-күйі туралы, процестің жай-күйін сипаттайтын режимдік-технологиялық параметрлер туралы дұрыс ақпарат болуы тиіс. MATLAB қолданбалы бағдарламалық пакетінде параметрлерді нақты өлшеу және есептеу арқылы ақпарат алу үшін жалын температурасын есептеу моделі жасалды. Бұл модель нақты объектіні сипаттайтын логикалық қатынастар жүйесі бола отырып, блоктармен есептеудің құрылымдық схемасында көрсетілген барлық операцияларды орындау арқылы бастапқы температураны реттейді. Осы модельді модельдеу кезінде реттелген температураның бірнеше мәні алынды. Белгілі бір қоспаның жану температурасын есептеу өте қиын болып табылады, өйткені қоспаның құрамынан басқа бастапқы температура мен қысым қатты әсер етеді. Бастапқы компоненттер температурасы мен қысымының жоғарылауы жану температурасының өсуіне алып келеді. Қоршаған ортамен жылу алмасу және диссоциация реакциялары, керісінше, жану температурасын төмендетеді. Жұмыста газ айдайтын агрегаттың автоматты басқару жүйесінің құрылымы әзірленді, ол газ тасымалдауға қажетті энергетикалық көрсеткіштер мен турбинаның жұмыс корпусын құруға жұмсалатын отын шығындары арасындағы тепе-теңдік қатынастарына негізделген.

Түйін сөздер: газ тасымалдаушы агрегат, жану жылуы, диссоциация, турбина қуаты, автоматы басқару жүйесі.

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СИСТЕМА АВТОМАТИЧЕСКОГО УПРАВЛЕНИЯ ГАЗОПЕРЕКАЧИВАЮЩИМ АГРЕГАТОМ

Аннотация. В настоящее время основным видом внутриконтинентального транспорта газа во всех странах мира служит трубопроводный. Быстрое развитие трубопроводного транспорта газа объясняется тем, что перекачка его по трубопроводам более экономична, чем доставка другим видом транспорта. В статье рассматривается проблема регулирования температуры сгорания топлива в камере сгорания газоперекачивающего агрегата. Газоперекачивающий агрегат как объект управления относится к классу нелинейных, многомерных и быстродействующих объектов. Для правильного ведения технологического процесса транспорта газа оперативный персонал компрессорной станции должен иметь достоверную информацию о состоянии объекта управления, о режимно-технологических параметрах, характеризующих состояние процесса. В целях получения информации путём фактических измерений параметров и вычислений в пакете прикладных программ MATLAB разработана модель расчета температуры пламени. Данная модель, являясь системой логических соотношений, которые описывают реальный объект, регулирует стартовую температуру, выполняя все операции, которые были указаны в структурной схеме расчета с блоками. В ходе имитирования данной модели было получено несколько значений отрегулированной температуры. Расчетное определение температуры горения конкретной смеси является достаточно сложной задачей, так как кроме состава смеси на температуру сильно влияют начальная температура, давление. Увеличение температуры и давления исходных компонентов приводит к росту температуры горения. Теплообмен с окружающей средой и реакции диссоциации, наоборот, снижают температуру горения. В работе разработана структура системы автоматического управления газоперекачивающего агрегата, который основывается на балансных соотношениях между энергетическими показателями необходимых на транспортировку газа и топливными затратами на создание рабочего тела турбины.

Ключевые слова: газоперекачивающий агрегат, теплота сгорания, диссоциация, мощность турбины, система автоматического управления.

Introduction. In connection with the constant increase in gas production, the network of product pipelines is expanded – the most economical type of gas transportation.

The main economic factors for the efficient use of pipeline transportation are the possibility of full automation of gas pipelines.

Gas moves through the gas pipeline from the gas field to the consumer, overcomes the pipeline resistance and loses pressure. Excessive pressure loss leads to a reduction in carrying capacity and irrational use of the pipeline (Farukhshina et al., 2022). Compressor stations are constructed for the economic pumping of gas at large distances with maximum utilization of the pipelines' bearing capacity (Anuchin et al., 2004). Compressor stations of main gas pipelines are a complex of structures designed for gas compression (Gorbiychuk et al., 2019).

Gas-pumping units (GPUs) are complex power plants designed for compression of natural gas entering the compressor station on the main gas pipeline.

The task of gas-pumping units at compressor stations is to increase the pressure of blue fuel to the specified value. GPUs with gas turbine aircraft and marine, as well as electric engines, are used for gas transportation by main gas pipelines. The most common drive is a gas turbine.

The compression process is a complex technological process with a large number of variables, so GPUs can be applied to multidimensional control objects.

In addition, it is necessary to note that the main dependencies between variables, such as the compression coefficient ε and the gas consumption Q, carry a nonlinear character. Therefore, GPU control systems generally work in modes of automatic stabilization in a narrow range of variable variations, only in this case it is possible to linearize the characteristics and adjust the regulators.

The duration of the gas flow in GPU is calculated in split seconds, the number of revolutions of the supercharger reaches 4000-6000 rpm, so it is necessary to note that the compression process is fast (Vesely et al., 2000). All this imposes certain requirements on the choice of technical means of automation, on its speed and accuracy (Singh, 2016).

Thus, it can be said that GPU as an object of control belongs to the class of nonlinear, multidimensional and fast-acting objects.

Research Material and methods. GPU is a complex technological unit, there is a large number of models that reflect dependencies (Guha, 2003).

- flow characteristics on the number of GPU revolutions;
- pressure at the output of the device on P_i, Q_d;
- pressure at the inlet of the device on ω of GPU.

In our case, in order to solve the problem of optimal distribution of pressure on the units, it is necessary to have a model that reflects the compressive dependence of consumption:

$$\varepsilon = (Q_d, \omega, T) \quad (1)$$

This characteristic is taken experimentally and represents a family of curves that reflect the dependence ε on Q_d

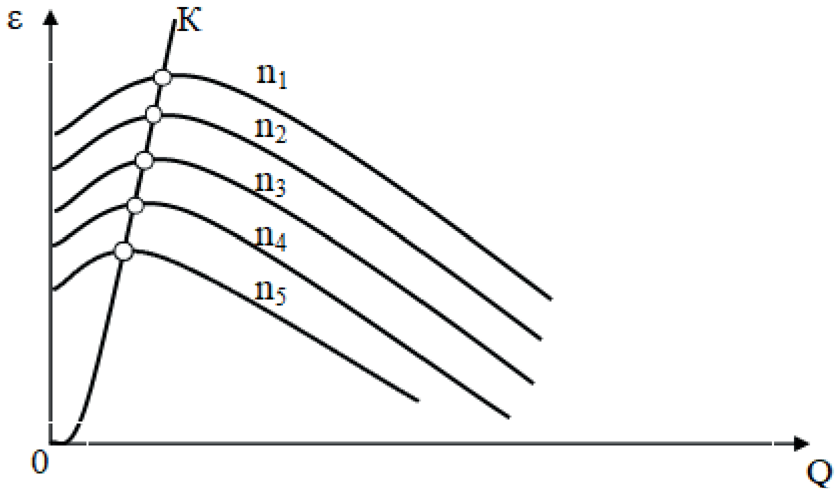

Figure 1 – Diagram of the dependence ε on Q_d

Equation (1) is well approximated by the following expression:

$$\varepsilon = \frac{p_L}{p_i} = a_0 + a_1 Q_d + a_2 Q_d^2 + a_3 \omega + a_4 T, \quad (2)$$

where □□ – number of GPU revolutions;

T – gas outlet temperature at HPT outlet (high pressure turbine) (Giro et al., 2021).

Combustion is a complex physicochemical process based on exothermic oxidative-restorative reactions, which is characterized by a significant flow rate, separation of a large amount of heat, mass exchange with the surrounding area, etc (Altshul et al., 2019).

The calculation of a particular mixture's combustion temperature is a rather difficult task, as the initial temperature, pressure strongly affect the mixture's composition (Soudarev et al., 1997). The increase in temperature and pressure of the initial components leads to the combustion temperature increase (Sukhinenko et al., 1995). Heat exchange with the surrounding medium and dissociation reactions, on the contrary, reduce the burning temperature (Krasnov et al., 2018).

Heat exchange with the surrounding medium and dissociation reactions, on the contrary, reduce the combustion temperature (Orynbayev et al., 2021).

The general equation of any hydrocarbon's combustion reaction has the following form:

$$C_mH_n + \left(m + \frac{n}{4}\right)O_2 = mCO_2 + \left(\frac{n}{2}\right)H_2O + Q, \quad (3)$$

where m, n – the corresponding number of carbon and hydrogen atoms in the molecule;

Q – the combustion heat.

The heat combustion Q is called the amount of heat released during full combustion of 1 m^3 (1 kg, 1 kilomole) under normal physical conditions (P = 101325 Pa, t = 0°C). The values of high and low heat combustion of the main components of natural gas are specified in GOST 30319.1-96.

Adiabatic (without heat exchange with the surrounding medium) combustion temperature of the known composition mixture may be calculated in accordance with the first law of thermodynamics: heat, released during combustion, is completely spent on heating the combustion products.

The following adiabatic temperatures of gas combustion are distinguished in the calculations: calorimetric, theoretical, actual (calculated) and heating. These temperatures differ by taking into account the external factors that affect the combustion temperature. Thus, the heating determines the mixture's combustion temperature at a=1 (the amount of oxidizer corresponds to the minimum required for full combustion) and the initial temperature of the gas and air at 0°C. The calorimetric temperature takes into account the actual coefficient of excess air and the mixture's temperature, which is fed to the combustion. The theoretical temperature additionally takes into account the heat spent on the dissociation (Tumanov et al., 2014). The actual temperature is determined from the product of the theoretical by the coefficient taking into account losses for heat exchange with the surrounding medium (furnace walls), heat transfer by radiation, flow rate, etc.

The formula for determining the theoretical temperature is as follows:

$$t_T = \frac{Q_L^P + q_{ph} - q_d}{\sum V_i * C_{P_i}} \quad (4)$$

where Q_L^P – the lowest combustion heat of the gas, kJ/m^3;

q_{ph} – the heat content (physical heat) of the gas and air, which is counted from 0°C, kJ/m^3;

q_d – the heat amount, which is absorbed during the process of dissociation of carbon dioxide and water vapor, kJ/m^3;

$\sum\left(V_i \cdot C_{P_i}\right)$ – the sum of the products of the volumes and average volumetric heat capacities of the gas combustion product components at constant pressure.

The dissociation of water vapor and carbon dioxide is an endothermic reaction, i.e. a reaction with the heat absorption and increase in volume.

Tabulated values of the degrees of dissociation for partial pressures from 0.004 to 0.04 MPa and temperatures from 1500 to 3000°C. Based on these data, three-dimensional fields of dissociation coefficients were constructed (Fig. 2 and 3).

Figures 2 and 2 show that the degree of dissociation increases with increasing temperature and decreases with increasing partial pressure. Based on this tendency, the extrapolation of the tabular data to a partial pressure of 2.5 MPa and a temperature of 4000°C was performed.

The calculation of the gas combustion products' temperature after mixing with air and water vapor is based on the constancy of the heat energy before and after mixing:

$$Q_{1+2} = Q_1 + Q_2.$$

The heat capacity of the mixed flows is determined by the heat capacities of the flows in proportion to their volumes. Hence, the formula for determining the temperature after mixing takes the following form:

$$T_{1+2} = \frac{Q_{1+2}}{\left(c_{p1} \cdot \left(\frac{V_1}{V_1 + V_2}\right) + c_{p2} \cdot \left(\frac{V_2}{V_1 + V_2}\right)\right) \cdot \left(V_1 + V_2\right)}, \quad (5)$$

where Q_{1+2} – the heat capacity of the mixed flows;

$V_{1,2}$ – the volume of the mixed flows;

C_{p1} – the average volumetric heat capacity of the gases.

After reviewing this technique for determining the combustion temperature, the following block diagram for determining the combustion temperature is built (Fig.4).

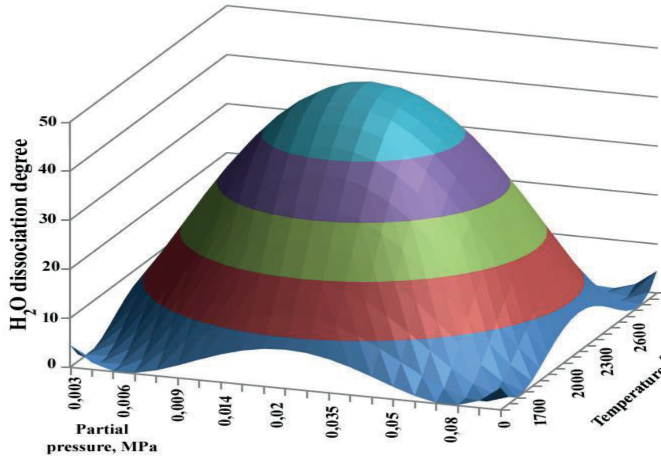

Figure 2 – Graphical dissociation of water vapor

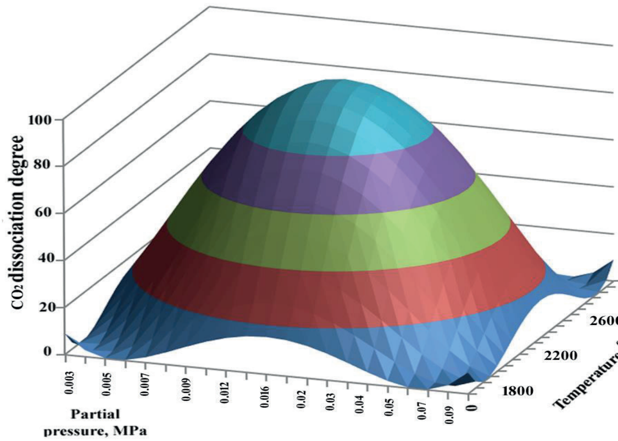

Figure 3 – Graphical dissociation of carbon dioxide

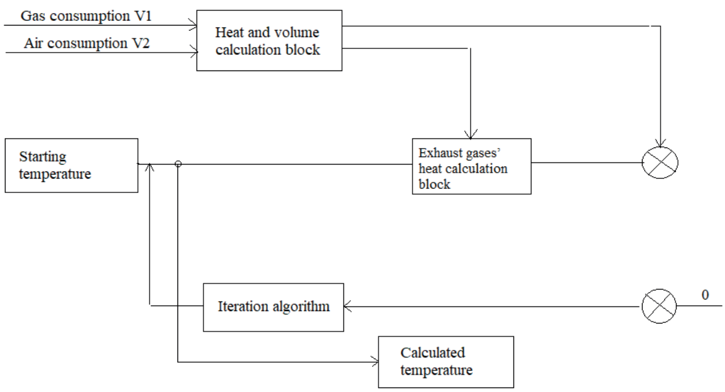

Figure 4 – Block diagram of the flame temperature determination

Let's consider each block separately.

The heat and volume calculation block – this block, taking into account the gas consumption V_1 and air consumption V_2, calculates the total volume of consumed fuel according to the formula:

$$V = V_1 + V_2. \qquad (6)$$

The corresponding released combustion heat is selected depending on the type of fuel. In our case, natural gas was chosen, its combustion heat was Q = 36000 kJ/m^3.

Result and discussion. A model is a simplified representation of a real system. A mathematical model is a system of logical relationships that describe a real object. However, this is not an exact copy of physical systems, they only describe the most essential features of physical systems. In this project, a model was developed for calculating the flame temperature using the MATLAB program (Fig. 5).

This model controls the starting temperature, performing all the operations that were indicated in the structural diagram of the calculation with blocks (Scott et al., 2006). Its task is to compare the combustion heat released from the gas with the heat released from the exhaust gases (Temirbekova et al., 2022). Since the released heat of the exhaust gases is greater than that of the fuel, the search regulator lowers the starting temperature and controls it more precisely until the material balance is established (Orynbayev et al., 2019). The following results were obtained from the model: $T_{starting}$ = 1300°C, and $T_{calculated}$ = 1245°C.

Several experiments were carried out and the following results were obtained (Table), diagram of the dependence of the average volumetric heat capacity on the combustion temperature (Fig. 6).

$T_{starting,}$ °C	$T_{calculated}$, °C
1200	1262
1300	1245
1350	1244
1370	1229
1400	1192

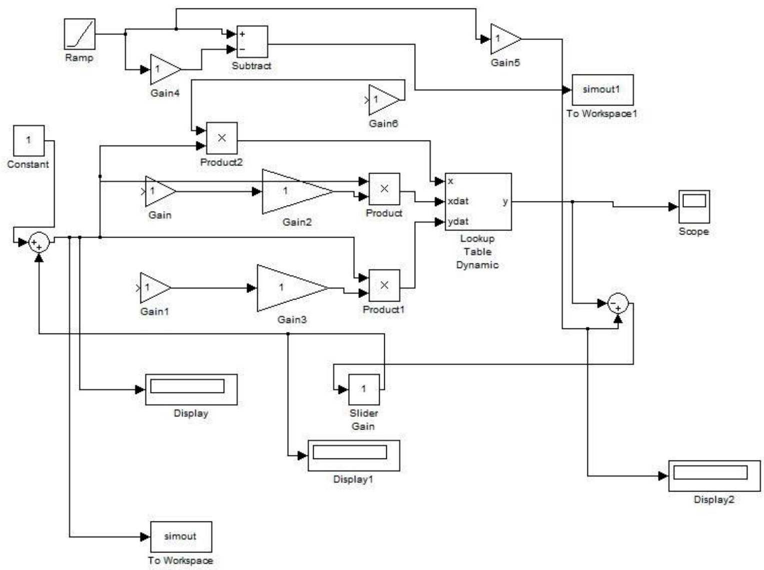

Figure 5 – Model for calculating the flame temperature

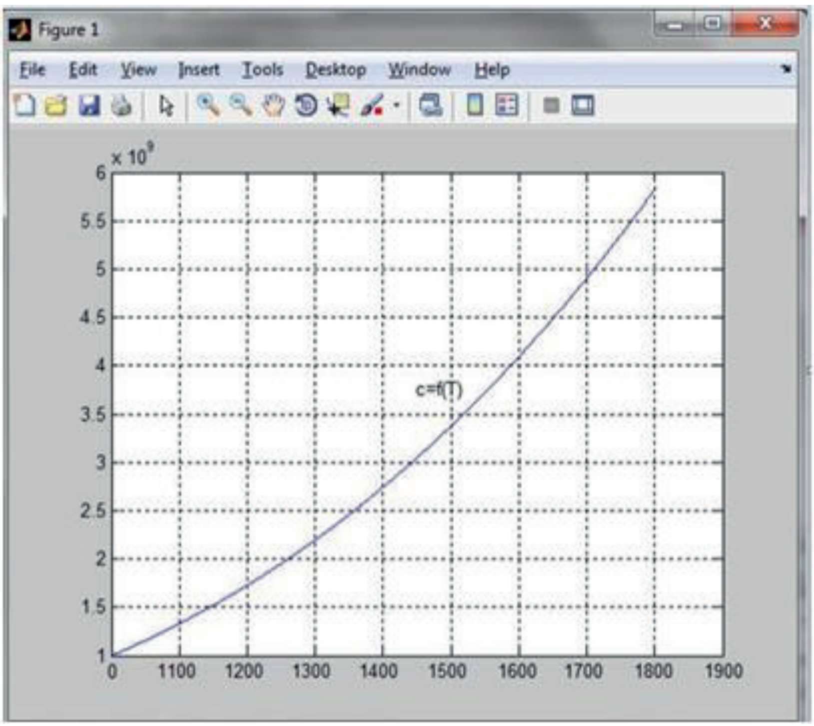

Figure 6 – Diagram of the dependence of the average volumetric heat capacity on the combustion temperature

Synthesis of the automatic control system's structure. The automatic control system is based on the balance ratio between the energy indicators necessary for the gas transportation and fuel costs for the turbine working body construction (Fig. 7).

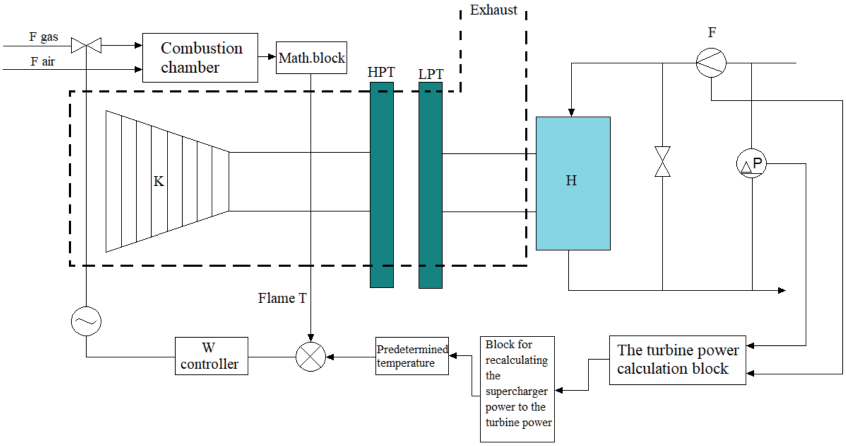

Figure 7 – Structure of the automatic control system of a gas-pumping unit

To calculate the predetermined temperature, it is necessary to find the turbine power. The turbine power is determined from the diagram of the turbine and supercharger power dependence (Fig. 8).

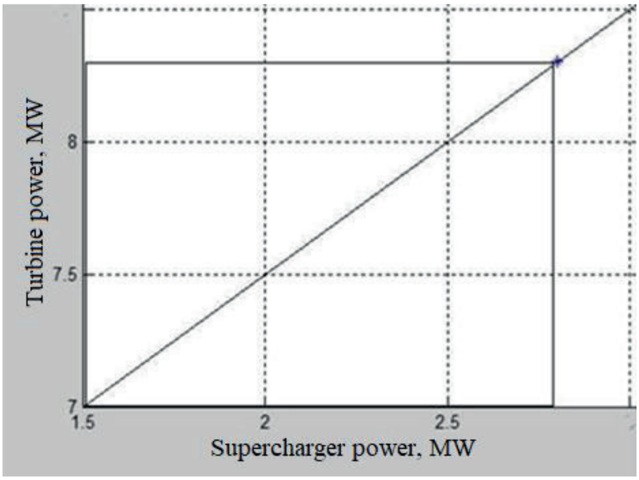

Figure 8 – Diagram of the turbine and supercharger power dependence

Since the supercharger power was equal to $N_{supercharger}$ = 2.8 MW, then from the diagram it is possible to determine the turbine power, which will be equal to $N_{turbine}$ = 8.3 MW.

The predetermined temperature is determined using the following formula:

$$T_{pr} = \frac{N_{turbine}}{Q_{wb} * C_{av}} \quad (7)$$

where $N_{turbine}$ is the turbine power, C_{av} is the average volumetric heat capacity, Q_{wb} is the working body consumption.

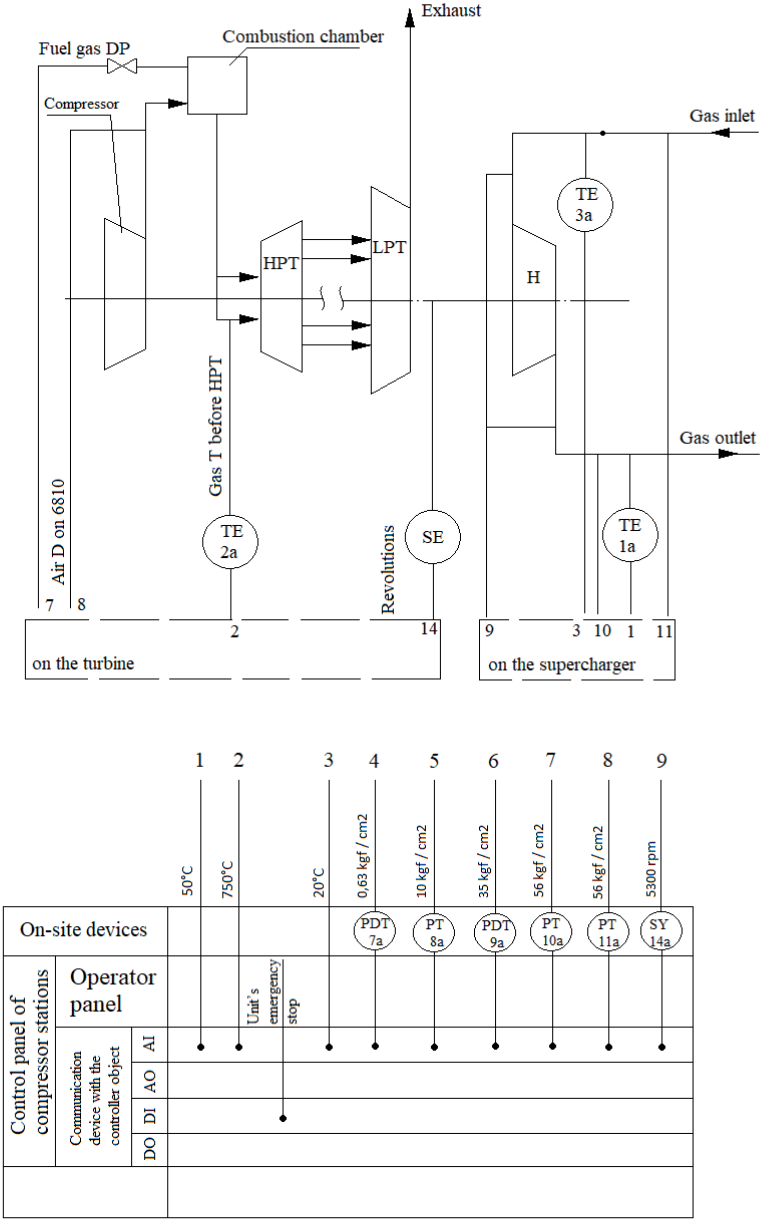

Figure 9 – Functional diagram of GPU

All types of sensors are field-installed (Fig. 9). All sensors were from Metran. Each sensor has dx index, since they are all anti-explosive.

Conclusion. As a result of this work, the mathematical model for calculating the combustion temperature in the combustion chamber was developed. During the simulation of this model, a few values of the controlled temperature were obtained. The structure of the automatic control system of the gas-pumping unit was developed, which is based on the balance ration between the energy indicators necessary for the gas transportation and fuel costs for the turbine working body construction.

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