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Mathematical modeling of thermal effectiveness of a ternary combined cycle plant

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Abstract. The urgency of this work is determined by the intensification of the role of steam-gas technologies (combined cycle technologies) in the field of power engineering in Russia and throughout the world. Developed mathematical model of ternary combined cycle plants, which is based on balance method includes system of mass balance and energy balance equations for ternary combined cycle plants and its units, equations of steam expansion in turbine and working fluids thermodynamic properties. On the basis of a model was carried out the analysis of the impact of the structure and thermodynamic parameters on thermal effectiveness of heat-recovery ternary combined cycle plants which cycle is the combination of three working substance cycles, one of which is low-boiling substance. The analysis of the thermal effectiveness of ternary combined cycle plants was made by means of the small-deflection method. The optimal parameters of operating environment and structure of a ternary combined cycle plants were determined.

1. Introduction

Steam-gas technology (combined cycle technology) which contributes to the considerable effectiveness and environmental safety increase of thermal engineering has actively been implemented in the world power engineering. The launch of new generating equipment at thermal power plants is mainly carried out by the application of combined cycle plants [1]. The most efficient are combined cycle plants of heat-recovery type with different thermodynamic cycles and schemes, produced on the basis of modern high-temperature gas-turbine installation (GTI). The fuel energy in these kinds of combined cycle plants is fed to the working substance in the combustion chamber of GTI only, the heat of the gas burned (flue) in GTI is used in a boiler-utilizer for the generation of superheated steam which is further used in a steam-turbine plant.

The most currently wide-spread heat-recovery CCP are binary ones. Two working substances are used in these types of power plants: the mixture of air with fuel and steam combustion products. They considerably surpass the traditional steam-turbine power generating units concerning their thermodynamic effectiveness and ecological parameters. Their coefficient of efficiency can reach 60 %. The optimization of binary CCP is carried out on different efficiency criteria [2-3]. The tendency to improve the combined cycle plants effectiveness leads to the necessity to consider the combined cycles with the use of low-boiling substances, for example, binary CCP where gas-turbine cycle is combined with Rankine cycle on low-boiling substance. The selection and optimization of thermodynamic parameters of those CCPs is shown and carried out in works [4–6, 7–9]. The article [10] is devoted to the perspectives of the application of binary generating units with low-boiling working substance intended for co-generation. The analysis of literature on this topic has shown that at present either binary combined cycle plants or binary co-generation power plants are the objects of the research in the field of steam-gas technologies [11–15]. The object of the given research are ternary combined cycle plants.

2. Ternary combined cycle

Three thermodynamic cycles are gradually combined in a ternary combined cycle plant [16, 17]: in a gas-turbine plant – the Brighton cycle based on the mixture of air with combustion products, in a steam-turbine plant –Rankine cycle on low-boiling substance steam. The heat recovery in a in a ternary CCP occurs in two parts of the cycle: – water heating, steam generation and steam superheat by the cooling of burned (flue) gases of a gas-turbine plant; – steam generation of a low-boiling substance and steam superheat by waste steam condensation in a condenser-reboiler. Figure 1 illustrates one of the simplest ternary CCP scheme.

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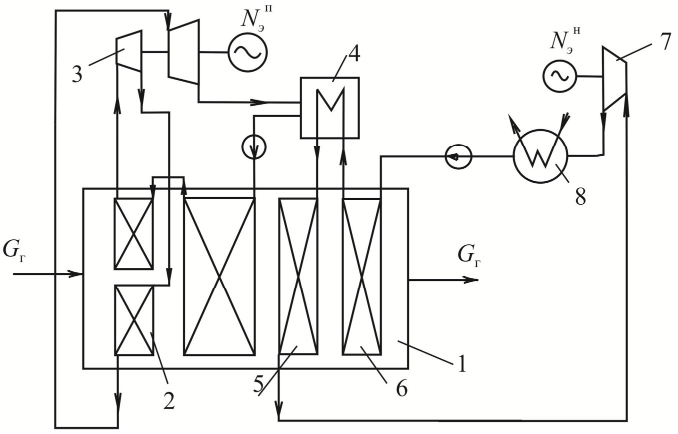

Figure 1. Ternary CCP scheme on steam and low-boiling substance (gas-turbine plant is not shown in the scheme): 1 – boiler –utilizer; 2 – steam reheater; 3 – steam turbine; 4 – steam condenser; 5 – low-boiling substance superheater; 6 – low-boiling substance economizer; 7 – low-boiling substance steam turbine; 4 – low-boiling substance condenser; G_g – gas-turbine plant gas consumption.

Pressure of waste steam is accepted below atmospheric pressure for steam generation of a low-boiling substance with sufficient high temperature. Pressure of low-boiling substance waste steam is determined by thermodynamic properties of low-boiling substance and limited by ambient temperature, therefore, its value is also higher than atmospheric pressure. The mentioned above factors eliminate one of the most complicated problems relating to the vacuum maintenance in turbine condensers. Due to high final pressure waste steam is in a superheated state, therefore the interim steam superheat is aimed at the increase of electric power of a turbo unit, but not at decrease of the final steam humidity.

3. Thermal effectiveness of a ternary combined cycle plant

The achievement of high effectiveness of a ternary CCP by the specified gas turbine plant parameters and characteristics is possible by the optimal values of thermodynamic parameters and the consumption of working substances; however, they are interconnected and not all of them can be controlled by optimization, for example, the live (working) steam saturation temperature of low-boiling substance and its pressure are determined by steam pressure values in a condenser.

To find out the influence of each plant (installation) on the effectiveness of a ternary CCP it is convenient to present the coefficient of efficiency as summands:

$$\eta_{CCP} = \frac{N_e^g + N_e^s + N_e^{lp}}{Q_{cc}} = \frac{N_e^g}{Q_{cc}} + \frac{N_e^s}{Q_{cc}} + \frac{N_e^{lp}}{Q_{cc}}. \quad (1)$$

Where N_e^g, N_e^s are the capacity (output) of gas and water-steam stages of CCP; N_e^{lp} is the steam turbine capacity operating on low-boiling substance; Q_{cc} is fuel heat, delivered to combustion chamber of CCP. The first summand in this equation is coefficient of efficiency of gas turbine plant (GTP) $\eta_{CCP} = \frac{N_e^g}{Q_{cc}}$.

Let's express the boiler-utilizer useful output from this balance:

$$(Q_{cc} - N_e^g)\eta_{bu} = Q_{bu}^s + Q_{bu}^{lp} \quad (2)$$

Where η_{bu} is the coefficient of efficiency of a boiler-utilizer; Q_{bu}^s, Q_{bu}^{lp} are the values of thermal power of a boiler-utilizer, used to generate electricity in a steam-water cycle and low-boiling substance cycle; $Q_{bu}^s = \frac{N_e^g}{\eta_{stp}} \cdot Q_{bu}^{lp}$ value can be expressed from the equation applied to determine the coefficient of efficiency of low-boiling substance.

In a low-boiling substance cycle heat is delivered to the working substance in a boiler-utilizer Q_{bu}^{lp} and in a steam condenser in the quantity which equals $\frac{N_e^s}{\eta_{stp}} - N_e^s$, therefore, the coefficient of efficiency of low-boiling substance cycle is equal to:

$$\eta_{lbw} = \frac{N_e^{lp}}{Q_{bu}^{lp} + \left(\dfrac{N_e^s}{\eta_{stp}} - N_e^s \right)}. \qquad (3)$$

Expressing $Q_{bu}^{lp} = \dfrac{N_e^{lp}}{\eta_{lbw}} - \dfrac{N_e^s}{\eta_{stp}} + N_e^s$ and replacing Q_{bu}^s and Q_{bu}^{lp} in (2), we will get:

$(Q_{cc} - N_e^g)\eta_{bu} = \dfrac{N_e^s}{\eta_{stp}} + \dfrac{N_e^{lp}}{\eta_{lbw}} - \dfrac{N_e^s}{\eta_{stp}}$, and then: $(Q_{cc} - N_e^g)\eta_{bu} = \dfrac{N_e^{lp}}{\eta_{lbw}} + N_e^s$.

The output of a steam-water cycle turbine can be expressed from the last equation: $N_e^s = (Q_{cc} - N_e^g)\eta_{bu} - \dfrac{N_e^{lp}}{\eta_{lbw}}$

Replacing N_e^s in (1) we will get:

$$\eta_{stp} = \frac{N_e^g}{Q_{cc}} + \frac{N_e^s}{Q_{cc}} + \frac{N_e^{lp}}{Q_{cc}} = \eta_{stp} + \frac{\left(Q_{cc} - N_e^g\right)\eta_{bu}}{Q_{cc}} - \frac{N_e^{lp} / \eta_{lbw}}{Q_{cc}} + \frac{N_e^{lp}}{Q_{cc}}$$

Carrying on the further mathematical manipulation the following equation is obtained:

$$\eta_{stp} = \eta_{ccp} + \left(1 - \eta_{stp}\right)\eta_{bu} - \frac{N_e^{lp}}{Q_{cc}}\left(\frac{1}{\eta_{lpw}} - 1\right) \qquad (4)$$

However, the factors related to the water-steam cycle such as the coefficient of efficiency η_{CCP} and steam turbine plant output N_e^s are absent; therefore, the following conclusion can be made: the effectiveness of a ternary CCP does not depend on the STI output and efficiency. It can be explained by the fact that CCP operates without any losses in the cycle: condensation heat of waste steam is completely used up for steam generation of a low-boiling substance.

The last summand in the equation (4) has a negative influence on TCCP efficiency. The higher the coefficient of efficiency of low-boiling substance cycle η_{lbw} and low the generated output (power) N_e^{lp} the lower the influence. The concurrent execution of these conditions is possible only by means of optimization of the ratio of thermal load of low-boiling substance, covered by a boiler-utilizer to the ratio of the total thermal load of this turbine plant. One of the solutions is presented in TCCP scheme in figure 2. In this scheme the heat-exchange surfaces of low-boiling substance are only in the boiler-utilizer in the form of an economizer. Steam cooler is used to superheat low-boiling substance steam.

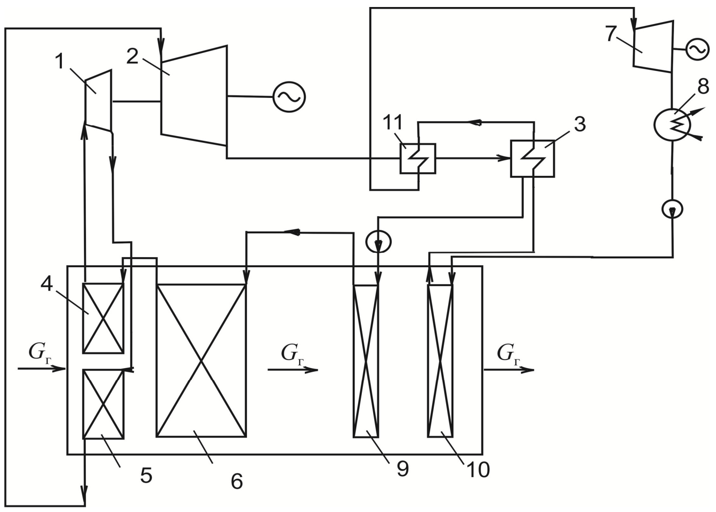

Figure 2. Scheme of a simple TCCP with steam superheat of low-boiling substane in a steam cooler (gas turbine plant is not illustrated in this scheme): *G*г – consumtion of discharged (burned) gases of GTP; 1, 2 – HPC and LPC of a steam turbine; 3 – a condenser-reboiler; 4, 5 – superheater and interim steam superheater; 6 – steam eveporating surfaces; 7 – low- boiling substance steam tubine; 8 – a steam condenser of low-boiling; 9 – a water economizer; 10 – low-boiling substance economizer; 11 – steam cooler (steam superheater of LBS)

This type of scheme sets the problem of finding a working substance of a low-boiling substance cycle with certain properties: it should ensure high thermodynamic effectiveness of Rankine cycle and have appropriate thermalphysic characteristics

– maximal heat of evaporation and lower heat capacity of liquid at saturation temperature [10]. When choosing the type of working substance of LBS it is necessary to take into account that the coefficient of efficiency of Rankine cycle η_{lbw} is determined, first of all, by the maximal and minimal temperature values in the cycle.

To determine the investigation margin it makes sense to find out under what conditions the coefficient of efficiency of a three cycle combined cycle plant (gas-turbine, water-steam and low-boiling substance cycle) will be higher compared with the coefficient of efficiency of a binary heat-recovery CCP with a steam turbine installation operating on steam. The coefficient of efficiency can be expressed from (1) by the exclusion of the last summand:

$$\eta_{ccp}^{s} = \eta_{ccp} + \left(1-\eta_{ccp}\right)\cdot\eta_{bu}\cdot\eta_{stp} \qquad (5)$$

To carry out the comparison we will designate the coefficient of efficiency of three cycle CCP like this – η_{ccp}^{s+lp}, the coefficient of efficiency of heat-recovery CCP with steam turbine unit as $-\eta_{ccp}^{s}$ and then we will write down the inequation:

$$\eta_{ccp}^{s+lp} > \eta_{ccp}^{s}. \qquad (6)$$

The coefficient of efficiency from (4) and (5) we will replace and carry out mathematical manipulation of inequation:

$$\eta_{ccp} + \left(1-\eta_{ccp}\right)\cdot\eta_{bu} - \frac{N_e^{lp}}{Q_{cc}}\left(\frac{1}{\eta_{lpw}}-1\right) > \eta_{ccp} + \left(1-\eta_{ccp}\right)\cdot\eta_{bu}\cdot\eta_{stp},$$

$$\frac{N_e^{lp}}{Q_{cc}}\left(1-\frac{1}{\eta_{lpw}}\right) > \left(1-\eta_{ccp}\right)\cdot\eta_{bu}\cdot(\eta_{stp}-1),$$

$$\eta_{lpw} > \frac{1}{1-\left(1-\eta_{ccp}\right)\cdot\eta_{bu}\cdot(\eta_{stp}-1)\dfrac{Q_{cc}}{N_e^{lp}}}. \qquad (7)$$

Thus inequation (7) expresses the conditions of CCP efficiency enhancement when introducing CCP into the structure of low-boiling substance cycle.

The basic value of variables are determined for a ternary combined cycle plant presented in figure 1 and by the parameters illustrated in table 1. The base of a ternary CCP is SGT5-8000H Siemens gas-turbine plant with the coefficient of efficiency of 40 %. Its electric power constitutes 375 megawatts, burned (flue) gas consumption makes up 820 kg/s, its temperature equals $625\ ^{\circ}C$, which allows to get steam with supercritical parameters which consumption is up to o135 kg/s; working substance of a low-boiling substance plant is ammonia.

Table 1. The governing thermodynamic parameters of TCCP of the basic case

№ p/p	Characteristics	Steam	Ammonia
1.	Initial pressure, MPa	24	7,57
2.	Initial temperature, °C	600	150
3.	Pressure of interim superheat, MPa	3,5	–
4.	Temperature of interim superheat, °C	600	–
5.	Pressure of exhaust gas, MPa	0,14	0,10
6.	Saturation temperature of waste steam, °C	109	20

The indices of TCCP in the basic case:

$$\eta_{ccp0} = 0{,}597;\ \eta_{bu0} = 0{,}877;\ N_{e0}^{lp} = 60{,}4\ \text{MWt};\ Q_{cc0} = 937{,}5\ \text{MWt};\ \eta_{lbw0} = 0{,}173.$$

By substitution of the basic values η_{ccp}, η_{bu}, η_{stp}, N_e^{lp}, Q_{cc}, we get that the coefficient of efficiency of a ternary CCP where ammonia is used as low-boiling substance is higher than the coefficient of efficiency of a binary heat-recovery CCP with STU if the coefficient of efficiency is $\eta_{lpw} > 0{,}17$. If butane is used then this condition is as follows: $\eta_{lpw} > 0{,}15$.

4. The analysis of ternary combined cycle plant effectiveness by the small deviation method

The small deflection method [18] allows to obtain the solution in a general and numerical forms, using the results of calculation of some combination of the plant. This method is based on equation linearization – a mathematical device including the equation differentiation with a further replacement of value of a quantity by fractional variations. As a result the initial analytic equation is replaced by the argument (independent variable) equation in small deflections.

The obtained analytic dependence binds (links) the variations of the original variable and changes of function. It allows to carry out analysis of function change by means of influence coefficient of variable quantities It is vital by the great number of arguments (independent variables) and nonlinear relation between them and a function. Let's differentiate the equation in accordance with the small deflection method (4):

$$d\eta_{ccp} = \frac{\partial \eta_{ccp}}{\partial \eta_{gti}} d\eta_{gti} + \frac{\partial \eta_{ccp}}{\partial \eta_{bu}} d\eta_{bu} + \frac{\partial \eta_{ccp}}{N_e^{lp}} dN_e^{lp} + \frac{\partial \eta_{ccp}}{Q_{cc}} dQ_{cc} + \frac{\partial \eta_{ccp}}{\partial \eta_{lbw}} d\eta_{lbw} \tag{8}$$

The partial derivatives are here: $\frac{\partial \eta_{ccp}}{\partial \eta_{gti}} = 1 - \eta_{bu}$; $\frac{\partial \eta_{ccp}}{\partial \eta_{bu}} = 1 - \eta_{gti}$; $\frac{\partial \eta_{ccp}}{\partial N_e^{lp}} = -\frac{1}{Q_{cc}}\left(\frac{1}{\eta_{lbw}} - 1\right)$; $\frac{\partial \eta_{ccp}}{\partial Q_{cc}} = \frac{N_e^{lp}}{Q_{cc}^2}\left(\frac{1}{\eta_{lbw}} - 1\right)$.

Replacing the partial derivative in (4), we will get:

$$d\eta_{ccp} = (1-\eta_{bu})\, d\eta_{gti} + (1-\eta_{gti})\, d\eta_{bu} - \frac{1}{Q_{cc}}\left(\frac{1}{\eta_{lbw}} - 1\right) dN_e^{lp} + \frac{N_e^{lp}}{Q_{cc}^2}\left(\frac{1}{\eta_{lbw}} - 1\right) dQ_{cc} + \frac{N_e^{lp}}{Q_{cc}} \cdot \frac{1}{\eta_{lbw}^2} d\eta_{lbw}.$$

Let's turn to the finite decrements and then to relative departures:

$$\Delta\eta_{ccp} = (1-\eta_{bu})\, \Delta\eta_{gti} + (1-\eta_{gti})\, \Delta\eta_{bu} - \frac{1}{Q_{cc}}\left(\frac{1}{\eta_{lbw}} - 1\right) \Delta N_e^{lp} + \frac{N_e^{lp}}{Q_{cc}^2}\left(\frac{1}{\eta_{lbw}} - 1\right) \Delta Q_{cc} + \frac{N_e^{lp}}{Q_{cc}} \cdot \frac{1}{\eta_{lbw}^2} \Delta\eta_{lbw}.$$

$$\frac{\Delta\eta_{ccp}}{\eta_{ccp}} = \frac{1}{\eta_{ccp}}\left[\begin{array}{l}(1-\eta_{bu})\eta_{gti}\frac{\Delta\eta_{gti}}{\eta_{gti}} + (1-\eta_{gti})\eta_{bu}\frac{\Delta\eta_{bu}}{\eta_{bu}} - \frac{N_e^{lp}}{Q_{cc}}\left(\frac{1}{\eta_{lbw}} - 1\right)\frac{\Delta N_e^{lp}}{N_e^{lp}} + \\ + \frac{N_e^{lp}}{Q_{cc}}\left(\frac{1}{\eta_{lbw}} - 1\right)\frac{\Delta Q_{cc}}{Q_{cc}} + \frac{N_e^{lp}}{Q_{cc}} \cdot \frac{1}{\eta_{lbw}}\frac{\Delta\eta_{lbw}}{\eta_{lbw}}\end{array}\right].$$

Turning to the labeling of the coefficients by variable quantities we will get:

$$\delta\eta_{ccp} = K_1 \delta\eta_{gti} + K_2 \delta\eta_{bu} + K_3 \delta N_e^{lp} + K_4 \delta Q_{cc} + K_5 \delta\eta_{lbw}. \tag{9}$$

The influence coefficients K_1 - K_5 are determined through the quantities of "the basic" variant which have in the formula the «0» index:

$K_1 = \frac{(1-\eta_{bu0})\eta_{gti0}}{\eta_{ccp0}}$; $K_2 = \frac{(1-\eta_{gti0})\eta_{bu0}}{\eta_{ccp0}}$; $K_3 = -\frac{N_{e0}^{lp}}{\eta_{ccp0} \cdot Q_{cc0}}\left(\frac{1}{\eta_{lbw0}} - 1\right)$; $K_4 = \frac{N_{e0}^{lp}}{\eta_{ccp0} \cdot Q_{cc0}}\left(\frac{1}{\eta_{lbw0}} - 1\right)$; $K_5 = \frac{N_{e0}^{lp}}{\eta_{ccp0} \cdot Q_{cc0} \cdot \eta_{lbw0}}$.

Where the values of influence coefficients are: $K_1 = 0{,}082$, $K_2 = 0{,}881$, $K_3 = -0{,}516$, $K_4 = 0{,}516$, $K_5 = 0{,}624$.

The relation of coefficient of efficiency in the considered steam-gas plant from influencing factors is presented below in the equation form in small deflections:

$$\delta\eta_{ccp} = 0.082 \cdot \delta\eta_{gti} + 0.881 \cdot \delta\eta_{bu} - 0.516 \cdot \delta N_e^{lp} + 0.516 \cdot \delta Q_{cc} + 0.624 \cdot \delta\eta_{lbw}. \tag{10}$$

The analysis of this equation shows that the greatest influence on the coefficient of efficiency has the value η_{bu}, i.e. the effectiveness of heat use of burned (flue) gases in the boiler –utilizer. By replacing of $\eta_{bu}$by 1 % the coefficient of efficiency of steam-gas plant changes on 0,881 %. The increase on 1 % of heat quantity applied by fuel combustion in a combustion chamber leads to the increase on 0,516 % of CCP output. Influence coefficient of electric power of a turbine on low-boiling substance steam has a negative value, i.e. the increase of its value results in TCCP output (efficiency) decrease which confirms the conclusion made above. On the other hand, the plant efficiency on a low-boiling substance has a positive influence coefficient, the second one concerning the value ($K_5 = 0{,}624$), i.e. the increase of $\delta\eta_{lbw}$ efficiency on 1% leads to the increase of $\delta\eta_{ccp}$ efficiency on 0,624 %.

5. Modeling of thermal effectiveness of ternary combined cycle plants

The investigation of the influence of working substances on ternary CCP structure and thermodynamic parameter was carried out on the mathematical model of TCCP. The model is based on a balance method and is a system of equation of material and power balances of steam-gas plant and its certain elements, the equations of the process of steam expansion in turbines and the equations of thermodynamic properties of working substances.

16 different variants (types) of TCCP structure by the application of different combinations were considered. This was done to increase the efficiency of TCCP on different types of low-boiling substance (R134a, R21, R290, R600, R717). The combinations were as follows:

- additional circuit of a water-steam cycle (TCCP of two or three pressures);
- interim steam superheat of low-boiling substance;
- interim steam superheat of low-boiling substance steam to increase the turbine and steam gas plant output;
- steam refrigerants of waste steam (steam refrigerant -water) and low-boiling substance steam (steam refrigerant of low-boiling substance);
- regenerative heating of low-boiling substance (RH of LBS).

As an example the obtained values of indices and influence coefficients in equation (9) for some plants are presented in tables 2 and 3.

Upon the analysis it can be concluded that the magnitudes of influence coefficient do not depend on the structure, but undergoes changes within a small range by the transition to the other type of low-boiling. The influence of the structural factor in the plant with a butane turbine is a bit higher compared with the plant using ammonia.

The coefficient of efficiency of a ternary CCP increases by exclusion (output) of the heat surfaces terminals of a low-boiling substance from a boiler-utilizer. However, the total electric power of such type of TCCP is low compared with the analogues binary CCP of three circuit type. The temperature of outgoing gases is high (145 ^{o}C and higher), the coefficient of efficiency of a boiler-utilizer does not exceed 78,7 %.

Table 2. Basic indices of TCCPs with an ammoniac turbine

Value	Scheme			
	Simple	C on water	With RH HKB low-boiling substance	With SC (water) and RH (low-boiling substance)
Coefficient of efficiency of steam-turbine plant	0,327	0,327	0,327	0,327
Electric power of low-boiling substance turbine, megawatt	60,4	60,4	74,0	73,7
Coefficient of efficiency of low-boiling substance turbine plant	0,173	0,173	0,211	0,211
Temperature of outgoing gases, ^{o}C	90,1	90,2	89,8	89,9
Coefficient of efficiency of a boiler-utilizer	0,877	0,877	0,877	0,877
Coefficient of efficiency of steam-gas plant	0,597	0,597	0,610	0,611
K1	0,082	0,082	0,081	0,081
K2	0,881	0,881	0,863	0,861
K3	-0,516	-0,516	-0,484	-0,481
K4	0,516	0,516	0,484	0,481
K5	0,624	0,624	0,612	0,610

Table 3. The key indicators of ternary combined cycle plants with a butane turbine

Value	Scheme				
	Simple	With SC of LBS	WITH RH of LBS	With SC (water)	With SC (water) and SC (LBS)
Coefficient of efficiency of steam-turbine plant	0,323	0,324	0,323	0,323	0,323
Electric power of low-boiling substance turbine, megawatt	52,8	62,5	62,2	54,4	69,3
Coefficient of efficiency of low-boiling substance turbine plant	0,151	0,178	0,177	0,151	0,193
Temperature of outgoing gases, ^{o}C	90,1	89,8	89,5	90,2	90,5
Coefficient of efficiency of a boiler-utilizer	0,877	0,877	0,878	0,877	0,876
Coefficient of efficiency of steam-gas plant	0,587	0,596	0,596	0,589	0,605
K1	0,084	0,083	0,082	0,084	0,082
K2	0,896	0,883	0,901	0,893	0,869
K3	-0,539	-0,517	-0,518	-0,554	-0,511
K4	0,539	0,517	0,518	0,554	0,511
K5	0,635	0,628	0,629	0,652	0,633

The capacity and coefficient of efficiency of a steam-water cycle increase by the steam pressure decrease in a condenser. Simultaneously it leads to the decrease of initial pressure of low-boiling substance circuit and the reduction of its thermal effectiveness. In a plant without a superheater of low-boiling substance the steam temperature of low-boiling substance is also determined by final steam pressure. Steam consumption in a low-boiling substance loop depends on the heat quantity removed from steam in a condenser and can vary remarkably in a wide range by the variation of steam consumption and its back pressure. The introduction of regenerative heating in the plant with low-boiling substance causes the coefficient efficiency increase of the whole TCCP on 3 – 4 %.

The introduction of steam-water loop of average pressure by the maintenance of the outgoing gases in the range 80 – 100 °C does not have practically any influence on the TCCP efficiency; however, it leads to the plant scheme complication. Therefore, two circuit TCCP has advantages over three circuit one. The most effective is two circuit TSGP presented in figure 3. Besides the main elements, its scheme includes a steam reheater, steam cooler of waste steam and low-boiling substance steam, and a single-stage regenerative heating of low-boiling substance. Butane R600 turned up to be the best low-boiling substance in this plant.

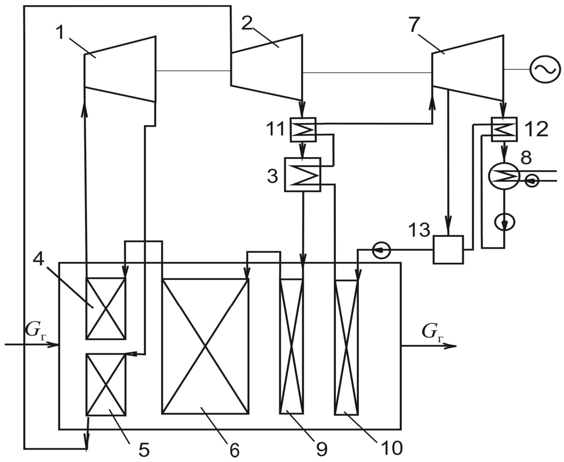

Figure 3. Scheme of a two loop ternary heat-recovery steam-gas plant with regenerative heating of low-boiling substance and a steam cooler of waste steam (TCCP with SC and RH of LBS): 12 – steam cooler of waste steam of low-boiling substance; 13 – regenarative condenser preheater of freon; other elements are the same as in Fig.2

The investigation of ternary CCP efficiency depending on thermodynamic parameters has enabled to find the best optimal combinations for each plant configuration. The combinations of TCCP with interim superheating and maximal values of thermodynamic parameters are preferable.

The most efficient are combinations where the values of thermodynamic parameters guarantee the maximal possible steam consumption and the thermal loading of low-boiling substance economizer has a minimal value.

6. Conclusions

New mathematical model of thermal effectiveness for a new ternary CCP of variable structure was developed. The investigations conducted on the basis of this type of plant allow us to make a conclusion, that the choice of the structure and parameters of the working substances of TCCP should be made by taking into account the level of influence of certain plants (GTP, STP, LBS) on the CCP effectiveness. Thermodynamic properties of a low-boiling substance have a considerable influence on the effectiveness of a ternary combined cycle plant. In some options (combinations) the use of butane concerning the thermal effectiveness is more profitable than the use of ammonia.

For a ternary CCP independently of the plant structure and the type of low-boiling substance the following dependences (relations) are typical:

1. The greatest influence on thermal effectiveness of a ternary CCP has the completeness of the use of burned (flue) in GTP gases in a boiler-utilizer.
2. Steam turbine installation efficiency does not have any influence on thermal effectiveness of a ternary CCP, since this turbine installation operates without any losses in the cycle. The increase of steam parameters and its interim superheating allows to increase the effectiveness of a ternary CCP due to the steam turbine and the whole steam-gas plant capacity (output) increase.
3. With the increase of turbine electric power operating on low-boiling substance the effectiveness of a ternary CCP decreases: to maintain its effectiveness it is necessary to optimize steam consumption of low-boiling substance.
4. The removal of evaporative and superheating surface of low-boiling substance heat-exchange from the boiler-utilizer and the transmission of the corresponding loads on steam turbine plant leads to the increase of thermal effectiveness of a ternary CCP.
5. Plant coefficient of efficiency on a low-boiling substance has a positive influence coefficient on SGP performance and, therefore it makes sense to increase the initial steam temperature of low-boiling substance and to complicate the plant scheme by steam cooler introduction of waste steam or regenerative heating of low-boiling substance. установки на низкокипящем веществе имеет положительный коэффициент влияния на КПД ПГУ, поэтому имеет смысл повышение начальной температуры пара НКВ и усложнение схемы установки введением пароохладителя отработавшего пара или регенеративного подогрева НКВ.

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