Contemporary Engineering Sciences, Vol. 9, 2016, no. 32, 1559 - 1574
HIKARI Ltd, www.m-hikari.com
https://doi.org/10.12988/ces.2016.69155

Design and Feasibility Study of Energy-Conserving Thermal Schemes for Gas Turbine-Based CHP

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Abstract

The paper deals with the design problem of gas turbine-based CHP oriented for working on temperature chart of a district heating (DH) 150/70 °C. This problem is caused by the low temperature corrosion of heating surface during the non-heating season. The existing solutions, which base on blending water at the exit from a gas-water heat exchanger (GWHE) on the recirculation line, cannot provide the acceptable parameters of a heat carrier in a heat exchanger during the whole year and involve high power costs for own needs. It was offered to form a preheating circuit of delivery water, where return delivery one warms up to minimum permissible temperature at the entrance to GWHE. Based on this offer, there were designed two options of energy-conserving thermal schemes of a gas turbine-based CHP and was conducted comparative economic analysis.

Keywords: distributed generation, gas turbine-based CHP, gas turbine units, thermal chart, thermal scheme, feasibility study

1 Introduction

Energy production effectiveness is one of the determining factors of the development of society. Nowadays it is impossible to solve the task of the improvement of industrial and economic activities without energy-conserving sources of electric and thermal energies [8, 13]

Traditional energy production based on the transformation of chemical energy of organic fuel into electric one at the thermal power plants (TPP) is core in providing energy safety and reliability of the power supply of most economies [6, 8].

Cogeneration of heat and electricity at combined heat and power plants (CHP) has widely implications in Russia. Combined heat and electricity production in providing centralized heat supply is named the cogeneration-based district heating in the academic literature and practice. Cogeneration units called CHP were built into the USSR common energy system in rational way and were distinguished by high indices of performance [2, 12].

In today's Russia energy sector faces serious problems, which ask for immediate solutions. There has been a significant decompression of the charts of heat and electricity loads for last 30 years. On the one hand, this decompression was caused by a drastic reduction of industrious consumption share, on the other hand, by a rising domestic electrification. There appeared to be the shortage of peak capacities, large condensing power plants have to function in abnormal modes, the electric/heat output ratio has decreased. The beneficial impact of fuel saving during cogeneration has significantly declined because of increasing transporting losses of heat and electric energy [1, 14].

The above-mentioned factors have led to the decline of energy production effectiveness in the whole energy system and rising tariffs. There is a trend of the decentralization of energy and heat production and the development of distributed power generation [4, 12, 16].

According to the country doctrine of energy security, the main goal of the energy system development is the growth of net energy while reducing natural resources consumption. Following this doctrine in Russia's energy strategy up to 2035 quite a bit of attention is paid to the development of distributed generation, which will allow transforming the country energy sector into the sector of a higher quality level due to the structural transformation of the electric power industry [11, 17].

The rising effectiveness of low-powered thermal and mechanical equipment enhances of the usage relevance of decentralized sources for cogeneration in a single thermodynamic cycle [5, 18, 20].

According to [5, 16], the significant part of Russia's regions is experiencing power shortages in the context of their ability to supply themselves with own electric power. Meanwhile, the gasification level is quite high in these regions. The opportunities for building low and medium power cogeneration units working on gas have arisen in the regions. This decision will allow to compensate the shortage of own electric power and to increase the share of electric power that is produced on heat-end mode thus providing fuel saving.

The construction of gas turbine-based CHP (GT CHP) is one of the most perspective directions in the development of small-scale distributed power generation [15, 18]. The main advantages of this energy production technology are high fuel utilization, the possibility of CHP electricity production, relatively low capital cost. High annual energy and financial-economic indicators may be achieved at industrial and industrial-heating GT CHP [3, 7].

Despite the above-mentioned advantages, the practical deployment of GT CHP meets the following technologic difficulties [9, 19, 10, 21]:

- the need in heat energy release varies with outdoor temperature;
- the parameters of gas turbine vary with outdoor temperature;
- heat-absorption capability of the heating surfaces of a waste heat boiler (WHB) varies with outdoor temperature;
- limitations on the minimum temperature of a heat carrier at the entrance into a WHB to prevent heating surfaces from corrosion; on the permissible speed of a heat carrier in WHB heating surfaces; on the minimum exhaust gas temperature (EGT).

In order to create the thermal schemes of heating type GT CHP, it is necessary to solve these problems. Simultaneously, the solution leads to the usage of additional support equipment and schemes complexity that result in reducing reliability and increasing capital cost. If a new plant is built for heating reasons, it must provide heat energy release during the whole year and, at the same time, it must be competitive on power markets. Thus, the development of thermal schemes expects the analysis of annual energy and financial-economic indicators.

The article deals with new energy-conserving thermal schemes of a heating type GT CHP designed for functioning in the system of distributed regional power generation. The survey of schedule and ways of base-load thermal provision is conducted for the proposed schemes. The comparative analysis of thermal schemes is made on annual energy and financial-economic indicators.

2 The analysis of gas turbine units appliance for the combined production of electric and thermal power

The current trends in the energy production development are to increase energy efficiency and to decrease emissions release, which is possible to achieve through cogeneration process in a single thermodynamic cycle. As new power plants operate in competitive business environment, they are subject to the requirements of safety and efficiency of power-generating equipment as well as control response. The high level of gas turbine technologies development allows to build new efficient power plants.

Gas turbine unit (GTU) consists of a gas turbine, a compressor, a combustion chamber, an electric generator, a control system and auxiliary equipment. Natural gas is used as primary fuel, diesel fuel is used as contingency or back-up one. Power load range which can be covered by GTU is from 2 MW to 100 MW (some manufacturers supply GTU with capacity more 100 MW) [9, 15].

The main merits of modern GTUs are:

- low mounting price (325 US dollars/kW [15]);
- small size;
- small mass;
- low emissions content (within the limits from a base indicator);
- high control response;

The main demerits are:

- short lifetime
- low power generation efficiency in self-driven mode
- considerable functioning noise level (comparing with steam turbine units)

The most reasonable usage of GTUs is to make cogeneration production at combined heat and power plants. Gas turbine-based CHP and steam turbine-based CHP provide maximum energy conservation and environment friendly production [12, 18].

Several layout arrangements of GTU adoption can be pointed out [9, 15]:

1. GT CHP construction on a stand-alone ground or a new construction.
2. GTU mounting in a functioning boiler-house as a build-up.
3. GTU placement with steam waste-heat boilers at a functioning steam turbine-based CHP instead of current steam boilers and saving steam-turbine part of CHP.

The selection of a thermal scheme of GTU depends on a wide range of factors and each case needs feasibility justification. It is necessary to take into consideration climate conditions for a specific region, the needs in thermal and electric energy, utilities availability, housing density and many other factors.

The main advantage of the arrangements on a boiler-house build-up or the substitution of steam boilers for GTUs with waste-heat boilers is relatively low cost of its implementation. Nevertheless, an available free ground for placement of a gas turbine part is required. Besides that, it is necessary to take into consideration the difference in the lifespan of gas turbine and steam power equipment.

When building new plants the most cost efficient ones are industrial and industrial-heating GT CHP due to the permanent demand for steam among industrial consuming. A plant can function with high thermal efficiency indicators during the whole year. The disadvantage of this kind of plants is the dependence on the existence of the industrial heat consumers.

If building a heating type GT CHP, it becomes difficult to follow the thermal schedule as the consumer needs highly depend on outdoor temperature. Maximum heat release is required during the winter season at a minimum outdoor temperature. The higher outdoor temperature is, the less are the flow and temperature of a delivery water. The task becomes more difficult because of the significant influence of outdoor temperature on a gas turbine characteristics and the alteration of heat-absorption capability of the heating surfaces of a WHB during the year. There appear additional costs for heat load regulation, which most often result in the decline of the production energy effectiveness. The development of a thermal scheme requires the solution of the stated problems.

3 The analysis of thermal scheme GT CHP and design problems

Heating GT CHP are designed for cogeneration. The heat energy of a gas turbine exhaust is used for the heat up of delivery water in a gas-water heat exchanger (GWHE). The simplest scheme of a heating GT CHP representing cogeneration process is shown in Figure 1.

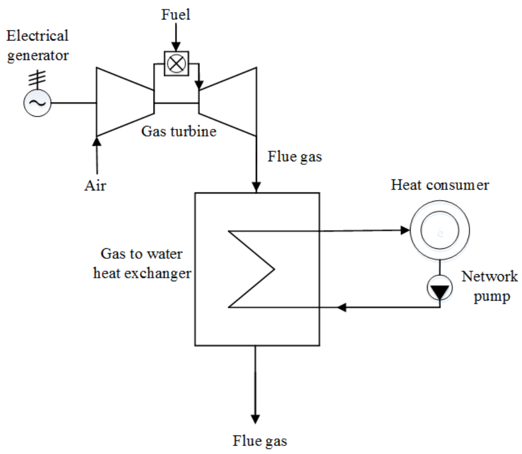

Figure 1: Elementary thermal scheme of GT CHP
Source: authors' development based on [9, 20]

Annual schedule of heat energy release requires the solution of the problem on thermal load regulation.

The development of the thermal schemes of GT CHP is carried out with engineering constraints [9, 20]:

- minimum temperature of a heat carrier at the entrance into the GWHE is 55 ^{o}C;
- heat carrier speed in the tubes of GWHE is between 0.8 and 2.5 m/s.

A minimum temperature of a heat carrier at the entrance into the GWHE is chosen on the basis of the prevention condition of low-temperature corrosion. When firing natural gas, dew-point temperature is ranging from 50 to 60 ^{o}C depending on the excess air coefficient in an exit-gases flow. The decreasing temperature of exit-gases to the dew-point temperature leads to the condensation of sulphuric acid on low-temperature heat absorption surfaces. To avoid the corrosion wear of the material of GWHE, the temperature of in-going heat carrier medium must be more 55 ^{o}C.

The lower limit of water speed in the tubes of GWHE is defined by the creation necessity of developed turbulent flow (Reynolds number Re > 10000), which provides high indicators of heat-transfer coefficients. This condition is observed with water speed not less than 0.8 m/s for applicable tubes diameters [9, 20].

The upper limit of heat carrier medium is confined to device restriction as well as flow-accelerated erosion of tubes material. The tubes of GWHEs are more often made of admiralty brass or steel. The permissible speed of water flow in brass tubes is 2.5 m/s [9, 20].

The most evident and simplest solution to the problem of low-temperature corrosion of heat absorption surfaces of heating GT-CHP is the blending water at the exit from a GWHE to the water at the entrance to a GWHE on the recirculation line (Figure 2).

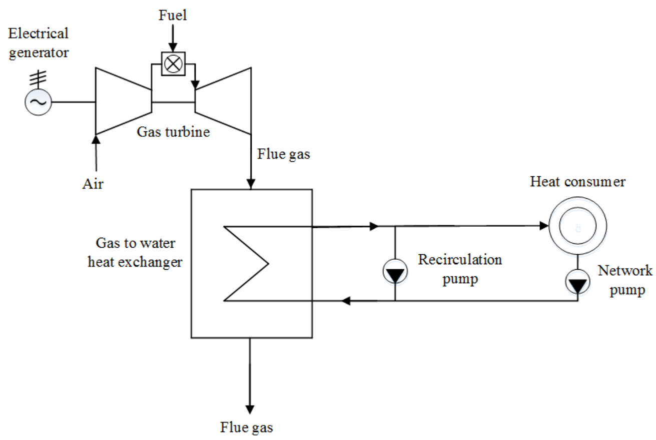

Figure 2: Thermal scheme of GT CHP with recirculation line of GWHE
Source: authors' development based on [9, 20]

The disadvantage of this arrangement is the limited scope of application. In summer period during the work on temperature chart of a district heating 150/70 ^{o}C, the temperature of return delivery water is 40 ^{o}C and heating water temperature is 70 ^{o}C. A demand to provide minimum water temperature at the entrance to a GWHE results in a two-fold increase of heat carrier medium flow. The result of it is non-compliance with heat exchanger hydraulic control.

The classic solution to the problem of low-temperature corrosion of heat absorption surfaces of GWHE is the mounting of an intermediate water-to-water heat exchanger (WWHE) allowing to avoid the entrance of return network water to a GWHE (Figure 3).

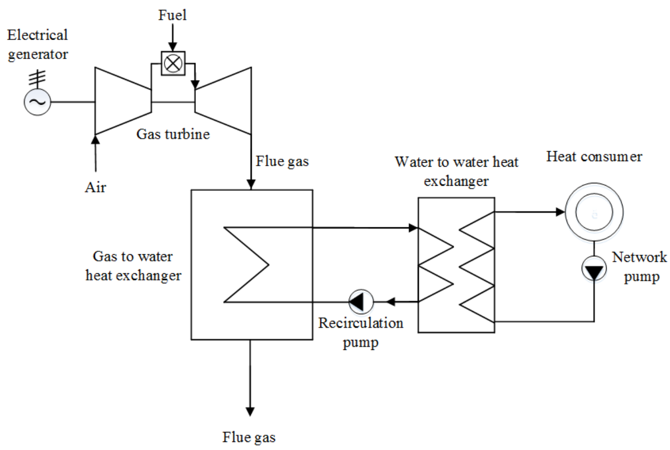

Figure 3: Thermal scheme of GT CHP with intermediate WWHE
Source: authors' development based on [9, 20]

The main disadvantages of this engineering solution are:

- additional year-around power costs on the circulation of a heat carrier medium in the intermediate loop;
- rising capital costs at the expanse of the mounting necessity of an additional heat exchanger and circulating pump.

4 The development of new thermal schemes of heating GT CHP

The main product of a heating CHP is thermal energy. Shortage or surplus of produced electric power during the plan operating in a parallel or synchronous mode can be compensated by power grid. The development of thermal schemes of heating GT CHP is carried out of covering the thermal load chart.

When the generator operates off-line and the consumer does not have any other sources of thermal and electric power, thermal power plant provides variable electric and thermal load charts.

When designing heating GT CHP it is necessary [9, 21]:

- to analyze temperature schedule of district heating and thermal load chart;
- to develop thermal schemes of heating GT CHP within current technology limitations;
- to choose the number of energy blocks on the basis of the need of heat supplied control during the annual thermal chart;
- to choose the additional ways of heat supply regulation;
- to choose applicable gas turbine for the provision of thermal load chart;
- to choose the engineering design points of heat exchangers;
- to settle the engineering designs of heat exchangers;
- to make check calculations of thermal schemes for different outdoor temperatures;
- to verify compliance with technology limitations on a year-on-year basis;
- to define annual energy and financial-economic indicators of GT CHP.

The chart of district heating 150/70 °C was considered as a temperature schedule of a district heating (typical for the Moscow region [14]) (Figure 4).

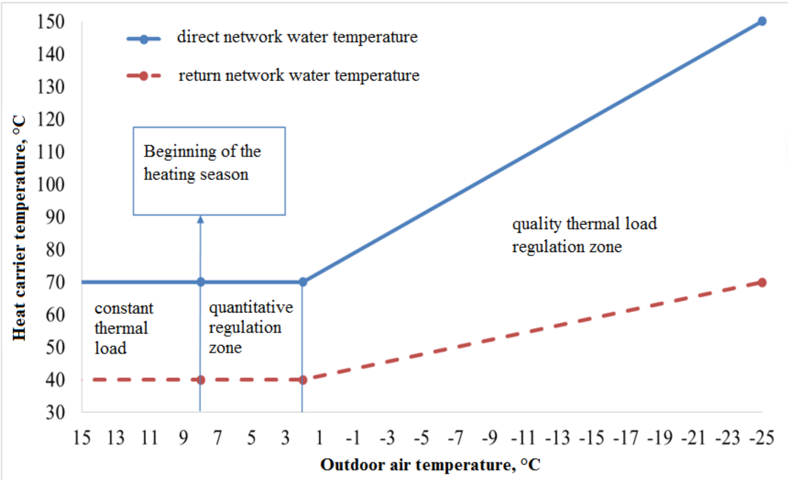

Figure 4: Temperature scheme of district heating 150/70 °C
Source: authors' development based on the data of the Moscow region [14]

Two thermal schemes were developed that allow the combined heat and power plant to increase specific electric energy production on thermal input during the year when working due to district heating chart and thus to decrease the cost of energy product and to improve the competitiveness on the power market.

The difference between two schemes is in the way of heat up of a heating agent, entering to water-to-water heat exchanger:

- at the expense of fuel combustion in hot water boilers (Figure 5);
- at the expense of the heat energy of flue gases, entering dedicated heat-absorption surface of a gas-water heat exchanger (Figure 6). [10]

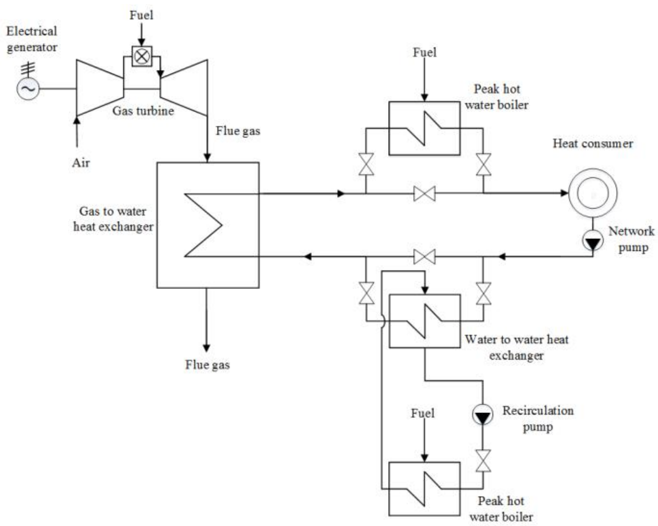

Figure 5: The first thermal scheme of heating GT CHP
Source: authors' development

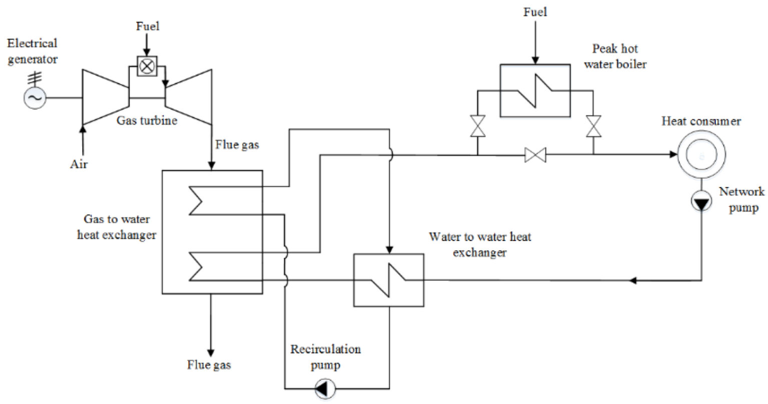

Figure 6: The second thermal scheme of heating GT CHP
Source: authors' development

The main advantage of the first thermal scheme is the possibility to cut off the circuits of the preheating of return delivery water. This possibility allows to decrease annual power costs for own needs. If low outdoor temperatures and the water temperature at the entrance out of a GWHE exceeds minimum permissible level, a WWHE bypasses.

A gas-water heat exchanger of the second scheme consists of two heating surfaces. The first along gas flow thermal characteristic is designed for heat transportation into heat carrier medium circulating in complete circuit of the preheating of return network water. The main advantages of this engineering solution are:

- decrease of power cost for circulating pump at the expense of lower consumption of heat carrier medium circulating in a complete circuit;
- reduction of the area of an intermediate water-to-water heat exchanger.

The comparison of energy effectiveness of the developed thermal schemes of heating GT CHP is made based on the provision temperature schedule for climate conditions common for Moscow region (Figure 4). The ratio of thermal characteristics in non-heating season to the maximum thermal load is accepted as 1:5.

The main characteristics of thermal schemes appear in Table 1.

Table 1: The main characteristics of the developed thermal schemes of heating GT CHP

Characteristics	*Scheme 1*	*Scheme 2*
Number of blocks, units	3	3
Model of a gas turbine	Siemens SGT-400	Rolls Royce Avon-2648
Electrical capacity of CHP netto in design mode, MW	41.2	47.3
Sendout thermal capacity of CHP in design mode, MW	83.4	

Table 1: (Continued): The main characteristics of the developed thermal schemes of heating GT CHP

Engineering design point of gas-water heat exchanger, ºC	*-2.2*	*-2.2*	
Engineering design point of the second along gas flow thermal surface of gas-water heat exchanger, ºC	-	2	25
Peak heat source	Peak hot water boilers		
Way of heat supplied control	Uniform unloading gas turbine and off the number of working units		

Source: authors' development

Engineering designs and check calculations of thermal schemes are made using specialized software "Thermoflow".

5 Comparative study of new thermal schemes of heating GT CHP

It is necessary to develop criteria for making a comparative study of the developed solutions.

The comparison of different thermal schemes of GT CHP operating off-line is made on the condition of the provision of the specified charts of thermal and power base-loads. And economic effectiveness criterion is the annual fuel consumption.

The availability of connection to an external electricity grid allows to release generated on thermal output electric energy. In this case, we can compare the options of thermal schemes on the condition of the provision of thermal base-load chart. The decision criterion is a marginal revenue derived by a generating company on power market.

It is necessary to point out that above-mentioned criteria do not take into consideration investment cost and characterize only production activity of CHP. The final decision on a scheme must be made based on the calculation of such financial-economic indicators as payback time period and net present value.

The informative indicators in the analysis of economic effectiveness of schemes GT CHP are also the following:

1. specific electricity supply, which is equal to the ratio of total quantity of supplied energy and total quantity of supplied heat at CHP per year
2. fuel heat utilization coefficient, which is equal to the ratio of quantity of produced heat and electricity and consumed fuel heat.

The rising annual specific electricity supply with retaining high fuel heat utilization coefficient shows the increase of low-cost electric power supplied for the power market and thus the increase of its marginal revenue.

The offered schemes of GT CHP are characterized of the list of relative economic advantages. High fuel utilization coefficient characterizes the first scheme, which is explained by high efficiency coefficient of peak heat sources.

At the same time, in non-heating season, according to the first scheme, thermal base-load provision is distributed between a gas-water heat exchanger and peak hot water boiler resulting in the decreasing electric/heat output ratio. That is why, annual specific electricity supply in the first scheme will be dramatically lower than in the second one (Table 2).

Table 2: The calculation results of annual economic indicators of thermal schemes of GT CHP

Indicator	*Scheme 1*	*Scheme 2*	
	ver. 1	ver. 2.1	ver. 2.2
Net output electric energy, GWh	195.4	241.0	247.2
Net output thermal energy, ths. Gcal	484.2		
Consumed fuel, mln. nm^3	90.45	102.8	102.5
Number of supplied with fuel heat, ths. GJ	3174	3607	3597
Fuel utilization coefficient, %	86.04	80.26	81.11
Specific electric energy supply, kW/Gcal	403.6	497.7	510.5
Tariff for electric power supply, rubles/kWh	1.6		
Tariff for thermal energy supply, rubles/MWh	780		
Fuel price, rubles/ths. nm^3	4000		
Returns on sold electric power, mln. rubles per year	313.2	386.1	396.2
Returns on sold heat, mln. rubles per year	439.4	439.5	439.6
Total returns on sold electric power and heat, mln. rubles per year	752.7	825.3	835.3
Fuel cost, mln. rubles per year	362.6	411.4	410.2
Marginal revenue, mln. rubles per year	390.7	414.6	425.4

Source: authors' results

Figure 7 presents the dependence of functioning units on outdoor temperature for each of scheme options of GT CHP. The increase in the area of the second along gas flow heat-absorption surface results in the capital cost increase on water-to-water heat exchanger, circulating pump, increasing emissions release and rising cost for own needs. However, in summer period enough heat capacity of this heat-absorption surface is important for providing the requested parameters of heat exchanger while working of specified power-units number.

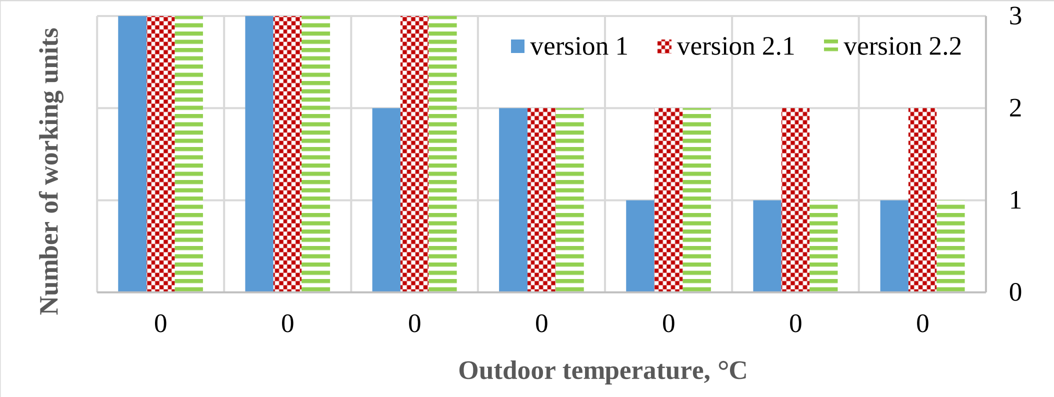

Figure 7: Dependence of the number working units on the outside temperature
Source: authors' results

The most optimal in terms of operation modes of gas turbines is the second scheme of GT CHP in which the area of the second – along the gas direction – heating surface of gas heat exchanger is designed for pre-heating water at outside temperature of 25 °C.

Load of gas turbines in a wide range of investigated outdoor temperature is greater than 60%, which determines the high efficiency of power units, operating on the proposed schemes (Figure 8).

In a second version of the scheme of GT CHP in summer mode two units with a load of 42-43% run. Work of gas turbine with a load close to the minimum has negative impact on efficiency and durability of the machine. The inability to pass on the mode of covering heat output by one gas turbine is explained in this case with the lack of power of the surface of heating the gas-water exchanger.

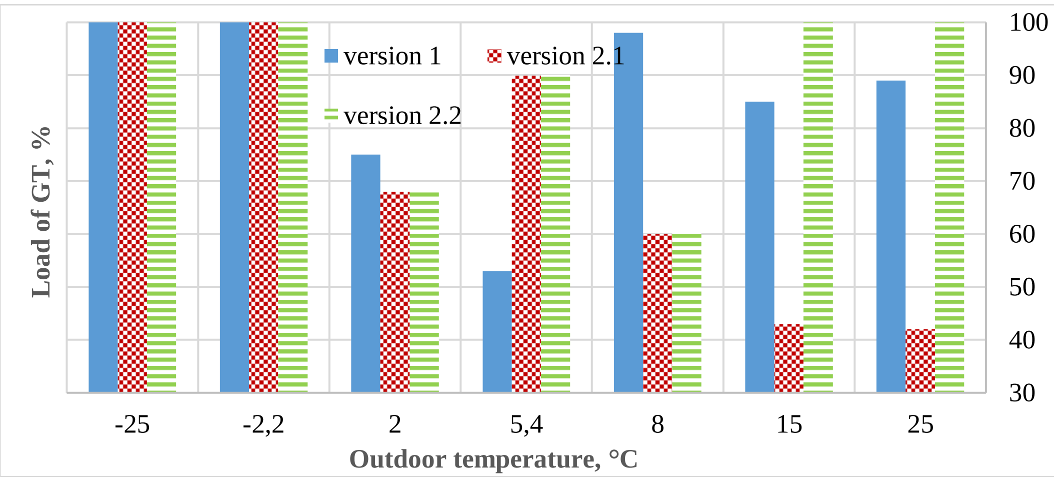

Figure 8: Dependence of the total load of the gas turbine on the outside temperature
Source: authors' results

The temperature of the flue gas in an annual cut is at a relatively low level, which provides a low loss into the environment and high fuel utilization rate (Figure 9).

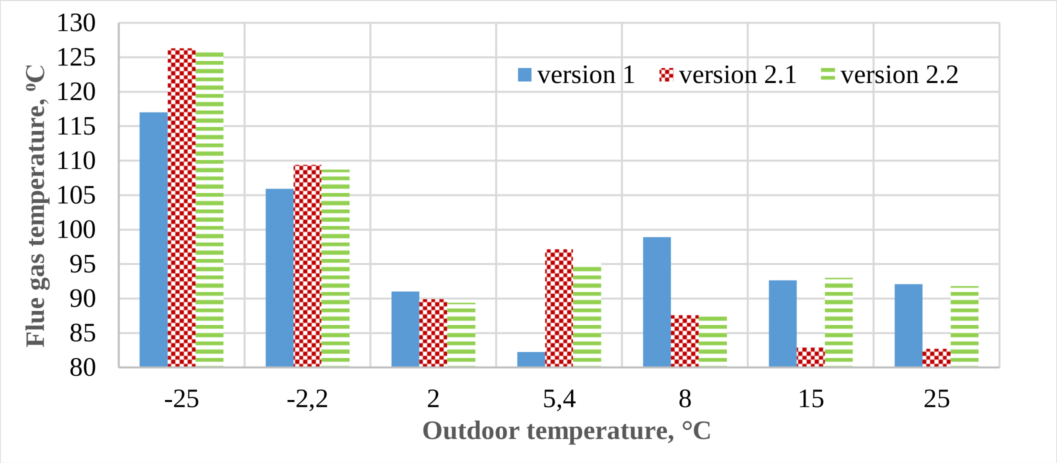

Figure 9: Dependence of the flue gas temperature on the outdoor temperature
Source: authors' results

When the GT CHP works in a mode where the generated electricity is sold on the electricity market, the second version of the power station scheme is the best from a position of indicator of marginal income. This result is associated with a significant power generation at thermal consumption, while maintaining low losses into the environment. Best financial-economic indicators for this scheme are achieved by selecting a version 2.2.

6 Conclusion

The falling power production effectiveness in the united energy system resulting in the increase of energy products tariffs has led to the forming trend of decentralization of electric and thermal power production and the developing distributed generation.

The rising effectiveness of low-powered thermal and mechanical equipment contributed to this trend that has enhanced the relevance of the usage of decentralized sources for cogeneration in a single thermodynamic cycle.

Due to power shortages of the majority of Russia's regions in the context of their ability to supply themselves with own electric power and their high gasification level the opportunities for building GT CHP plants of low and medium power cogeneration units have arisen. These plants are distinguished by high fuel utilization coefficient, the possibility of CHP electricity production, relatively low capital costs and emissions output.

When designing heating GT-CHPs oriented for working on temperature chart of district heating 150/70, there appears a goal to prevent the low temperature corrosion of heating surface during the non-heating season. The blending water at the exit from a GWHE on the recirculation line cannot provide the acceptable parameters of a heat carrier medium in a heat exchanger during the whole year. Heat transportation through an intermediate water-to-water heat exchanger presents high power costs for own needs.

To reduce power cost for own needs, it was offered to form a preheating circuit of delivery water where return delivery one warms up to minimum permissible temperature at the entrance into a gas-water heat exchanger.

There were developed two thermal schemes. The advantage of the first option is the possibility to cut off the circuits of delivery water preheating in the period when the temperature of return delivery water is more than 55 ^{o}C. Furthermore, power costs for own needs reduce. The advantage of the second option is higher indicator of specific electric energy production which can reach 510.5 kW/Gcal.

The paper asserted that offered scheme versions of GT CHP are defined by the list of relative economic advantages. The first scheme is marked by high fuel utilization coefficient. Meanwhile, the net output energy made on heat-end mode is significantly more on the second scheme of GT CHP. This scheme is more appropriate for power plant functioning in market conditions. That allows to increase marginal revenue due to the greater production of cheap electricity on thermal input with retaining low emissions.

Acknowledgements. The reported study was partially supported by the Ministry of Education and Science of the Russian Federation, research project №26.1795.2014/K

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Received: October 2, 2016; Published: November 27, 2016