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SPHERES OF HIGH ENERGY EFFICIENCY OF ENERGY SUPPLY SYSTEMS WITH COGENERATION-HEAT PUMP INSTALLATIONS OF SMALL POWER AND FUEL-FIRED BOILERS IN HEAT SUPPLY SYSTEMS

The approach, aimed at determination of the spheres of high energy efficiency of energy supply systems (ESS) with cogeneration-heat pump installations (CHPI) of small power and fuel-fired boilers (FB) in heat supply systems, on conditions of optimal operation modes of CHPI, with the account of complex impact of variable operation modes, sources of drive energy for steam compressor heat pump installations (HPI) of small power, with the account of energy losses in the process of generation, supply and conversion of electric energy, is suggested.

***Key words**: sphere of high energy efficiency, energy efficiency, energy supply system, cogeneration-heat pump installation, fuel-fired boiler, heat supply system, dimensionless criterion of energy efficiency.*

Introduction

Studies of energy efficient operation modes of energy supply systems with cogeneration-heat pump installations are performed in a number of publications [1 – 13]. Study and assessment of energy efficiency of ESS with peak sources of heat (PSH) and combined CHPI with gas-piston engines-generators (GPE) were performed in [9], efficient operation modes of these ESS were determined, with the account of complex impact of variable operation modes, sources of drive energy for steam compressor HPI of various power levels, with the account of energy losses in the process of generation, supply and conversion of electric energy. In research [10], on the base of the developed methodical fundamentals, the energy efficiency assessment of energy supply systems with combined CHPI and PSH was calculated, on conditions of optimal operation modes of CHPI for heat supply systems, energy efficient operation modes of ESS with CHPI and PSH were determined with the account of complex impact of variable operation modes, sources of drive energy for steam compressor HPI of various power levels, with the account of energy losses in the processes of generation, supply and conversion of electric energy.

In accordance with [9 – 12] optimal distribution of loading between CHPI and PSH (for instance, hot-water fuel-fired boiler, electric boiler, solar collectors, etc.) within ESS greatly determines energy efficiency of these ESS. Such distribution is characterized by the share of CHPI load within ESS β, that is determined as the ratio of thermal capacity of CHPI to thermal capacity of ESS $\beta = Q_{CHPI}/Q_{ESS}$. Optimal values of β index for ESS with different sources of heat for CHPI in case of variable operation modes of thermal grid were determined, proceeding from the analysis of the results of research, carried out [14 – 16].

In research [9] complex assessment of ESS energy efficiency with CHPI and PSH is suggested to the performed, applying complex dimensionless criterion of energy efficiency:

$$K_{ESS} = (1-\beta)\cdot K_{PSH} + \beta \cdot K_{CHPI}, \quad (1)$$

where K_{PSH} – dimensionless criterion of energy efficiency of peak source of heat within ESS (hot-water fuel-fired boiler (FB), electric boiler (EB), solar collectors, etc.), K_{CHPI} – dimensionless criterion of energy efficiency of combined CHPI within ESS from the research [3, 8 – 10].

Dimensionless criterion of energy efficiency of steam compressor HPI with cogeneration drive K_{CHPI}, suggested in the research [3, 8 – 10], was obtained on the base of energy balance equation for the system «Source of drive energy of HPI – HPI – consumer of heat from HPI», with the account of the impact of drive energy sources of steam compressor HPI and with the account of en-

ergy losses in the process of generation, supply and conversion of electric energy to HPI. On condition $K_{CHPI}=1$ combined CHPI transmits to ESS the same thermal capacity as the capacity, that was used for generation of electric energy for HPI drive. The greater is the value of this index, the more efficient and competitive ESS with CHPI will be.

In research [9] spheres of energy efficient operation of CHPI of various power levels are determined. The data are obtained on the base of the research [8] and determined by means of dimensionless criterion of energy efficiency of CHPI K_{CHPI}, depending on real values of HPI coefficient of performance φ_r and GPE efficiency factor η_{EGPE}. Energy efficient operation modes of CHPI correspond to the condition $K_{CHPI} > 1$. High values of dimensionless criterion of energy efficiency for ESS with CHPI, obtained in [9], affirm high energy efficiency of such combined systems of energy supply.

Dimensionless criterion of energy efficiency of peak source of heat– hot-water fuel-fired boiler – within ESS K_{PSH}, according to [9], is obtained on the base of energy balance equation for the systems «Sources of electric energy and fuel – fuel-fired boiler – heat consumer from ESS» with the account of energy sources impact for peak fuel-fired boiler and with the account of energy losses in the process of generation and supply of electric energy to the boiler (boiler house). It is determined in research [10], that energy efficiency of ESS with CHPI and peak fuel-fired boilers can exceed almost two times energy efficiency of modern high efficient electric and fuel-fired boilers for operation in heat supply systems.

In research [11] on conditions $K_{CHPI} > 1$ and $K_{ESS} > \eta_{FB}$ and CHPI energy efficient operation modes, spheres of energy efficient operation and energy efficient modes of operation of ESS with CHPI and peak fuel-fired boilers for various power levels and energy efficiency of ESS elements are determined. It is determined, that ESS with CHPI and peak fuel-fired boilers, suggested in research [11], will be energy efficient, if the share of CHPI loading in ESS is $\beta > 0{,}4$. Under such condition these ESS could be recommended as energy efficient energy supply systems.

For energy efficient operation modes of CHPI in ESS and if $K_{CHPI} > 1$ and $K_{ESS} > \eta_{FB}$ in research [12] spheres of energy efficient operation and energy efficient operation modes of ESS with CHPI and peak fuel-fired boilers in heat supply systems are determined for various different levels of power and energy efficiency of ESS elements.

In papers [1 – 13] the authors did not determine the spheres of high energy efficiency of energy supply systems with CHPI of small power and FB in heat supply systems, on conditions of optimal operation modes of CHPI, with the account of complex impact of variable operation modes, sources of drive energy for steam compressor HPI of small power, with the account of energy losses in the process of generation, supply and conversion of electric energy.

The objective of the research is determination of the spheres of high energy efficiency of energy supply systems with CHPI of small power and FB in heat supply systems, on conditions of optimal operation modes of CHPI, determination of high efficient operation modes of ESS with CHPI of small power and FB with the account of complex impact of variable operation modes, sources of drive energy for steam compressor HPI of small power, with the account of energy losses in the process of generation, supply and conversion of electric energy.

Main part

The research contains the assessment of high efficient operation modes of energy supply systems with cogeneration-heat pump installations of small power and fuel-fired boilers in the process of operation in heat supply systems. Energy efficiency of energy supply systems with steam compressor HPI of small power (up to 1 MW) with cogeneration drive from gas-piston engine-generator was studied. Fuel-fired boilers were provided to be used as peak sources of heat in ESS. Investigated ESS with combined CHPI and FB can completely or partially provide auxiliary needs in electric

energy and provide the consumers needs in heating and hot water supply. Schemes of the energy supply systems with combined CHPI of small power and FB are shown in research [1, 17]. Methodical fundamentals of energy efficiency assessment of ESS with CHPI and FB for heat supply systems are presented in the research [10, 12].

Spheres of high energy efficiency of ESS with CHPI of small power and peak FB for heat supply could be defined from the dependences, suggested in the research [12], on conditions $K_{CHPI} > 1$ and $K_{ESS} > 1$ for energy efficient operation modes of CHPI and ESS. Under these conditions the above-mentioned ESS could be recommended as high efficient energy supply systems that could be competitive with modern high efficient electric and fuel-fired boilers in heat supply and energy supply systems. In our research spheres of high energy efficiency of ESS with CHPI of small power and FB for heat supply systems are defined on conditions of optimal operation modes of CHPI on the base of the research performed [8 – 12].

The suggested approach, aimed at determination of the spheres of high energy efficiency of ESS with CHPI of small power and FB for heat supply systems has a number of advantages:

— it takes into account variable operation modes of ESS for heat supply during the whole year with the change of load distribution among steam compressor CHPI of small power and peak fuel-fired boilers in ESS;

— it enables to determine the areas and modes of high energy efficiency of ESS with CHPI of small power and peak fuel-fired boilers for heat supply, at which energy efficiency of the investigated ESS considerably exceeds energy efficiency of modern high efficient electric and fuel-fired boilers;

— methodical fundamentals, suggested in [9, 10, 12], and results of the research, given in this paper can be used for determination of high energy efficiency areas of ESS with FB and steam compressor CHPI of small power with different refrigerants, sources of low temperature heat and scheme solutions in heat supply systems;

— it enables to develop recommendations, concerning high efficient operation of ESS with CHPI of small power and FB with different scheme solutions for heat supply systems.

Application of the suggested approaches, aimed at determination of high energy efficiency spheres of ESS with CHPI of small power and FB for heat supply systems we will demonstrate on the specific examples.

Figs. 1 – 2 show the results of research, aimed at determination of high energy efficiency areas of ESS with CHPI of small power and peak FB in heat supply systems for the cases of variable load of CHPI within ESS and optimal values of CHPI loading share β for energy efficient operation modes of CHPI on the base of research results [8 – 12]. The values of the dimensionless criterion of energy efficiency of ESS with CHPI of small power and peak FB for the cases of seasonal variable loading of CHPI within ESS is studied for optimal values of CHPI loading share the range of $\beta = 0{,}16\ldots0{,}63$ [14 – 16], that corresponds to temperature modes of heat supply systems operation. The research is performed for energy efficient operation modes of CHPI with $K_{CHPI} = 1{,}1\ldots2{,}1$ (on conditions of maximum efficiency of GPE) and with $K_{CHPI} = 1{,}1\ldots1{,}6$ (on conditions of minimum efficiency of GPE), on the base of the research results [8 – 9]. The above-mentioned values of energy efficiency criteria of CHPI K_{CHPI} correspond to the values of real coefficient of performance of CHPI within the limits of $\varphi_r = 3{,}0\ldots5{,}4$ for CHPI of small power, in accordance with [9]. On conditions of $K_{CHPI} > 1$ and $K_{ESS} > 1$ dependences, suggested in the given research, determine the spheres of high energy efficiency of the studied ESS for operation in heat supply systems.

Fig. 1 shows the sphere of high energy efficiency of ESS with CHPI of small power and peak fuel-fired boiler for heat supply, on conditions of minimal efficiency of GPE and FB. In the given research, according to [3, 8], the following values are taken into account: value of efficiency factor of GPE $\eta_{EGPE} = 0{,}31$ and value of efficiency factor of electric motor with the account of energy

losses in the control unit of the motor $\eta_{ED} = 0{,}8$. In these conditions fuel-fired boiler house with $\eta_{FB} = 0{,}8$ is provided to be peak source of heat in ESS. Value of dimensionless criterion of energy efficiency of fuel-fired boiler will be $K_{PSH}^{FB} = 0{,}8$. Values of complex dimensionless criterion of ESS energy efficiency for the investigated high efficient operation modes of ESS for heat supply systems is $K_{ESS} = 1{,}01...1{,}304$ on condition of $\beta = 0{,}421\ldots0{,}63$ and may be $K_{ESS} = 1{,}6$ [10 – 11] on condition of $\beta = 1$.

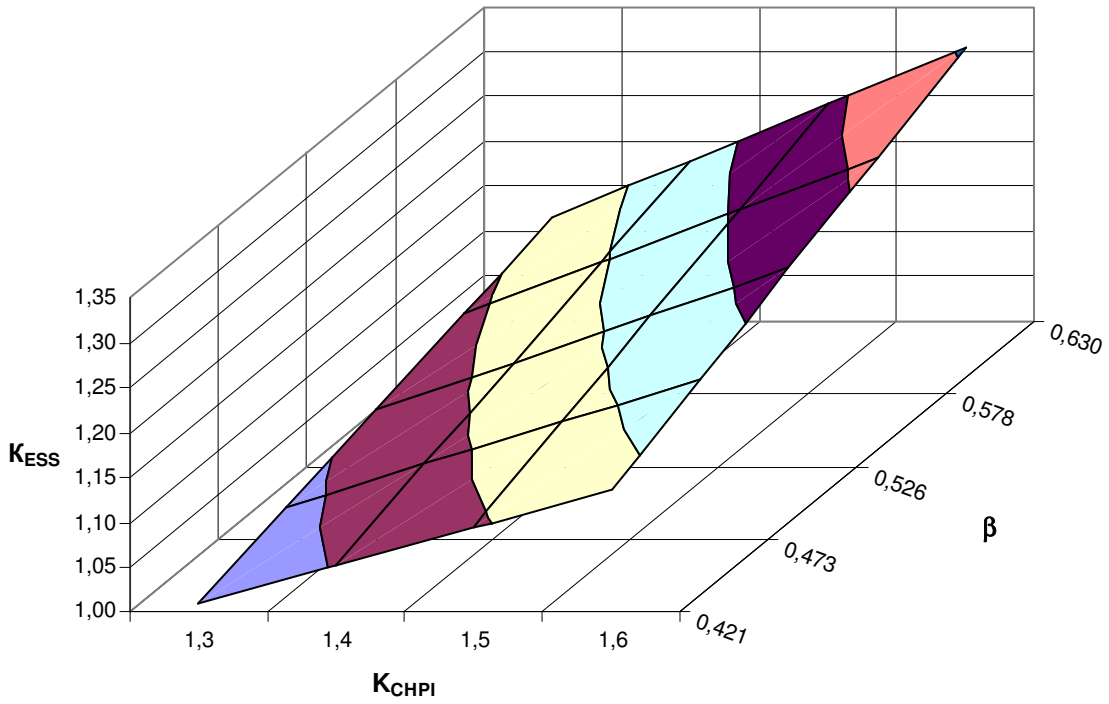

Fig. 1. Area of high energy efficiency of ESS with CHPI of small power for heat supply, on conditions of minimal efficiency of GPE and peak fuel-fired boiler

As it is seen from Fig. 1, the values of complex dimensionless criterion of ESS energy efficiency are $K_{ESS} = 1{,}01...1{,}115$ on condition of minimal value of energy efficiency criterion of CHPI $K_{CHPI} = 1{,}3$; for ESS with $K_{CHPI} > 1{,}3$ operation modes, values of ESS dimensionless criterion of energy efficiency change within the range $K_{ESS} = 1{,}053...1{,}304$. High energy efficiency modes of these ESS are provided on conditions of energy efficient operation modes of CHPI with the values of energy efficiency index of $K_{CHPI} = 1{,}3...1{,}6$.

Fig. 2 shows the area of high energy efficiency of ESS with CHPI of small power and peak fuel-fired boiler for heat supply, on conditions of maximum efficiency of GPE and FB. In the given research, according to [3, 8], the following values are taken into account: value of GPE efficiency factor $\eta_{EGPE} = 0{,}42$ and value of electric motor efficiency factor with the account of energy losses in the control unit of the motor $\eta_{ED} = 0{,}8$. Fuel-fired boiler house with $\eta_{FB} = 0{,}9$ is provided to be peak source of heat in ESS for these conditions. The value of dimensionless criterion of energy efficiency of fuel-fired boiler will be $K_{PSH}^{FB} = 0{,}9$. For the studied operation modes of ESS for heat supply systems, values of the complex dimensionless criterion of ESS energy efficiency are $K_{ESS} = 1{,}01...1{,}656$ on condition of $\beta = 0{,}264\ldots0{,}63$ and could be $K_{ESS} = 2{,}1$ [9] on condition of $\beta = 1$.

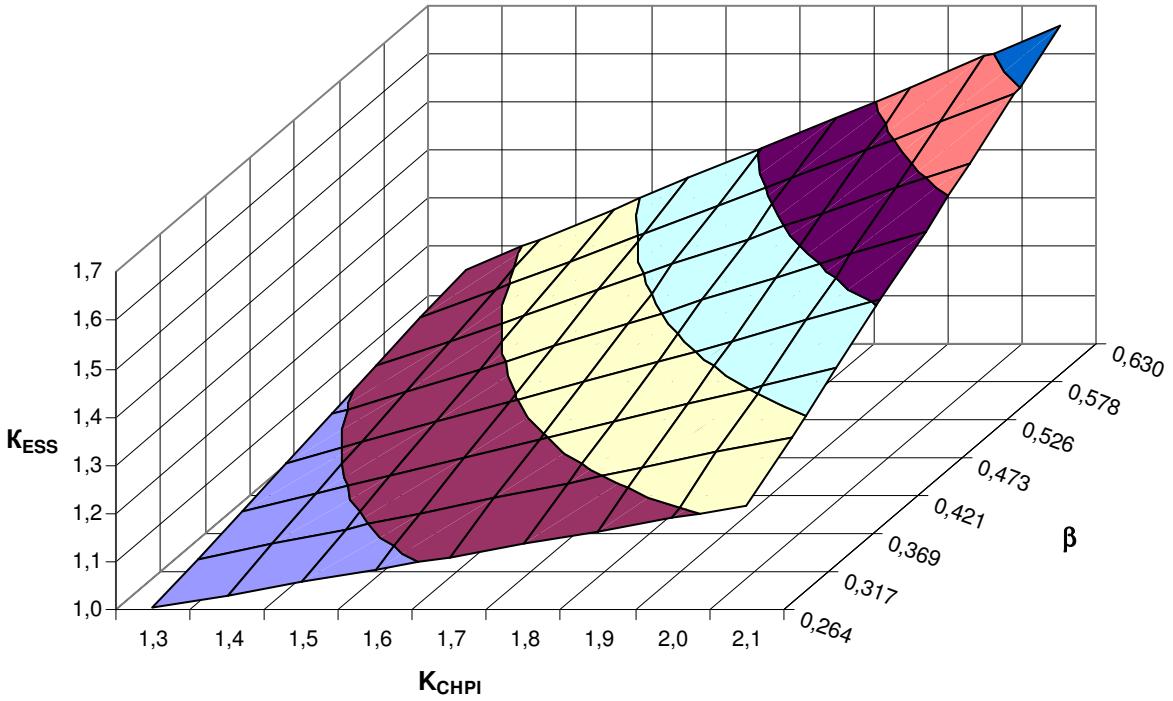

Fig. 2. Area of high energy efficiency of ESS with CHPI of small power for heat supply, on conditions of maximum efficiency of GPE and peak fuel-fired boiler

As it is seen from Fig. 2, the values of complex dimensionless criterion of ESS energy efficiency are $K_{ESS} = 1{,}01...1{,}152$ on condition of minimal value of energy efficiency criterion of CHPI $K_{CHPI} = 1{,}3$; for ESS operation modes with $K_{CHPI} > 1{,}3$, the values of dimensionless criterion of ESS energy efficiency changes within the limits $K_{ESS} = 1{,}032...1{,}656$. High energy efficiency modes of these ESS are provided on conditions of energy efficient operation modes of CHPI with the values of energy efficiency index of $K_{CHPI} = 1{,}3...2{,}1$.

It should be noted, that the dependences, shown in Figs. 1 – 2, are obtained for energy efficient operation modes of CHPI on the base of the results of the research [8 – 12].

Dependence, shown in Fig. 1 determine the area of high energy efficiency of ESS with CHPI of small power and peak fuel-fired boiler (boiler house) for heat supply, on conditions of minimal efficiency of GPE and fuel-fired boiler (boiler house). On conditions of $\beta = 0{,}421…0{,}63$ and $K_{CHPI} = 1{,}3...1{,}6$ these ESS can be recommended as high efficient energy supply systems, as their efficiency is almost one and a half times exceeds energy efficiency of high efficient electric and fuel-fired boilers.

Dependence, shown in Fig. 2, determines the area of high energy efficiency of ESS with CHPI of small power and peak fuel-fired boiler (boiler house) for heat supply, on conditions of maximum efficiency of GPE and fuel-fired boiler (boiler house). On conditions of $\beta = 0{,}264…0{,}63$ and $K_{CHPI} = 1{,}3...2{,}1$ these ESS can be recommended as high efficient energy supply systems, as their efficiency is more than one and half times exceeds energy efficiency of high efficient electric and fuel-fired boilers. Studied ESS can be competitive with modern high efficient electric and fuel-fired boilers in heat supply and energy supply systems.

In the research [10] it is determined, that the investigated ESS with CHPI and peak fuel-fired boilers will be high efficient in heat supply systems, if the share of CHPI loading in ESS is $\beta > 0{,}4$; that corresponds to the results of research, shown in Figs. 1 – 2. In research [12] it is determined, that on conditions of maximum efficiency of GPE and fuel-fired boiler, the investigated ESS with

CHPI and peak fuel-fired boilers will be energy efficient if the share of CHPI loading in ESS is $\beta > 0{,}16\ldots0{,}26$, depending on the level of CHPI power. On condition of minimal efficiency of GPE and fuel-fired boiler, ESS with CHPI and fuel-fired boilers, studied in [12], will be energy efficient, if the share of CHPI loading in ESS is $\beta > 0{,}32\ldots0{,}37$, depending on the level of CHPI power.

In our research it is determined that on conditions of maximum efficiency of GPE and fuel-fired boiler investigated ESS with CHPI of small power and peak fuel-fired boilers will provide high energy efficiency, if the share of CHPI loading in ESS is $\beta > 0{,}264$. On conditions of minimal efficiency of GPE and fuel-fired boiler, investigated ESS with CHPI of small power and peak fuel-fired boilers will provide high energy efficiency, if the share of CHPI loading in ESS is $\beta > 0{,}421$.

The suggested approaches, aimed at determination of the spheres of high energy efficiency of ESS with CHPI of small power and FB in heat supply systems enable to determine high efficient operation modes of the given ESS, with the account of complex impact of variable operation modes, sources of drive energy for steam compressor CHPI of small power, with the account of energy losses in the process of generation, supply and conversion of electric energy.

Scientific results, regarding to determination of the spheres of ESS high energy efficiency, obtained in the paper, enable to elaborate recommendations, concerning high efficient operation of ESS with CHPI of small power and peak FB with different scheme solutions for operation in heat supply systems. In order to determine spheres of high energy efficiency for different variants of ESS with CHPI of small power and FB for heat supply systems, besides the above-mentioned approaches, we suggest using the results of previous research [1 – 16].

Conclusions

Spheres of high energy efficiency of energy supply systems with CHPI of small power and fuel-fired boilers in heat supply systems are determined, on conditions of optimal operation modes of CHPI, high efficiency operation modes of ESS with CHPI of small power and fuel-fired boilers are determined, with the account of complex impact of variable operation modes, sources of drive energy of steam compressor HPI of small power, with the account of energy losses in the process of generation, supply and conversion of electric energy.

The suggested approach, aimed at determination of the spheres of high energy efficiency of ESS with CHPI of small power and FB for heat supply systems has a number of advantages:

— it takes into account variable operation modes of ESS for heat supply during the whole year with the change of load distribution between steam compressor CHPI of small power and peak fuel-fired boilers in ESS;

— it enables to determine the spheres and modes of high energy efficiency of ESS with CHPI of small power and peak fuel-fired boilers for heat supply, at which energy efficiency of the investigated ESS considerably exceeds energy efficiency of modern high efficient electric and fuel-fired boilers;

— methodical fundamentals, suggested in [9, 10, 12], and results of the research, proposed in the given research, may be used for determination of the spheres of high energy efficiency of ESS with FB and steam compressor CHPI of small power with different refrigerants, sources of low temperature heat and scheme solutions in heat supply systems;

— it enables to develop recommendations, concerning high efficient operation of ESS with CHPI of small power and FB with different scheme solutions for heat supply systems.

Spheres of high energy efficiency of ESS with CHPI of small power and peak FB in heat supply systems in our research are determined for energy efficient operation modes of CHPI in ESS and on conditions of $K_{CHPI} > 1$ and $K_{ESS} > 1$ for various levels of energy efficiency of ESS elements.

On conditions of minimal efficiency of GPE and fuel-fired boiler (boiler house) the area of high energy efficiency of ESS with CHPI of small power and peak fuel-fired boiler (boiler house) for heat supply was determined, it corresponds to high efficient operation modes of ESS with CHPI

with $\beta = 0{,}421\ldots0{,}63$ and $K_{CHPI} = 1{,}3\ldots1{,}6$. The above-mentioned ESS can be recommended as high efficient systems of energy supply, as their efficiency is almost one and a half times exceeds energy efficiency of high efficient electric and fuel-fired boilers.

On conditions of maximum efficiency of GPE and fuel-fired boiler (boiler house) the spheres of high energy efficiency of ESS with CHPI of small power and peak fuel-fired boiler (boiler house) for heat supply is determined, it corresponds to high efficient operation modes of ESS with CHPI with $\beta = 0{,}264\ldots0{,}63$ and $K_{CHPI} = 1{,}3\ldots2{,}1$. The above-mentioned ESS can be recommended as high efficient energy supply systems, as their efficiency is more than one and a half times exceeds energy efficiency of high efficient electric and fuel-fired boilers. The investigated ESS can be competitive with modern high efficient electric and fuel-fired boilers in heat supply and energy supply systems.

It is determined, that:

— on conditions of maximum efficiency of GPE and fuel-fired boiler, the investigated ESS with CHPI of small power and peak fuel-fired boilers will provide high energy efficiency, if the share of CHPI loading in ESS will be $\beta > 0{,}264$;

— on conditions of minimal efficiency of GPE and fuel-fired boiler, the investigated ESS with CHPI of small power and peak fuel-fired boilers will provide high energy efficiency, if the share of CHPI loading in ESS is $\beta > 0{,}421$.

The suggested approaches, aimed at determination of the spheres of high energy efficiency of ESS with CHPI of small power and FB in heat supply systems enable to determine high efficient operation modes of the above-mentioned ESS, with the account of complex impact of variable operation modes, sources of drive energy for steam compressor CHPI of small power, with the account of energy losses in the process of generation, supply and conversion of electric energy.

Scientific results, regarding the determination of the spheres of high energy efficiency of ESS, obtained in the paper, enable to develop recommendations, concerning high efficient operation of ESS with CHPI of small power and peak FB with different scheme solutions in the process of operation in heat supply systems. To determine the spheres of high energy efficiency for different variants of ESS with CHPI of small power and FB for heat supply systems, besides the above-mentioned approaches, we suggest to use the results from previous research [1 – 16].

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