O. P. Ostapenko, Cand. Sc. (Eng.), Assist. Professor

SPHERES OF ENERGY EFFICIENT OPERATION OF ENERGY SUPPLY SYSTEMS WITH COGENERATION-HEAT PUMP INSTALLATIONS AND PEAK SOURCES OF HEAT

The approach, aimed at determination of the spheres of energy efficient operation of energy supply systems (ESS) with cogeneration heat pump installations (CHPI) and peak sources of heat (PSH), on conditions of optimal operation modes of CHPI, taking into consideration complex impact of variable operation modes, sources of drive energy for steam compressor heat pump installations (HPI) of various power levels, with the account of energy losses in the process of generation, supply and conversion of electric energy, is suggested.

Key words*: sphere of energy efficient operation, energy efficiency, energy supply system, cogeneration heat pump installation, peak source of heat, heat supply system, dimensionless criterion of energy efficiency.*

Introduction

The results of research, aimed at determination of energy efficient operation modes of energy supply systems with cogeneration heat pump installations are presented in a number of publications [1 – 12]. In research [5 – 6] energy advantages are evaluated and efficient real operation modes of HPI with electric and cogeneration drives are determined, with the account of the impact of drive energy sources of steam compressor heat pumps and energy losses in the process of generation, supply and conversion of electric energy to HPI. In research [7 – 8] methodical fundamentals of comprehensive assessment of energy efficiency of steam compressor heat pump plants (HPP) with electric and cogeneration drives, with the account of complex impact of HPP variable operation modes, peak sources of heat of HPP, sources of HPP drive energy and with the account of energy losses in the process of generation, supply and conversion of electric energy are suggested. In [8 – 9] scientific fundamentals are suggested and comprehensive assessment of energy efficiency of steam compressor HPP with cogeneration drive with the account of complex impact of HPP variable operation modes, HPP peak sources of heat, sources of drive energy of steam compressor HPP of various power levels, with the account of energy losses in the process of generation, supply and conversion of electric energy is performed. In research [10] the assessment of ESS energy efficiency on the base of combined CHPI are realized, efficient operation modes of ESS with the account of complex impact of variable operation modes, sources of drive energy of steam compressor HPI of various power levels, with the account of energy losses in the processes of generation, supply and conversion of electric energy are determined. In research [11] energy efficiency of ESS, based on combined CHPI and PSH is evaluated, efficient operation modes of these ESS 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 are determined. In research [12] methodical fundamentals are developed, assessment of energy efficiency of energy supply systems with combined CHPI and PSH, on conditions of optimal operation modes of CHPI for heat supply systems is performed, energy efficient operation modes of ESS with CHPI and PSH 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, is performed.

In accordance with [11 – 12], optimal distribution of loading between CHPI and PSH (for instance, hot-water fuel-fired boiler, electric boiler, solar collectors, etc.) within the frame of ESS largely determines energy efficiency of the above-mentioned ESS. Such distribution is characterized by the share of CHPI loading within the frame of ESS β, that is determined as the ratio of thermal capacity of CHPI to thermal capacity of ESS $\beta = Q_{CHPI}/Q_{ESS}$. The value of CHPI thermal capacity is determined with the account of utilization equipment capacity of cogeneration drive and is $Q_{CHPI} = Q_c + \Sigma Q_{ut}$, where Q_c – capacity of HPI condenser, ΣQ_{ut} – capacity of utilization equipment of HPI cogeneration drive.

In the paper [11] it is suggested to realize comprehensive assessment of ESS with CHPI and PSH energy efficiency by 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 combined CHPI within ESS energy efficiency.

In research [5, 10 – 11] dimensionless criterion of energy efficiency of steam compressor HPI with cogeneration drive K_{CHPI} was suggested. This criterion is obtained on the base of energy balance equation for the system «Source of drive energy of HPI – HPI – heat consumer from HPI», with the account the impact of drive energy sources of steam compressor HPI and with the account of energy losses in the process of generation, supply and conversion of electric energy to HPI. With the account of such approach, dimensionless criterion of energy efficiency of combined CHPI, in accordance with [5, 10] has the following form:

$$K_{CHPI} = Q_{CHPI}/Q_h = \eta_{EGPE}\cdot\eta_{ED}\cdot\varphi^{CHPI}\cdot\eta_{hf}, \quad (2)$$

where Q_h – power, spent by gas-piston engine-generator (GPE) for generation of electric energy for HPI drive, η_{EGPE} – efficient factor of gas-piston engine; η_{ED} – efficiency factor of electric motor with the account energy losses in motor control unit from [5], φ^{CHPI} – real coefficient of performance of CHPI from the research [10], that is determined as: $\varphi^{CHPI} = (\varphi_t + K^h_{GPE})\cdot\eta_{hp}$, where φ_t – theoretical value of the coefficient of performance of HPI, without the account of the power of utilization equipment of GPE; K^h_{GPE} –thermal coefficient of GPE, that equals the ratio of thermal utilization capacity of GPE to its electric power; η_{hp} – energy efficiency of HPI, that takes into account all losses of energy in heat pump from [5 – 6]; η_{hf} – efficiency factor of the heat flow, that takes into consideration losses of energy and working substance in pipe lines and equipment of HPI.

On condition $K_{CHPI} = 1$ combined CHPI transfers to the ESS the same thermal power 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 [11] spheres of energy efficiency operation of CHPI of various power levels, obtained on the base of the research [10] and determined and defined by CHPI energy efficiency dimensionless criterion K_{CHPI}, depending on real values of HPI coefficient of performance φ_r and efficient factor of GPE η_{EGPE}. Energy efficient operation modes of CHPI correspond to the condition $K_{CHPI} > 1$. High values of energy efficiency dimensionless criterion for ESS with CHPI, obtained in [11], confirm high energy efficiency of such combined energy supply systems.

Dimensionless criterion of energy efficiency of peak source of heat – electric boiler –within ESS K_{PSH}, according to [11], obtained on the base of energy balance equation for the systems «Source of electric energy – electric boiler – heat consumer from ESS», with the account the impact of the energy sources for peak electric boiler and with the account of energy losses in the process of generation and supply of electric energy to electric boiler. In research [11] assessment of energy efficiency of peak electric boiler in ESS, in case of electric energy usage from CHPI and for the cases of electric energy consumption from energy system, based on conventional or alternative sources of electric energy on the base of steam-gas installations, gas-turbine installations, solar power plants of thermodynamic cycle, wind energy plants is carried out.

Dimensionless criterion of energy efficiency of peak source of heat – hot-water fuel-fired boiler – within ESS K_{PSH}, according to [11], 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 the impact of the energy sources 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). In this case, consumption of electric energy by peak source of heat in ESS – fuel-fired boiler – is not directly connected with the process of heat generation in the boiler and the share of electric energy consumption for auxiliary needs is not great, that is why, it does not greatly influence the value of K_{PSH} index.

In research [11] it is noted, that in case of usage of the alternative peak sources of heat in ESS (for instance, solar collectors for ESS of small power) the value of dimensionless criterion of energy efficiency of peak source of heat for ESS K_{PSH} will equal the efficiency of the alternative peak source of heat η_{APSH} or the efficiency of additional system with alternative peak source of heat η^{s}_{APSH}.

From the research [11] it is determined, that for the cases of $K_{CHPI} < K_{PSH}$ the value of dimensionless criterion of ESS K_{ESS} energy efficiency will decrease with the increase of the share of CHPI β load. For other cases the value of dimensionless criterion of ESS K_{ESS} energy efficiency will increase with the growth of the share of CHPI β loading. In research [11 – 12] it is noted that complex dimensionless criterion of energy efficiency of ESS K_{ESS} from the formula (1) could be used for the selection of the most efficient peak source of heat for certain type of ESS and efficient operation modes of ESS.

ESS with CHPI and peak electric boilers, suggested in [12], will be energy efficient in heat supply systems, if the share of CHPI loading in ESS will be $\beta > 0{,}4$. On such condition modern high efficient electric and fuel-fired boilers would be inferior by energy efficiency to the above-mentioned ESS. In [12] it is determined that energy efficiency of ESS with CHPI and peak fuel-fired boilers almost two times exceeds the energy efficiency of modern high efficient electric and fuel-fired boilers, intended for operation in heat supply systems.

In [1 – 12] the authors did not determine the areas of energy efficient operation of energy supply systems with combined CHPI and PSH on conditions of optimal operation modes of CHPI, with the account of complex impact of variable operation modes, sources of drive energy of steam compressor HPI of various power levels, with the account of energy losses in the process of generation, supply and conversion of electric energy.

Aim of the research is the determination of the areas of energy efficient operation of energy supply systems with combined CHPI and PSH on conditions of optimal operation modes of CHPI, determination of energy efficient operation modes of ESS with CHPI and PSH with the account of complex impact of variable operation modes, sources of drive energy of steam compressor HPI of various power levels, with the account of energy losses in the process of generation, supply and conversion of electric energy.

Main part

The research contains the evaluation of energy efficient operation modes of energy supply systems with combined cogeneration heat pump installations and peak sources of heat. Energy efficiency of energy supply systems with steam compressor HPI of small (up to 1 MW) and large power with cogeneration drive from gas-piston engine-generator was studied. Electric and fuel-fired boilers were provided to be used as peak sources of heat in ESS (fuel-fired boiler houses of ESS of large power). The investigated ESS with combined CHPI and PSH 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 and PSH are presented in works [1, 13].

In our research the energy efficiency of the system «Source of drive energy of CHPI – ESS with CHPI and PSH – consumer of the heat from ESS» is analyzed on the example of ESS with steam compressor CHPI and PSH. The advantage of this approach is the account of energy losses in the process of generation, supply and conversion of electric energy in CHPI and PSH in order to determine energy efficiency of ESS operation modes. Methodical fundamentals of energy efficiency evaluation of ESS with CHPI and PSH are given in research [11].

Areas of energy efficient operation of ESS with CHPI and PSH can be determined from the dependences, suggested in the research [11-12], on conditions of $K_{CHPI} > 1$ and $K_{ESS} > \eta_{FB}$ (or $K_{ESS} > \eta_{EB}$) [11]. If the above-mentioned conditions are realized, the investigated ESS with CHPI and PSH can be recommended as high efficient energy supply systems that can be competitive with modern high-efficient electric and fuel-fired boilers in heat supply and energy supply systems.

In our study the areas of energy efficient operation of ESS with combined CHPI and PSH are defined on conditions of optimal operation modes of CHPI on the base of the research, carried out [10-11].

The suggested approach, aimed at determination of the areas of energy efficient operation of ESS with CHPI and PSH has a number of advantages:

— it takes into consideration variable operation modes of ESS with the change of loading share between steam compressor CHPI and peak source of heat in ESS;

— it enables to evaluate the complex impact of variable operation modes of ESS, peak sources of ESS heat, sources of drive energy of steam compressor CHPI with the account of energy losses in the process of generation, supply and conversion of electric energy;

— it takes into consideration the impact of drive energy sources of steam compressor CHPI of various power levels, with the account of energy losses in the process of generation, supply and conversion of electric energy in CHPI and ESS;

— it takes into consideration the impact of peak sources of heat for ESS and type of the energy, consumed by them, with the account of energy losses in the process of generation and supply of energy to peak sources of heat;

— as a result of complex approach to ESS energy efficiency assessment the selection of the most efficient PSH for certain type of ESS can be made;

— methodical fundamentals, suggested in [11], and the results of research, presented in the given paper can be used for the determination of the areas of energy efficient operation of ESS on the base of steam compressor CHPI with various refrigerants, sources of low temperature heat and scheme solutions;

— it enables to determine areas and modes of energy efficient operation of ESS with CHPI and PSH, at which energy efficiency of the investigated ESS exceeds almost two times energy efficiency of modern high energy efficient electric and fuel-fired boilers;

— it enables to evaluate comprehensively energy efficiency of numerous versions of ESS with CHPI and PSH;

— it enables to develop recommendations on energy efficient operation of ESS with CHPI and PSH with different scheme solutions.

Application of the suggested approaches, aimed at determination of the areas of ESS with CHPI and PSH energy efficient operation will be demonstrated on the specific examples.

Figs. 1 – 7 show the results of research, aimed at determination of the areas of energy efficient operation of ESS with CHPI and PSH for energy efficient operation modes of CHPI, based on the results of the studies [10 – 11]. The values of dimensionless criterion of ESS with CHPI and PSH energy efficiency for the cases of variable loading of CHPI within ESS on condition of CHPI share change within the range β = 0,1…1,0 are shown. The research is carried out for energy efficient operation modes of CHPI with K_{CHPI} =1,1…2,1 (on conditions of maximum efficiency of GPE) and with K_{CHPI} =1,1…1,6 (on conditions of minimum efficiency of GPE), based on the results of the studies [10-11]. The above-mentioned values of CHPI K_{CHPI} energy efficiency criterion correspond to the values of real coefficient of performance of CHPI within the limits of φ_r = 3,0…5,4 for CHPI of small power and φ_r = 2,7…5,4 for CHPI of large power, according to [11].

Fig. 1 shows the area of energy efficient operation of ESS with CHPI of small power and PSH, on condition of electric energy consumption by peak source of heat (electric boiler) from energy system of Ukraine. In the given research, according to [5], the following values are taken into account: averaged value of the efficiency factor of Ukrainian electric power plants η_{EPP} = 0,383 and efficiency factor value of distributive electric grids in Ukraine η_{DG} = 0,875. In these conditions, electric boiler house with η_{EB} = 0,95 is provided to be peak source of heat in ESS. It should be noted, that in case of electric boiler efficiency change in the range η_{EB} = 0,9…0,95 the value of dimensionless criterion of electric boiler energy efficiency for the cases of electric energy consumption from energy system will be $K_{PSH}^{ES} = 0,302...0,318$.

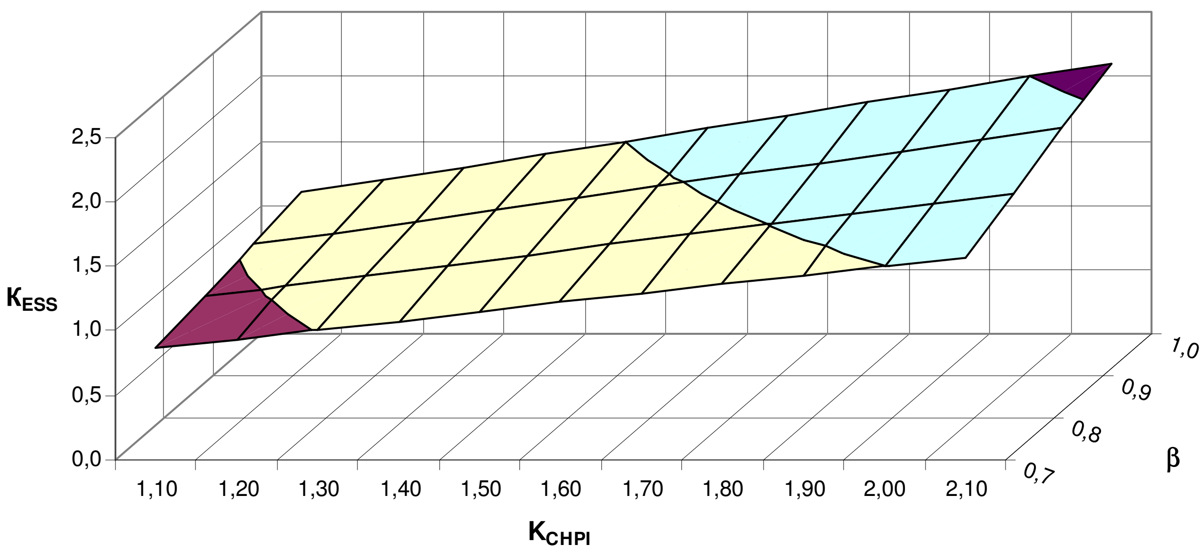

Fig. 1. Area of energy efficient operation of ESS with CHPI of small power on condition of electric energy consumption by peak electric boiler from energy system of Ukraine

As it is seen from Fig. 1, the values of complex dimensionless energy efficiency criterion of ESS are $K_{ESS} = 0,87...1,1$ on condition on minimal value of energy efficient criterion of CHPI K_{CHPI} = 1,1; for operation modes of ESS with K_{CHPI} > 1,1 the values of dimensionless criterion of ESS energy efficiency change within the limits of $K_{ESS} = 1,1...2,1$.

Fig. 2 shows the area of energy efficient operation of ESS with CHPI of small power, on conditions of minimal efficiency of GPE and PSH, with the consumption of electric energy by peak source of heat (electric boiler) from CHPI. In the given research, according to [5, 10], the following values are taken into consideration: value of GPE efficiency factor η_{EGPE} = 0,31 and value of electric motor efficiency with the account of energy losses in the control unit of electric motor

$\eta_{ED} = 0{,}8$. Electric boiler house with $\eta_{EB} = 0{,}9$ is provided to be peak source of heat in ESS for these conditions. The value of dimensionless criterion of electric boiler energy efficiency for the cases of electric energy consumption from CHPI will be $K_{PSH}^{EC} = 0{,}223$.

As it is seen from Fig. 2, the values of complex dimensionless criterion of ESS energy efficiency are $K_{ESS} = 0{,}84...1{,}1$ on condition on minimal value of energy efficient criterion of CHPI $K_{CHPI} = 1{,}1$; for operation modes of ESS with $K_{CHPI} > 1{,}1$ the values of dimensionless criterion of ESS energy efficiency change within the limits of $K_{ESS} = 0{,}91...2{,}1$.

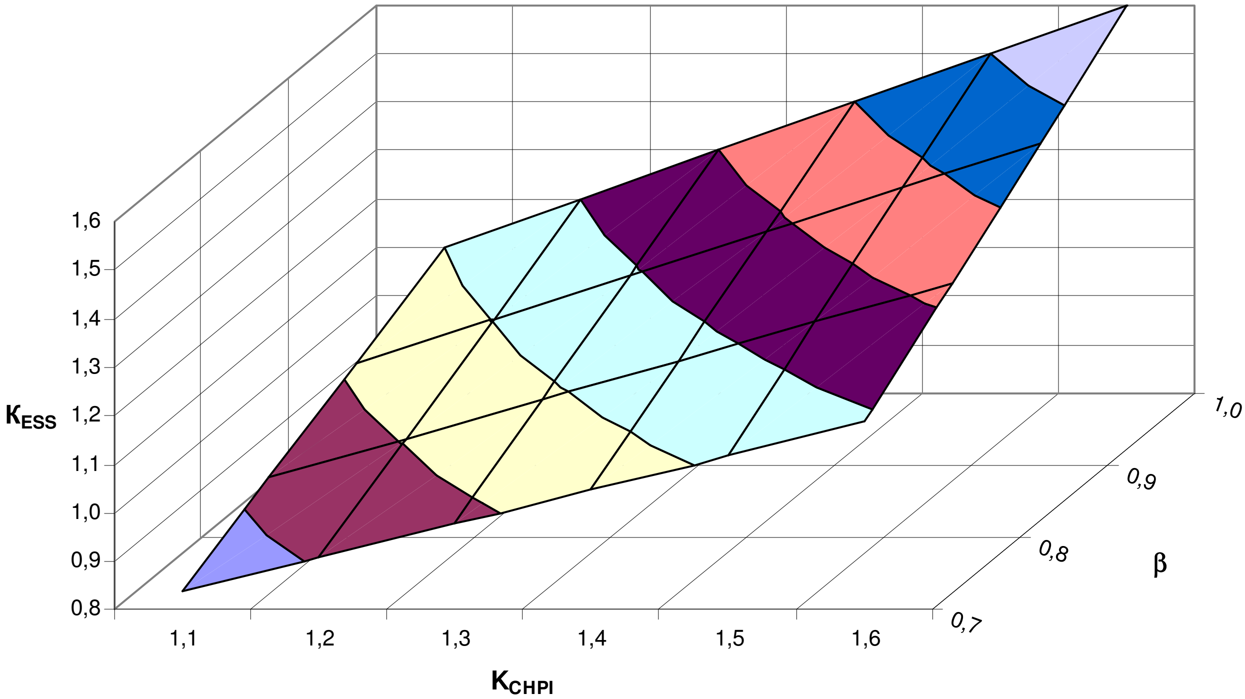

Fig. 2. Area of energy efficient operation of ESS with CHPI of small power, on conditions of minimal efficiency of GPE and peak electric boiler with the consumption of electric energy by electric boiler from CHPI

Fig. 3 shows the area of energy efficient operation of ESS with CHPI of small power and peak fuel-fired boiler, on conditions of minimal efficiency of GPE and PSH. In the given research, according to [5, 10], the following values are taken into consideration: value of GPE efficiency factor $\eta_{EGPE} = 0{,}31$ and value of electric motor efficiency with the account of energy losses in the control unit of electric motor $\eta_{ED} = 0{,}8$. Fuel-fired boiler house with $\eta_{FB} = 0{,}8$ is provided to be peak source of heat in ESS for these conditions. The value of dimensionless criterion of fuel-fired boiler energy efficiency will be $K_{PSH}^{FB} = 0{,}8$. As it is seen from Fig. 3, the values of complex dimensionless criterion of ESS energy efficiency are $K_{ESS} = 0{,}92...1{,}1$ on condition on minimal value of energy efficient criterion of CHPI $K_{CHPI} = 1{,}1$; for operation modes of ESS with $K_{CHPI} > 1{,}1$ the values of dimensionless criterion of ESS energy efficiency change within the limits of $K_{ESS} = 0{,}96...1{,}6$.

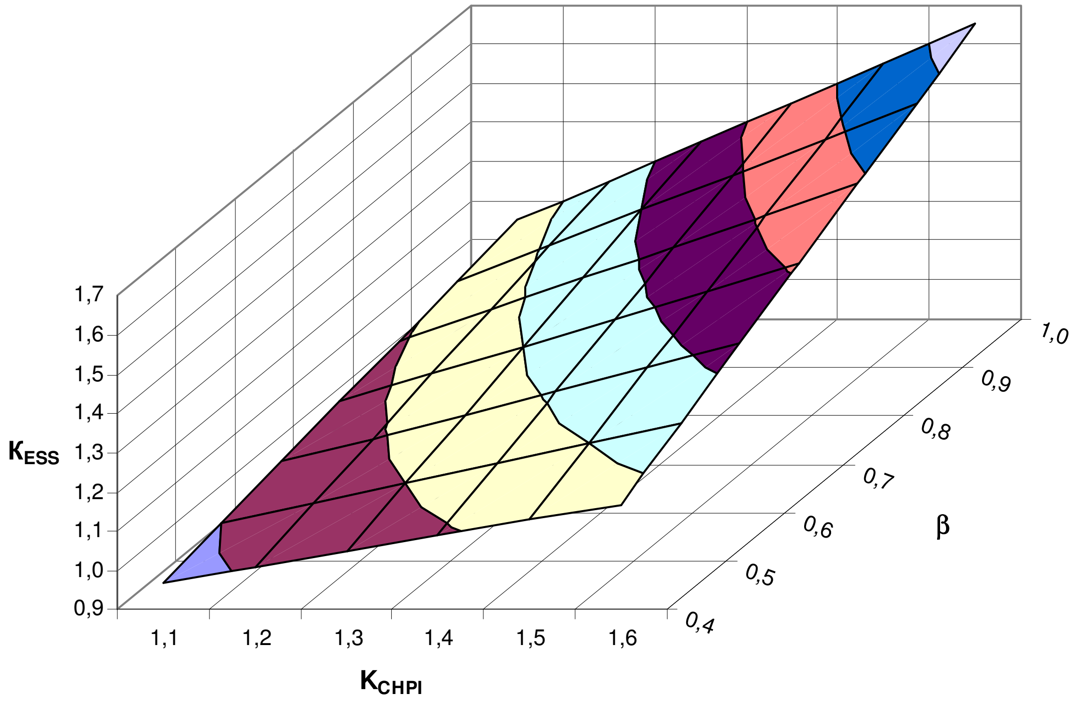

Fig. 3. Area of energy efficient operation of ESS with CHPI of small power, on conditions of minimal efficiency of GPE and peak fuel-fired boiler

Fig. 4 shows the area of energy efficient operation of ESS with CHPI of small power, on conditions of maximal efficiency of GPE and PSH, with the consumption of electric energy by peak source of heat (electric boiler) from CHPI. In the given research, according to [5, 10], the following values are taken into consideration: value of GPE efficiency factor η_{EGPE} = 0,42 and value of electric motor efficiency with the account of energy losses in the control unit of electric motor η_{ED} = 0,8. Electric boiler house with η_{EB} = 0,95 is provided to be peak source of heat in ESS for these conditions. The value of dimensionless criterion of electric boiler energy efficiency for the cases of electric energy consumption from CHPI will be $K_{PSH}^{EC} = 0{,}319$. As it is seen from Fig. 4, the values of complex dimensionless criterion of ESS energy efficiency are $K_{ESS} = 0{,}87...1{,}1$ on condition on minimal value of energy efficient criterion of CHPI K_{CHPI} = 1,1; for operation modes of ESS with K_{CHPI} > 1,1 the values of dimensionless criterion of ESS energy efficiency change within the limits of $K_{ESS} = 0{,}94...2{,}1$.

Fig. 5 shows the area of energy efficient operation of ESS with CHPI of small power and peak fuel-fired boiler, on conditions of maximal efficiency of GPE and PSH. In the given research, according to [5, 10], the following values are taken into consideration: value of GPE efficiency factor η_{EGPE} = 0,42 and value of electric motor efficiency with the account of energy losses in the control unit of electric motor η_{ED} = 0,8. Fuel-fired boiler house with η_{FB} = 0,9 is provided to be peak source of heat in ESS for these conditions. The value of dimensionless criterion of fuel-fired boiler energy efficiency will be K_{PSH}^{FB} = 0,9. As it is seen from Fig. 5, the values of complex dimensionless criterion of ESS energy efficiency are $K_{ESS} = 0{,}96...1{,}1$ on condition on minimal value of energy efficient criterion of CHPI K_{CHPI} = 1,1; for operation modes of ESS with K_{CHPI} > 1,1 the values of dimensionless criterion of ESS energy efficiency change within the limits of $K_{ESS} = 0{,}99...2{,}1$.

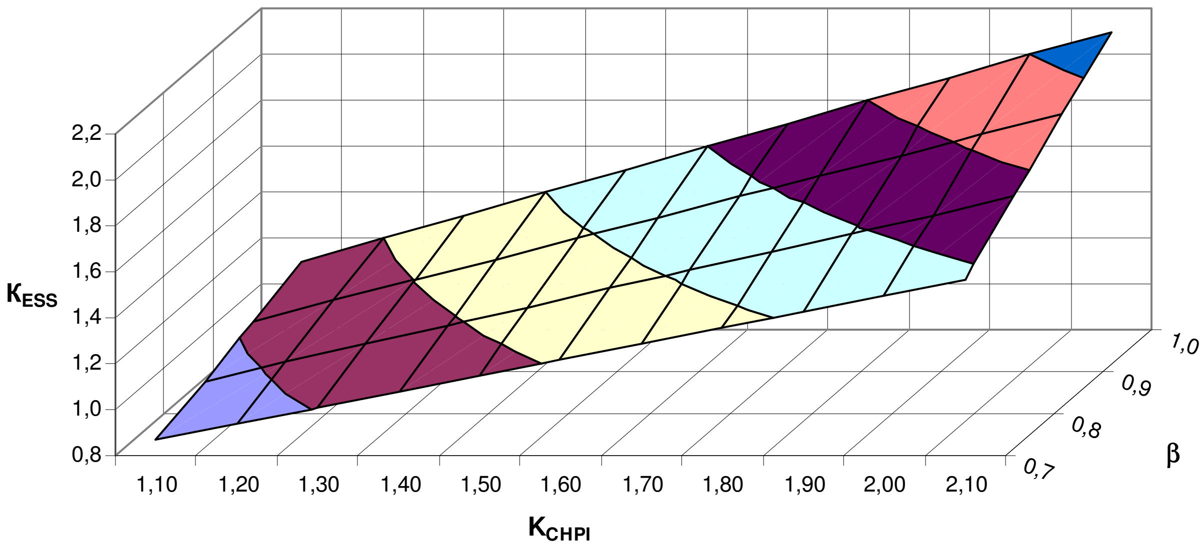

Fig. 4. Area of energy efficient operation of ESS with CHPI of small power, on conditions of maximal efficiency of GPE and PSH and electric energy consumption of by the electric boiler from CHPI

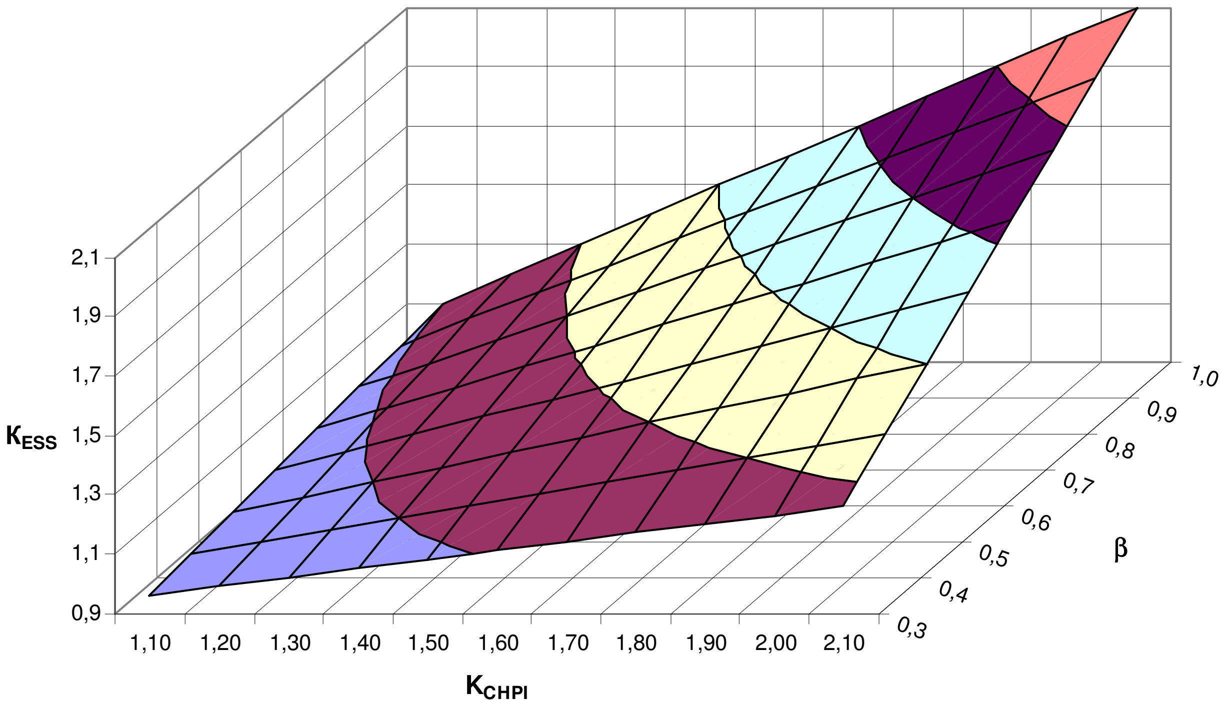

Fig. 5. Area of energy efficient operation of ESS with CHPI of small power, on conditions of maximal efficiency of GPE and peak fuel-fired boiler

Fig. 6 shows the area of energy efficient operation of ESS with CHPI of large power and peak fuel-fired boiler house, on conditions of minimal efficiency of GPE and PSH. In the given research, according to [5, 10], the following values are taken into account: value of GPE efficiency factor η_{EGPE} = 0,31 and value of electric motor efficiency with the account of energy losses in the control unit of electric motor η_{ED} = 0,9. Fuel-fired boiler house with η_{FB} = 0,8 is provided to be peak source of heat in ESS for these conditions. Value of dimensionless criterion of fuel-fired boiler energy efficiency will be $K_{PSH}^{FB} = \eta_{FB}$=0,8. As it is seen from Fig. 6, the values of complex dimensionless criterion of ESS energy efficiency are $K_{ESS} = 0{,}92...1{,}1$ on condition on minimal value of energy efficient criterion of CHPI K_{CHPI} = 1,1; for operation modes of ESS with K_{CHPI} > 1,1 the values of dimensionless criterion of ESS energy efficiency change within the limits of $K_{ESS} = 0{,}96...1{,}6$.

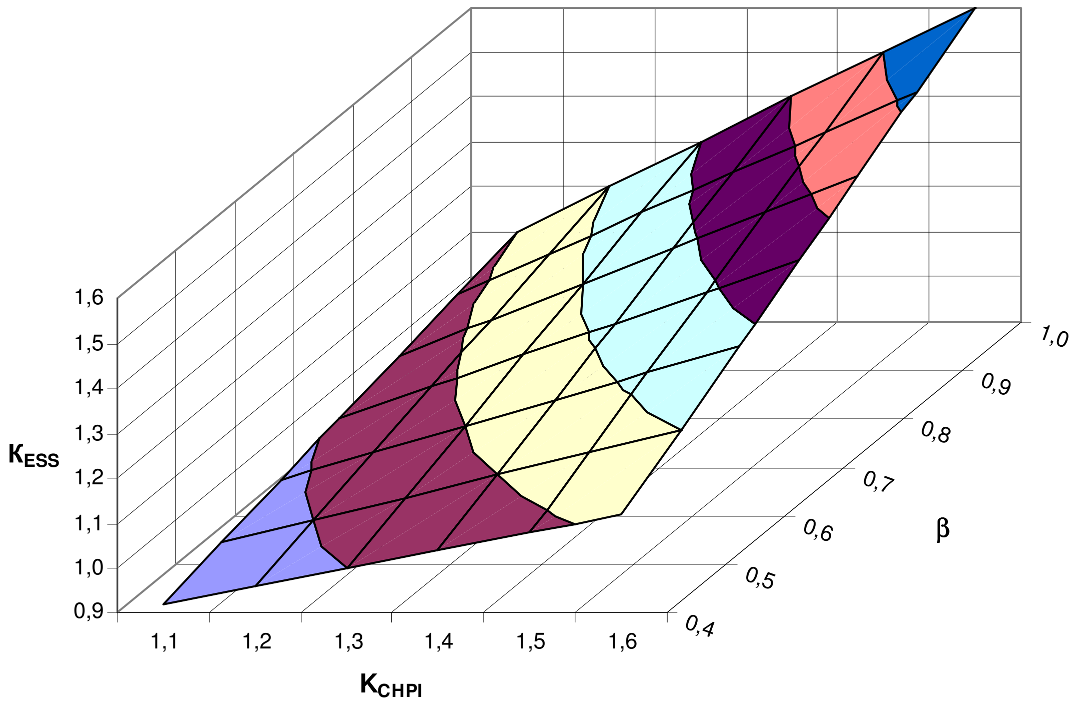

Fig. 6. Area of energy efficient operation of ESS with CHPI of large power, on conditions of minimal efficiency of GPE and peak fuel-fired boiler

Fig. 7 shows the area of energy efficient operation of ESS with CHPI of large power and peak fuel-fired boiler, on conditions of maximum efficiency of GPE and PSH. In the given research, according to [5, 10], the following values are taken into account: value of GPE efficiency factor η_{EGPE} = 0,42 and value of electric motor efficiency with the account of energy losses in the control unit of electric motor $\eta_{ED} = 0{,}9$. Fuel-fired boiler house with η_{FB} = 0,9 is provided to be peak source of heat in ESS for these conditions. The value of dimensionless criterion of fuel-fired boiler energy efficiency will be K_{PSH}^{FB} = 0,9. As it is seen from Fig. 7, the values of complex dimensionless criterion of ESS energy efficiency are $K_{ESS} = 0{,}98...1{,}1$ on condition on minimal value of energy efficient criterion of CHPI K_{CHPI} = 1,1; for operation modes of ESS with K_{CHPI} > 1,1 the values of dimensionless criterion of ESS energy efficiency change within the limits of $K_{ESS} = 1{,}02...2{,}1$.

It should be noted, that the dependences, shown in Figs. 1 – 7, are obtained for energy efficient operation modes of CHPI on the base of the results of the research [10 – 11].

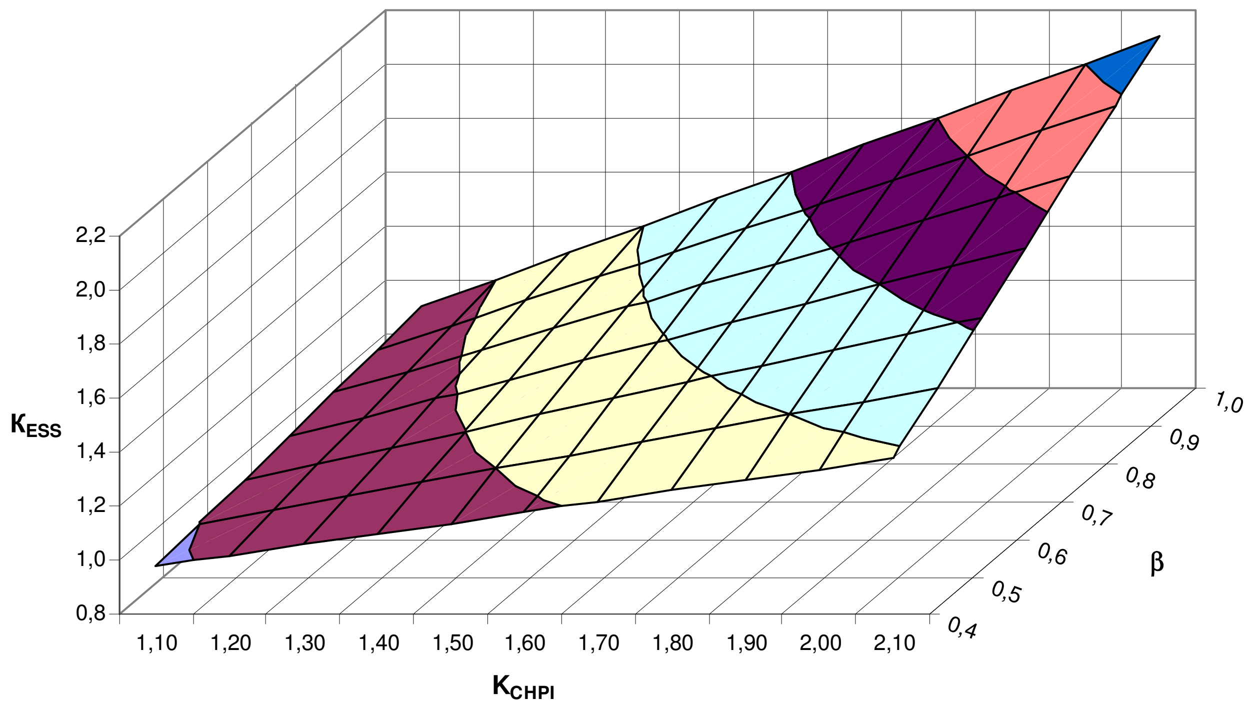

Fig. 7. Area of energy efficient operation of ESS with CHPI of large power, on conditions of maximum efficiency of GPE and peak fuel-fired boiler

As it is seen from Figs. 3 and 6, on conditions of $K_{CHPI} > 1$ and $K_{ESS} > \eta_{FB}$ [11], dependences, shown in Figs. 3 and 6, determine areas of energy efficient operation of ESS with CHPI of different power levels and peak fuel-fired boiler (boiler house), on conditions of minimal efficiency of GPE and fuel-fired boiler (boiler house). On these conditions, the above-mentioned ESS can be recommended as high efficient systems of energy supply, as their efficiency almost two times exceeds energy efficiency of high efficient electric and fuel-fired boilers. Such ESS could be competitive with modern high efficient electric and fuel-fired boilers in the systems of heat and energy supply.

As it is seen from Figs. 5 and 7, on conditions of $K_{CHPI} > 1$ and $K_{ESS} > \eta_{FB}$ [11], dependences, shown in Figs. 5 and 7, determine areas of energy efficient operation of ESS with CHPI of various power levels and peak fuel-fired boiler (boiler house), on conditions of maximal efficiency of GPE and fuel-fired boiler (boiler house). On such conditions, the above-mentioned ESS can be recommended as high efficient energy supply systems, as their efficiency more than two times exceeds energy efficiency of high efficient electric and fuel-fired boilers. The studied ESS can be competitive with modern high efficient electric and fuel-fired boilers in heat and energy supply systems.

It is determined, that ESS with CHPI and peak fuel-fired boilers, suggested in the research, will be energy efficient, if the share of CHPI loading in ESS will be $\beta > 0{,}4$; that corresponds to the results of research, shown in Figs. 3, 5 – 7. At this condition the areas of energy efficient operation of the above-mentioned ESS modern high efficient electric and fuel-fired boilers would be inferior by energy efficiency to the above-mentioned ESS, are determined. Under realization of this condition, modern high efficient electric and fuel-fired boilers will be inferior by energy efficiency to the above-mentioned ESS.

As it is seen from Figs. 1 – 2 and 4, on conditions of $K_{CHPI} > 1$ and $K_{ESS} > \eta_{EB}$ [11], dependences, shown in Figs. 1 – 2 and 4, determine areas of energy efficient operation of ESS with CHPI and electric boiler, with different versions of electric energy sources for peak electric boiler and on conditions of different energy efficiency of GPE and electric boiler. It is determined, that ESS with CHPI and peak electric boilers, suggested in the research, will be energy efficient, if the share of CHPI loading in ESS will be $\beta > 0{,}7$; that corresponds to the results of the research, shown in

Figs. 1 – 2 and 4. Under such conditions, the above-mentioned ESS can be recommended as high efficient energy supply systems, as even in case of minimal efficiency of GPE and boiler, energy efficiency of energy supply system almost two times exceeds energy efficiency of high efficient electric and fuel-fired boilers. On condition of ESS operation modes with $\beta > 0,7$ modern high efficient electric and fuel-fired boilers will be inferior by energy efficiency to the above-mentioned ESS. This ESS can be competitive with modern high efficient electric and fuel-fired boilers in the systems of heat and energy supply.

The suggested approaches, aimed at determination of the areas of ESS with CHPI and PSH energy efficient operation enable to determine energy efficient areas and 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 various power levels, with the account of energy losses in the process of generation, supply and conversion of electric energy.

Conclusions

Methodical fundamentals are developed, areas of energy efficient operation of ESS with CHPI and PSH, on conditions of optimal operation modes of CHPI are determined; energy efficient operation modes of ESS with CHPI and PSH with the account of complex impact of variable operation modes, sources of drive energy of steam compressor HPI of various power levels, with the account of energy losses in the process of generation, supply and conversion of electric energy are determined.

The suggested approach, aimed at determination of the areas of energy efficient operation of ESS with CHPI and PSH has a number of advantages:

— it takes into account variable operation modes of ESS with the change of load distribution between steam compressor CHPI and peak source of heat in ESS;

— it enables to evaluate the complex impact of variable operation modes of ESS, peak sources of heat of ESS, sources of drive energy of steam compressor CHPI with the account of energy losses in the process of generation, supply and conversion of electric energy;

— it takes into account the impact of drive energy sources of steam compressor CHPI of various power levels, with the account of energy losses in the process of generation, supply and conversion of electric energy in CHPI and ESS;

— it takes into account the impact of peak sources of heat for ESS and type of the energy, consumed by them, with the account of energy losses in the process of generation and supply of energy to peak sources of heat;

— as a result of complex approach to evaluation of ESS energy efficiency the most efficient PSH for certain type of ESS could be chosen;

— methodical fundamentals, suggested in [11], and the results of research, presented in the given paper, could be used for the determination of the areas of energy efficient operation of ESS on the base of steam compressor CHPI with various refrigerants, sources of low temperature heat and scheme solutions;

— it enables to determine areas and modes of energy efficient operation of ESS with CHPI and PSH, at which energy efficiency of the studied ESS almost two times exceeds energy efficiency of modern high energy efficient electric and fuel-fired boilers;

— it allows to perform comprehensive evaluation of greater part of ESS with CHPI and PSH variants;

— it allows to develop recommendations, aimed at energy efficient operation of ESS with CHPI and PSH with different scheme solutions.

Under conditions of $K_{CHPI} > 1$ and $K_{ESS} > \eta_{FB}$ and modes of energy efficient operation of CHPI, areas of energy efficient operation and energy efficient operation modes of ESS with CHPI and peak fuel-fired boilers for various power levels and ESS elements energy efficiency are determined. It is determined, that ESS with CHPI and peak fuel-fired boilers, suggested in the research, will be energy efficient, if the share of CHPI loading in ESS will be $\beta > 0{,}4$. If this condition is realized, modern high efficient electric and fuel-fired boilers will be inferior by their energy efficiency to the above-mentioned ESS. Under these conditions the above-mentioned ESS can be recommended as high efficient energy supply systems, as their efficiency more than two times exceeds energy efficiency of high efficient electric and fuel-fired boilers.

On conditions of $K_{CHPI} > 1$ and $K_{ESS} > \eta_{EB}$ and modes of energy efficient operation of CHPI, areas of energy efficient operation and energy efficient operation modes of ESS with CHPI and peak electric boilers with different variants of electric energy sources for peak electric boiler, for different levels of ESS elements energy efficiency are determined. It is determined, that ESS with CHPI and peak electric boilers, suggested in the research, will be energy efficient, if the share of CHPI loading in ESS will be $\beta > 0{,}7$. Under these conditions, the above-mentioned ESS can be recommended as high efficient energy supply systems, as even at minimal efficiency of GPE and boiler, energy efficiency of the system of energy supply almost two times exceeds energy efficiency of high efficient electric and fuel-fired boilers.

The suggested approaches, aimed at determination of the areas of energy efficient operation of ESS with CHPI and PSH enable to determine energy efficient operation modes and develop recommendations regarding energy efficient operation of ESS with different scheme solutions, 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.

REFERENCES

1. Ткаченко С. Й. Парокомпресійні теплонасосні установки в системах теплопостачання. Монографія / С. Й. Ткаченко, О. П. Остапенко. – Вінниця: УНІВЕРСУМ-Вінниця. – 2009. – 176 с.

2. Баласанян Г. А. Ефективність перспективних інтегрованих систем енергозабезпечення на базі установок когенерації малої потужності (теоретичні основи, аналіз, оптимізація) : автореф. дис. д-ра техн. наук : 05.14.06 «Технічна теплофізика і промислова теплоенергетика» / Г. А. Баласанян. – Одеса, 2007. – 36 с.

3. Билека Б. Д. Экономичность когенерационных и комбинированных когенерационно-теплонасосных установок с газопоршневыми и газотурбинными двигателями / Б. Д. Билека, Р. В. Сергиенко, В. Я. Кабков // Авиационно-космическая техника и технология. – 2010. – №7 (74). – С. 25 – 29.

4. Сафьянц С. М. Исследование схемы источника теплоэлектроснабжения с регулированием нагрузок на базе использования тепловых насосов / С. М. Сафьянц, Н. В. Колесниченко, Т. Е. Веретенникова // Промышленная теплотехника. – 2011. – Т. 33, № 3. – С. 79 – 85.

5. Енергетична ефективність парокомпресійних теплових насосів з електричним та когенераційним приводами [Електронний ресурс] / О. П. Остапенко, В. В. Лещенко, Р. О. Тіхоненко // Наукові праці ВНТУ. – 2014. – № 4. – Режим доступу до журн.: http://praci.vntu.edu.ua/index.php/praci/article/view/421/419.

6. Енергетичні переваги застосування парокомпресійних теплових насосів з електричним та когенераційним приводами [Електронний ресурс] / О. П. Остапенко, В. В. Лещенко, Р. О. Тіхоненко // Наукові праці ВНТУ. – 2015. – № 1. – Режим доступу до журн.: http://praci.vntu.edu.ua/index.php/praci/article/view/437/435.

7. Остапенко О. П. Методичні основи комплексного оцінювання енергетичної ефективності парокомпресійних теплонасосних станцій з електричним та когенераційним приводом / О. П. Остапенко // Наукові праці ОНАХТ. – 2015. – Вип. 47. – Т. 2. – С. 157 – 162.

8. Ostapenko O. P. Scientific basis of evaluation energy efficiency of heat pump plants: monograph / O. P. Ostapenko. – Saarbrücken, LAP LAMBERT Academic Publishing, 2016. – 62 p.

9. Комплексна оцінка енергетичної ефективності парокомпресійних теплонасосних станцій з когенераційним приводом [Електронний ресурс] / О. П. Остапенко // Наукові праці ВНТУ. – 2015. – № 3. – Режим доступу до журн.: http://praci.vntu.edu.ua/index.php/praci/article/view/2/2.

10. Енергетична ефективність систем енергозабезпечення на основі комбінованих когенераційно-теплонасосних установок [Електронний ресурс] / О. П. Остапенко, В. В. Лещенко, Р. О. Тіхоненко // Наукові праці ВНТУ. – 2015. – № 4. – Режим доступу до журн.: http://praci.vntu.edu.ua/index.php/praci/article/view/454/452.

11. Енергетична ефективність систем енергозабезпечення на основі комбінованих когенераційно-теплонасосних установок та пікових джерел теплоти [Електронний ресурс] / О. П. Остапенко // Наукові праці ВНТУ. – 2016. – № 1. – Режим доступу до журн.: http://praci.vntu.edu.ua/index.php/praci/article/view/462/460.

12. Енергоефективність систем енергозабезпечення з когенераційно-теплонасосними установками та пікови-

ми джерелами теплоти в системах теплопостачання [Електронний ресурс] / О. П. Остапенко // Наукові праці ВНТУ. – 2016. – № 2. – Режим доступу до журн.: http://praci.vntu.edu.ua/index.php/praci/article/ view/ 472/470.

13. Остапенко О. П. Холодильна техніка та технологія. Теплові насоси : навчальний посібник / О. П. Остапенко. – Вінниця : ВНТУ, 2015. – 123 с.

Ostapenko Olga – Cand. Sc. (Eng.), Assistant Professor of the Department of Heat Power Engineering, e-mail: ostapenko1208@gmail.com.

Vinnytsia National Technical University.