O. Ostapenko, Cand. Sc. (Eng.), Assis. Professor

COMPLEX EVALUATION OF ENERGY EFFICIENCY OF STEAM COMPRESSOR HEAT PUMP PLANTS WITH ELECTRIC DRIVE

The paper considers the suggested approach, dealing with complex evaluation of energy efficiency of steam compressor heat pump plants (HPP) with electric drive, taking into account complex impact of variable operation modes of HPP, peak sources of HPP heat, sources of HPP drive energy, taking into consideration energy losses in the process of generation, supply and conversion of electric energy.

Kew words*: complex evaluation, energy efficiency, heat pump plant, dimensionless criterion of energy efficiency, electric drive.*

Introduction

As a result of energy crisis, occurring in Ukraine, the problem of efficient consumption of energy resources and introduction of up-to-dale energy saving technologies becomes very urgent [1-2]. One of such technologies is the usage of steam compressor heat pump installations (HPI) with electric drive, that will promote the economy of fuel-energy resources and protection of the environment. Introduction of heat pump plants, where heat pump is combined with peak source of heat, will produce greater energy, resource saving and economic effect. That is why, the studies of energy efficiency of heat pump installations are very actual.

A number of publications, studying the problems of energy efficiency of steam compressor HPP have appeared in recent years [1 – 12]. In [1] the author performed the research, aimed at efficiency improvement and selection of rational parameters and operation modes of heat pump plants for heating and heat supply systems for equivalent fuel consumption. In [2] thermodynamic and exergy analysis of the efficiency of steam compressor cycle of heat pump plant of heat supply was carried out. Authors in the research [3] analyze thermodynamic efficiency of heat pump plants of heat supply. In the research [4] new approach of heat pumps efficiency evaluation is suggested. Thermodynamic analysis of various types of HPI is performed in [5]. However, in research [1 – 5] energy losses in the process of generation, supply and conversion of electric energy to HPP from different types of electric power stations are not taken into account. In the study [6] efficient real operation modes of HPI with electric and cogeneration drives, taking into consideration the impact of drive energy sources of steam compressor heat pumps and losses of energy during generation, supply and conversion of electric energy to HPI are determined. Energy advantages of steam compressor heat pumps with electric and cogeneration drives usage are analyzed in the research [7].

In publications [8, 9] energy and economic preconditions of efficient integration of HPP into the systems of heat supply of industrial enterprises and of utilities of municipal power engineering of Ukraine are defined. In [10] energy, ecological and economic efficiency of HPP with various kinds of compressor drive, on natural and industrial sources of low-temperature heat taking into consideration variable operation modes of heat supply systems in wide range of HPI capacity change is evaluated. The results of the study of energy efficiency of HPP with different sources of heat, on condition of variable operation modes, are given in [11]. In the research [12] energy ecological efficiency of HPP with various kinds of compressor drive, on natural and industrial sources of low-temperature heat on condition of variable operation modes of heat supply system is evaluated.

In [1–12] authors did not perform complex evaluation of energy efficiency of steam compressor HPP with electric drive, taking into account complex impact of HPP variable operation modes, peak sources of HPP heat, sources of drive energy of steam compressor HPP, taking into consideration losses of energy in the process of generation, supply and conversion of electric energy.

The aim of the research is the development of methodical fundamentals and carrying out of complex evaluation of energy efficiency of steam compressor heat pump plants with electric drive, taking into account complex impact of HPP variable operation modes, peak sources of HPP heat, sources of drive energy of steam compressor HPP with the account of energy losses in the process of generation, supply and conversion of electric energy.

Main part

The research contains complex evaluation of energy efficiency of steam compressor HPP with HPI of small (up to 1MW) and large capacities with electric drive. The research was carried out for the cases of usage in electrically-driven HPI of electric energy from various types of electric power stations and also for averaged efficiency values of electric power stations in Ukraine. The schemes of these HPP are given in [8].

Energy efficiency of HPP is largely determined by optimal distribution of the load between heat pump installation and peak source of heat (for instance, hot-water fuel-fired boiler, electric boiler, solar collectors, etc.) in HPP. This distribution is characterized by the share of HPI load within HPP β that is determined as a relation of thermal capacity of HPI to the capacity of HPP $\beta = Q_{\text{HPI}}/Q_{\text{HPP}}$.

Proceeding from the analysis of the results of the researches, carried out [10-12], optimal values of β index for HPP with electric drive, operating at various sources of heat at variable operation modes of heating system are determined. Each of these modes corresponds to certain value of thermal capacities of HPP, HPI and shares of HPI β load. The results of the study of energy efficiency of HPP with electric drive for conditions of variable operation modes, for various sources of low-temperature heat are shown in [11].

In our research energy efficiency of «Source of drive energy of HPP – HPP – heat consumer from HPP» system on the example of steam compressor heat pumps with electric drive is analyzed. The advantage of such approach is that energy losses in the process of generation, supply and conversion of electric energy to HPI and peak source of heat in order to determine the efficient operation modes of HPP with electric drive is taken into account.

It is suggested to perform complex evaluation of energy efficiency of steam compressor HPP with electric drive applying complex dimensionless criterion of HPP energy efficiency:

$$K_{HPP} = (1-\beta)\cdot K_{PSH} + \beta \cdot K_{HPI}, \tag{1}$$

where K_{PSH} – dimensionless criterion of energy efficiency of peak source of heat within HPP (hot-water fuel-fired boiler, electric boiler, solar collectors, etc.), K_{HPI} – dimensionless criterion of energy efficiency of steam compressor HPI with electric drive within HPP.

Dimensionless criterion of energy efficiency of steam compressor HPI with electric drive K_{HPI} is suggested in the research [6]. It is obtained on the basis of energy balance equation for the system «Source of drive energy of HPI – HPI – heat consumer from HPI», taking into account the impact of drive energy sources of steam compressor HPI and taking into consideration energy losses in the process of generation, supply and conversion of electric energy to HPI.

For steam compressor HPI with electric drive dimensionless criterion of energy efficiency will have the form [6]:

$$K_{HPI} = Q_{HPI}/Q_h = \eta_{EP}\cdot\varphi\cdot\eta_{hf}, \tag{2}$$

where Q_h – power, spent at electric power station for generation of electric energy for HPI drive, η_{EP} – total efficiency of generation, supply and conversion of electric energy from [6], φ – coefficient of performance of steam compressor HPI, η_{hf} – efficiency factor of the heat flow, that takes into account energy losses and working substance in pipe lines and equipment of HPI.

The value of total efficiency of generation, supply and conversion of electric energy to HPI with electric drive, according to [6], may be defined:

$$\eta_{EP} = \eta_{EPP} \cdot \eta_{DG} \cdot \eta_{ED}, \tag{3}$$

where η_{EPP} – averaged value of electric power plants efficiency in Ukraine or alternative sources of electric energy for HPI (on the base of steam-gas installations (SGI), gas-turbine installations (GTI), solar power plants of thermodynamic cycle (SPP), wind energy plants (WEP)), from the research [6]; η_{DG} – efficiency of distributive electric grids in Ukraine from [6], η_{ED} – efficiency of electric motor, taking into account energy losses in motor control unit from [6].

On condition $K_{HPI} = 1$ heat pump installation supplies to the consumer the same thermal power that was spent for generation of electric energy for HPI drive. The greater the value of this index is more efficient and competitive the heat pump will be.

In [6] the method of determination of the areas of efficient usage of steam compressor HPI with electric drive by dimensionless index of HPI K_{HPI} energy efficiency, taking into account the impact of the sources of steam compressor HPI drive energy and account of energy losses in the process of generation, supply and conversion of electric energy for HPI.

Dimensionless criterion of energy efficiency of peak source of heat – electric boiler –within HPP K_{PSH} can be obtained on the base of energy balance equation for the systems «Source of electric energy – electric boiler – heat consumer from HPP», taking into account the impact of the energy sources for peak source of heat (electric boiler) and with the account of energy losses in the process of generation and supply of electric energy to electric boiler.

For electric boiler as peak source of heat for HPP dimensionless criterion of energy efficiency will have the form:

$$K_{PSH} = Q_{EB} / Q_h = \eta_{EP}^b \cdot \eta_{EB}, \tag{4}$$

where Q_{EB} – heat power of hot-water electric boiler, that can be determined as: $Q_{EB} = Q_{HPP} - Q_{HPI}$; Q_h – power, spent at electric power station for generation of electric energy, η_{EP}^b – total efficiency of generation and supply of electric energy to electric boiler is determined, applying the formula: $\eta_{EP}^b = \eta_{EPP} \cdot \eta_{DG}$, η_{EB} – efficiency of the electric boiler.

Then dimensionless criterion of energy efficiency of electric boiler as peak source of heat for HPP will be determined:

$$K_{PSH} = \eta_{EPP} \cdot \eta_{DG} \cdot \eta_{EB}. \tag{5}$$

Dimensionless criterion of energy efficiency of peak source of heat – hot-water fuel-fired boiler – within HPP K_{PSH} may be obtained on the base of energy balance equation for the systems «Sources of electric energy and fuel – fuel-fired boiler – heat consumer from HPP», taking into consideration the impact of the energy sources for peak source of heat (fuel-fired boiler) and with the account of energy losses in the process of generation and supply of electric energy to boiler (boiler house).

For fuel-fired boiler as peak source of heat for HPP dimensionless criterion of energy efficiency will have the form:

$$K_{PSH} = Q_{FB} / Q_f = \eta_{FB}, \tag{6}$$

where Q_{FB} – heat power of hot-water fuel-fired boiler, that can be determined as: $Q_{FB} = Q_{HPP} - Q_{HPI}$; Q_f – power, spent for generation of heat energy from burning fuel in the boiler, η_{FB} – efficiency of hot-water fuel-fired boiler or fuel-fired boiler house (for HPP of large capacities).

For the cases of usage the alternative peak sources of heat in HPP (for instance, solar collectors for HPP of small capacity) the value of dimensionless criterion of energy efficiency of peak source of heat for HPP K_{PSH} will be equal to the efficiency of the alternative peak source of heat η_{APSH} or efficiency of additional system with alternative peak source of heat η_{APSH}^s.

It should be noted, that complex dimensionless criterion of HPP K_{HPP} energy efficiency may be used also for the selection of the most efficient peak source of heat for certain kind of steam compressor HPP.

The suggested complex approach to evaluation of energy efficiency of steam compressor HPP with electric drive has some advantages:

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

— it takes into account the operation modes of steam compressor HPI;

— it takes into account variable operation modes of HPP for heat supply during the year with the change of load distribution amony steam compressor HPI and peak source of HPP heat;

— it takes into account the impact of drive energy sourses of steam compressor HPP, with the account of energy losses in the process of generation, supply and conversion of electric energy to HPP;

— it takes into account energy efficiency of steam compressor HPP of various capacity levels with electric drive;

— it takes into account the impact of peak sources of heat of steam compressor HPP and kind of the consumed energy, 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 energy efficiency of electrically-driven HPP, the choice of the most efficient peak source of heat for certain kind of steam compressor HPP can be performed;

— the suggested methodical fundamentals can be applied for evaluation of energy efficiency of steam compressor HPP with different refrigerants and scheme solutions of HPI;

— it allows to evaluate in a complex manner energy efficiency of considerable number of variants of steam compressor HPP with electric drive.

The application of the suggested methodical fundamentals, regarding complex evaluation of energy efficiency of HPP with electric drive we will demonstrate on specific examples.

Figs. 1-3 show the results of complex evaluation of energy efficiency of small capacity HPP with electric drive. The figure shows the values of dimensionless criterion of energy efficiency of HPP with electric drive K_{HPP} for the cases of variable load of HPI within HPP with the values of HPI load share in range of $\beta = 0{,}1\ldots1{,}0$. Values of dimensionless criterion of energy efficiency of steam compressor HPI with electric drive K_{HPI}, in accordance with the research [6], are determined for the values of real coefficient of performance of HPI in the range $\varphi_r = 0{,}6\ldots6{,}0$. Peak source of HPP heat for these conditions is provided electric boiler house with $\eta_{EB} = 0{,}95$. According to [6], the value of distributive electric grids efficiency in Ukraine $\eta_{DG} = 0{,}875$ is taken into account.

Fig. 1 shows the values of dimensionless criterion of energy efficiency of small capacity HPP with electric drive, on condition of electric energy consumption from energy system of Ukraine. In the given research, in accordance with [6] the following values are taken into consideration: averaged efficiency value of electric power plants in Ukraine $\eta_{EPP} = 0{,}383$ and the value of total efficiency of generation, supply and conversion of electric energy to small capacity HPI with electric drive $\eta_{EP} = 0{,}268$.

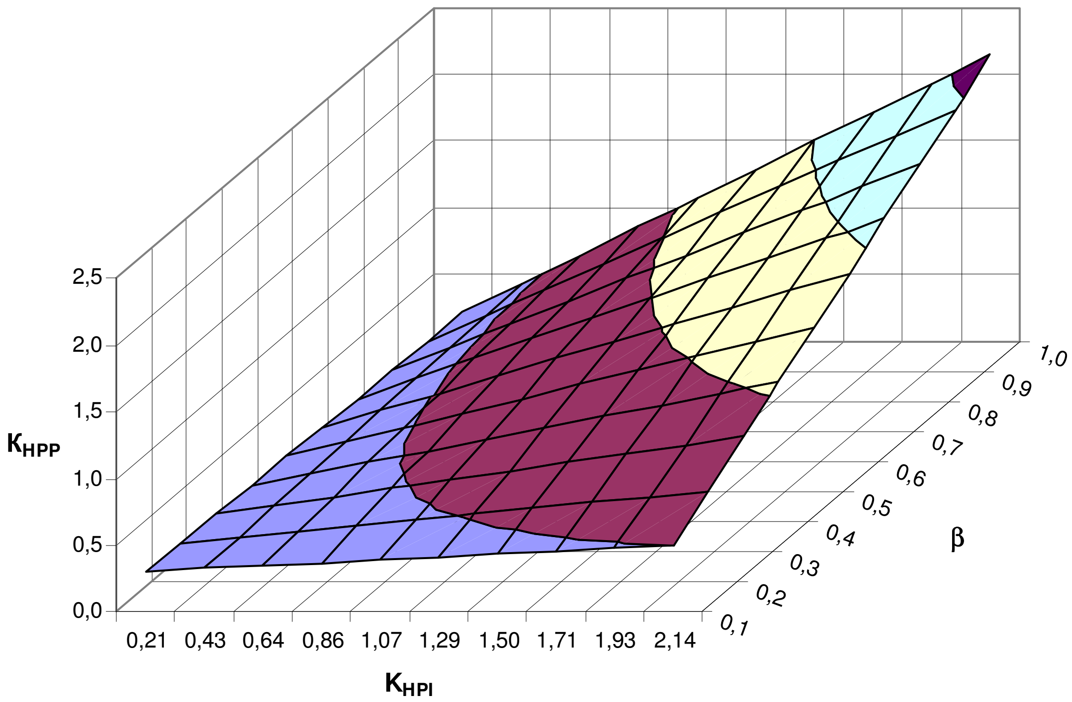

Fig. 1 – Values of dimensionless criterion of energy efficiency of small capacity HPP with electric drive for the cases of HPI variable load, on condition of electric energy consumption from energy system of Ukraine

Fig. 2 shows the values of dimensionless criterion of energy efficiency of small capacity HPP with electric drive, on condition of electric energy consumption from SGI. According to [6] in the given research the following values are taken into consideration: value of SGI efficiency $\eta_{EPP} = \eta_{SGI} = 0{,}55$ and the value of total efficiency of generation, supply and conversion of electric energy to small capacity HPI with electric drive $\eta_{EP} = 0{,}385$.

Fig. 3 shows the values of dimensionless criterion of energy efficiency of small capacity HPP with electric drive, on condition of electric energy consumption from GTI. In the given research, in accordance with [6], the following values are taken into consideration: value of GTI efficiency $\eta_{EPP} = \eta_{GTI} = 0{,}33$ and the value of total efficiency of generation, supply and conversion of electric energy to small capacity HPI with electric drive $\eta_{EP} = 0{,}231$.

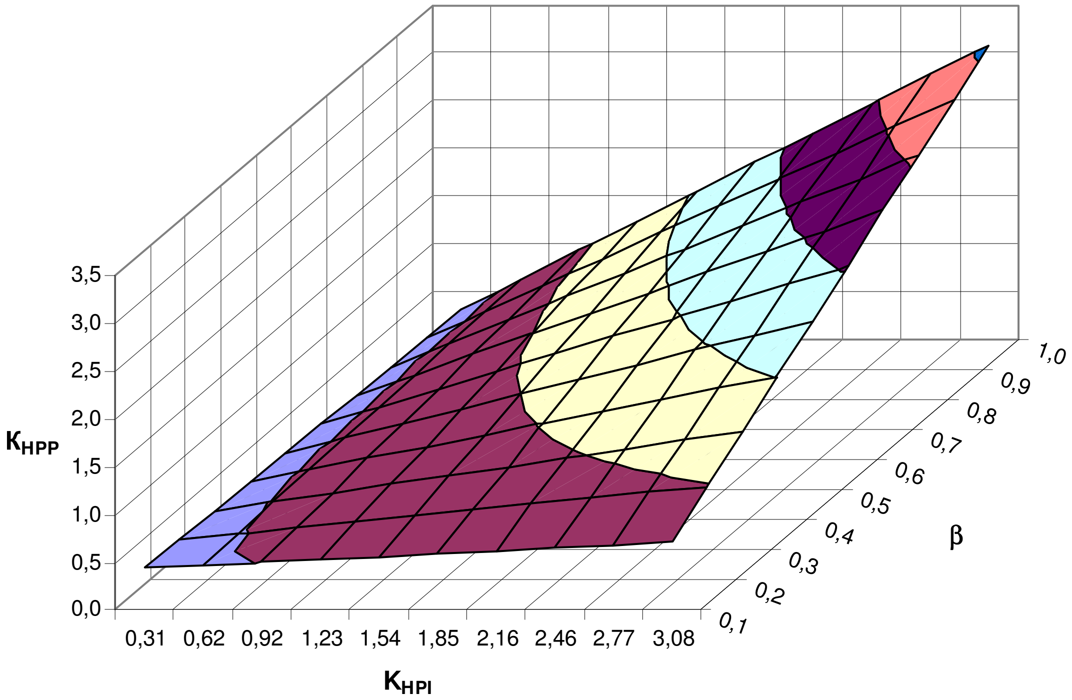

Fig. 2 – Values of dimensionless criterion of energy efficiency of small capacity HPP with electric drive for the cases of HPI variable load, on condition of electric energy consumption from SGI

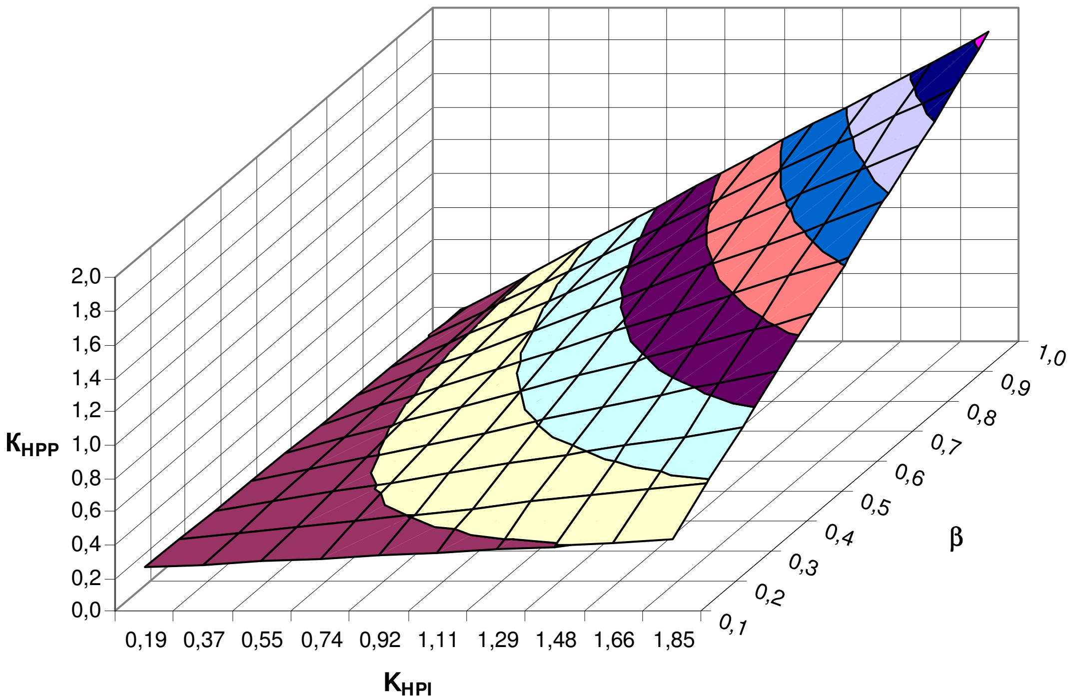

Fig. 3 – Values of dimensionless criterion of energy efficiency of small capacity HPP with electric drive for the cases of HPI variable load, on condition of electric energy consumption from GTI

Figs. 4-6 show the results of complex evaluation of energy efficiency of large capacity HPP with electric drive. The values of dimensionless criterion of energy efficiency of HPP with electric drive K_{HPP} for the cases of variable load of HPI within HPP with values of HPI load share in the range of β = 0,1…1,0 are shown here. Values of dimensionless criterion of energy efficiency of steam compressor HPI with electric drive K_{HPI}, according to the research [6], are determined for the values of real coefficient of performance of HPI in the range φ_r = 0,68…6,75. Peak source of HPP heat for these conditions is provided to be hot-water fuel-fired boiler house with η_{FB} = 0,85. According to [6], the value of efficiency of distributive electric grids in Ukraine η_{DG} = 0,875 is taken into account.

In fig. 4 the values of dimensionless criterion of energy efficiency of large capacity HPP with electric drive, on condition of electric energy consumption from energy system of Ukraine are shown. In this research, according to [6], the following values are taken into account: averaged value of electric power plants efficiency in Ukraine η_{EPP} = 0,383 and the value of total efficiency of generation, supply and conversion of electric energy to HPI of large capacity with electric drive η_{EP} = 0,301.

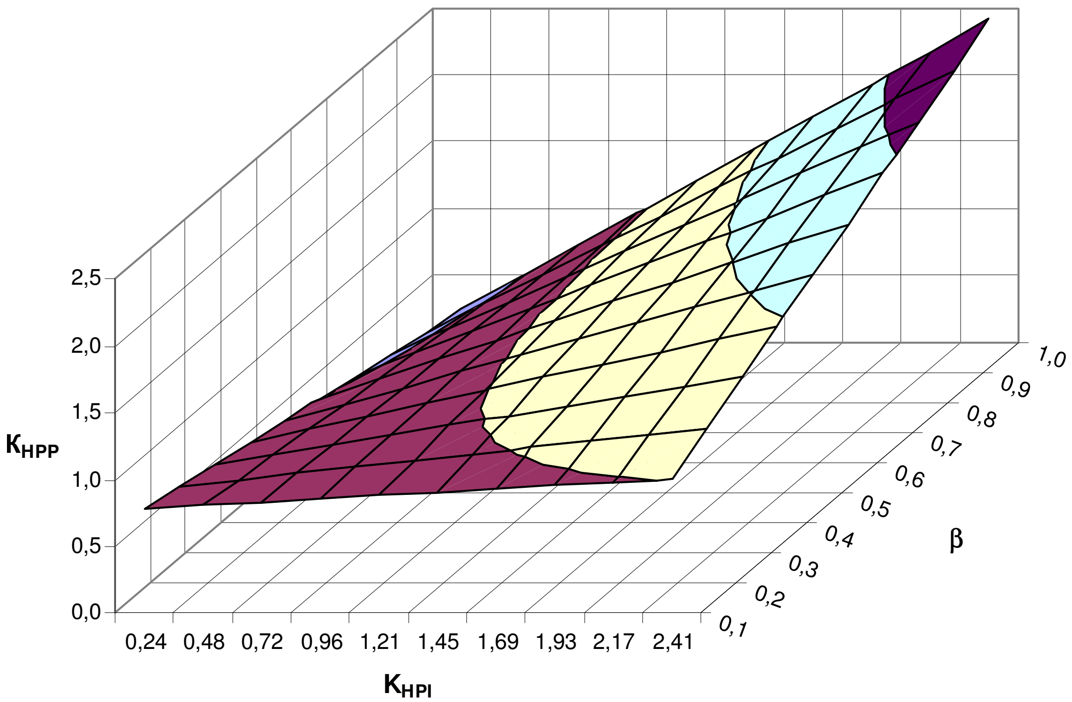

Fig. 4 – Values of dimensionless criterion of energy efficiency of large capacity HPP with electric drive for the cases of variable load of HPI, on condition of electric energy consumption from energy system of Ukraine

Fig. 5 shows the values of dimensionless criterion of energy efficiency of large capacity HPP with electric drive, on condition of electric energy consumption from SGI. In accordance with [6], the research takes into account: value of SGI efficiency $\eta_{EPP} = \eta_{SGI}$ = 0,55 and the value of total efficiency of generation, supply and conversion of electric energy to large capacity HPI with electric drive η_{EP} = 0,433.

Fig. 6 shows the values of dimensionless criterion of energy efficiency of large capacity HPP with electric drive, on condition of electric energy consumption from GTI. The given research, in accordance with [6], takes into account: value of GTI efficiency $\eta_{EPP} = \eta_{GTI}$ = 0,33 and the value of total efficiency of generation, supply and conversion of electric energy to large capacity HPI with electric drive η_{EP} = 0,26.

On the base of the analysis of the results of research, carried out [10-12], optimal values of β index for HPP at various sources of heat with different kinds of drive of HPI compressor at variable operation modes of heating system are determined.

In figs. 7-9 the results of complex evaluation of energy efficiency of small capacity HPP with electric drive for optimal values of load share of HPI β are shown. The values of dimensionless criterion of energy efficiency of HPP with electric drive K_{HPP} for the cases of variable load of HPI within HPP are shown here. The research is performed for the cases of season variable load of HPI within HPP for optimal values of HPI load share in the range of β = 0,16…0,63 [10-12], that corresponds to temperature operation modes of heat supply system. Values of energy efficiency criterion of HPI with electric drive K_{HPI} corresponds to the values of real coefficient of performance of HPI within the range φ_r = 0,6…6,0. Peak source of heat of HPP for these conditions is provided electric boiler house with η_{EB} = 0,95. In accordance with [6] the value of efficiency of distributive electric grids in Ukraine η_{DG} = 0,875 is taken into account.

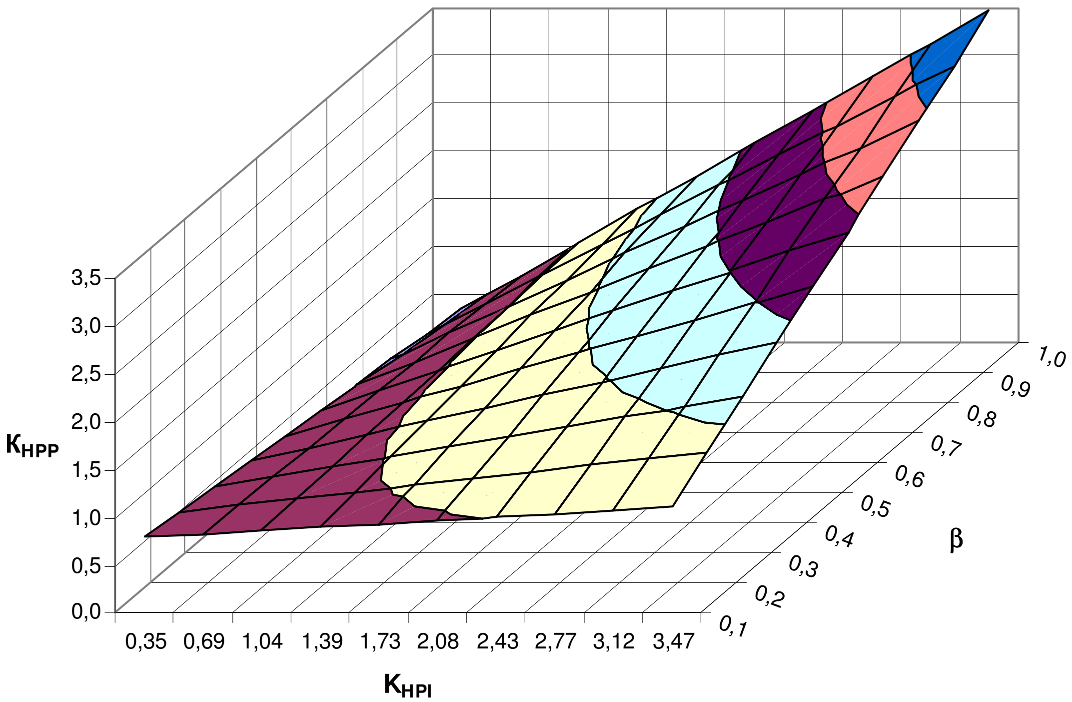

Fig. 5 – Values of dimensionless criterion of energy efficiency of large capacity HPP with electric drive for the cases of variable load of HPI, on condition of electric energy consumption from SGI

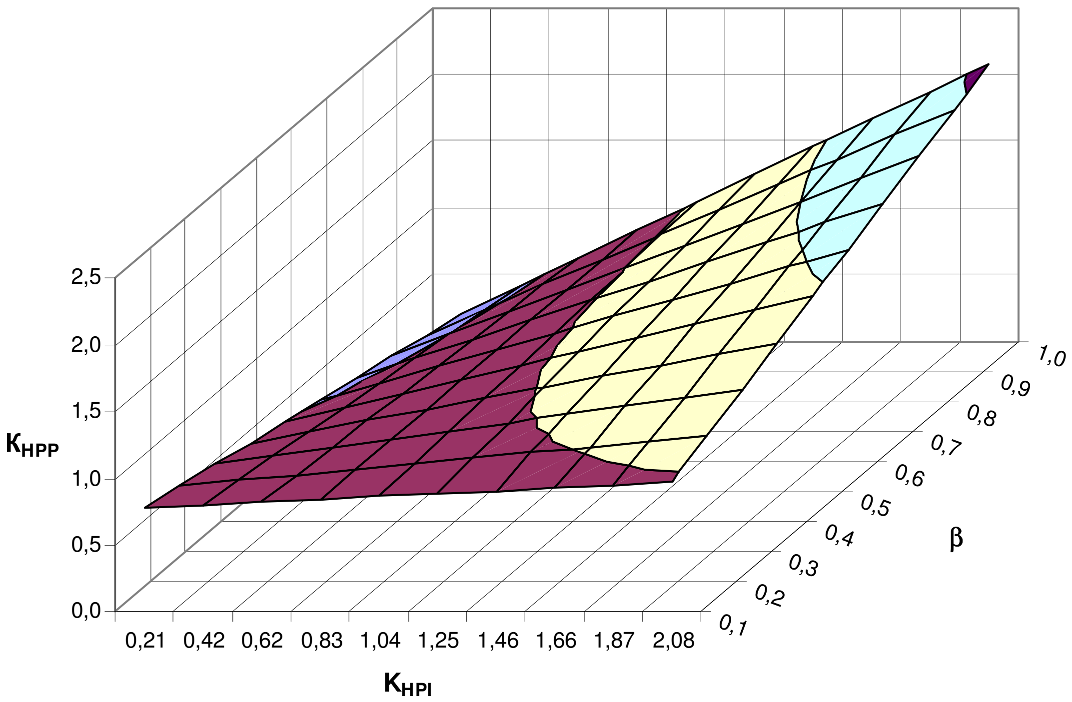

Fig. 6 – Values of dimensionless criterion of energy efficiency of large capacity HPP with electric drive for the cases of variable load of HPI, on condition of electric energy consumption from GTI

Fig. 7 shows the values of dimensionless criterion of energy efficiency of small capacity HPP with electric drive for optimal values of HPI β load share, on condition of electric energy consumption from energy system of Ukraine. The given research, in accordance with [6], takes into account: averaged value of electric power plants in Ukraine efficiency η_{EPP} = 0,383 and the value of total efficiency of generation, supply and conversion of electric energy to small capacity HPI with electric drive $\eta_{EP} = 0{,}268$.

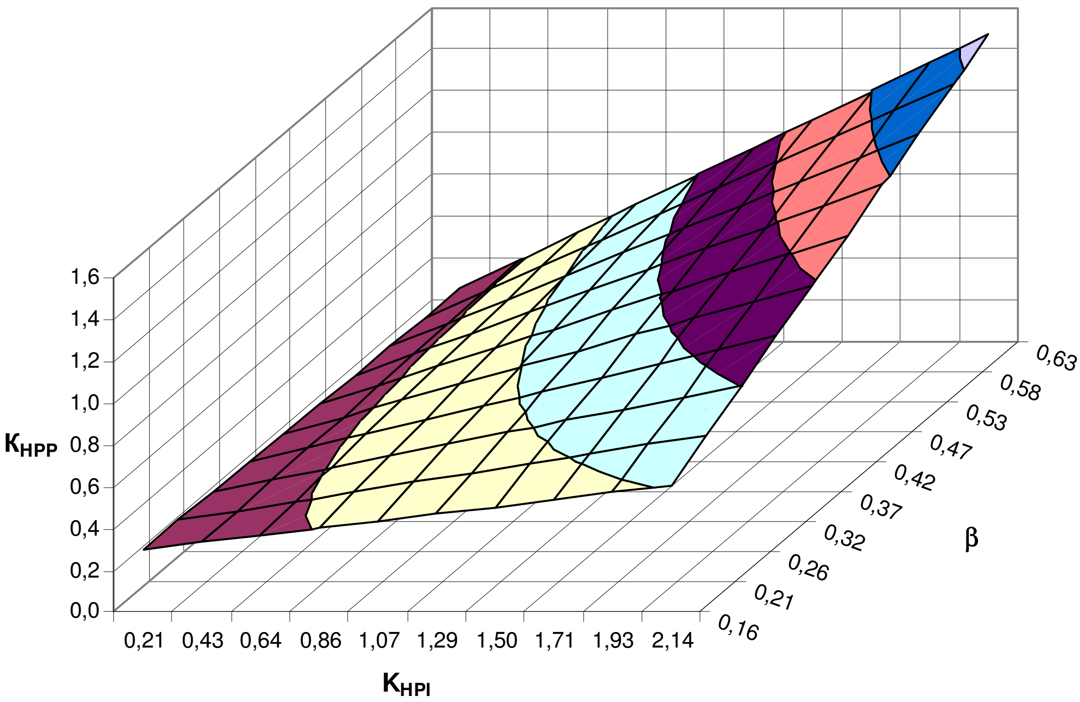

Fig. 7 – Values of dimensionless criterion of energy efficiency of small capacity HPP with electric drive for optimal values of HPI load share, on condition of electric energy consumption from energy system of Ukraine

Fig. 8 shows the values of dimensionless criterion of energy efficiency of small capacity HPP with electric drive for optimal values of HPI β load share, on condition of electric energy consumption from SGI. According to [6], this research takes into account: value of SGI efficiency $\eta_{EPP} = \eta_{SGI} = 0{,}55$ and the value of total efficiency of generation, supply and conversion of electric energy to small capacity HPI with electric drive $\eta_{EP} = 0{,}385$.

Fig. 9 shows the values of dimensionless criterion of energy efficiency of small capacity HPP with electric drive for optimal values of HPI β load share, on condition of electric energy consumption from GTI. The given research, according to [6], takes into account: value of GTI efficiency $\eta_{EPP} = \eta_{GTI} = 0{,}33$ and the value of total efficiency of generation, supply and conversion of electric energy to small capacity HPI with electric drive $\eta_{EP} = 0{,}231$.

Figs. 10-12 shows the results of complex evaluation of energy efficiency of large capacity HPP with electric drive for optimal values of HPI β load share. The values of dimensionless criterion of energy efficiency of HPP with electric drive K_{HPP} for the cases of variable load of HPI within HPP are shown here. The research was carried out for the cases of season variable load HPI within HPP for optimal values of HPI load share in the range of β = 0,16…0,63 [10-12], that corresponds to temperature operation modes of heat supply system. The values of energy efficiency criterion of HPI with electric drive K_{HPI} corresponds to the values of real coefficient of performance of HPI in the range of φ_r = 0,68…6,75. Peak source of heat of HPP for these conditions, hot-water fuel-fired boiler house with $\eta_{FB} = 0{,}85$ is provided. According to [6], the value of distributive electric grids efficiency in Ukraine $\eta_{DG} = 0{,}875$ is taken into account.

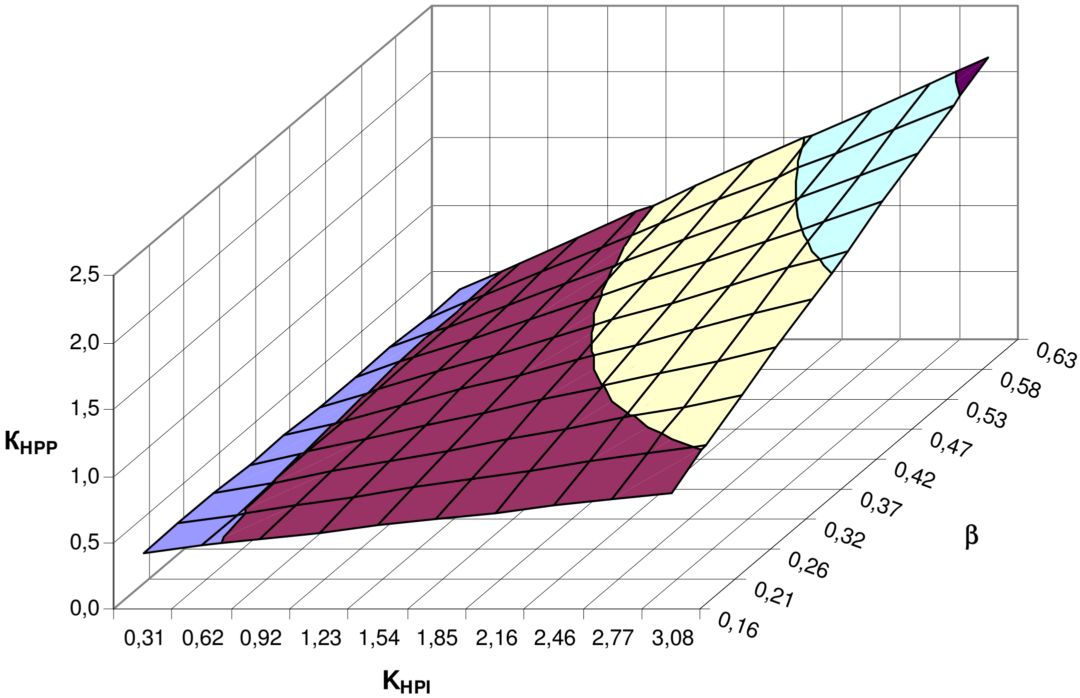

Fig. 8 – Values of dimensionless criterion of energy efficiency of small capacity HPP with electric drive for optimal values of HPI load share, on condition of electric energy consumption from SGI

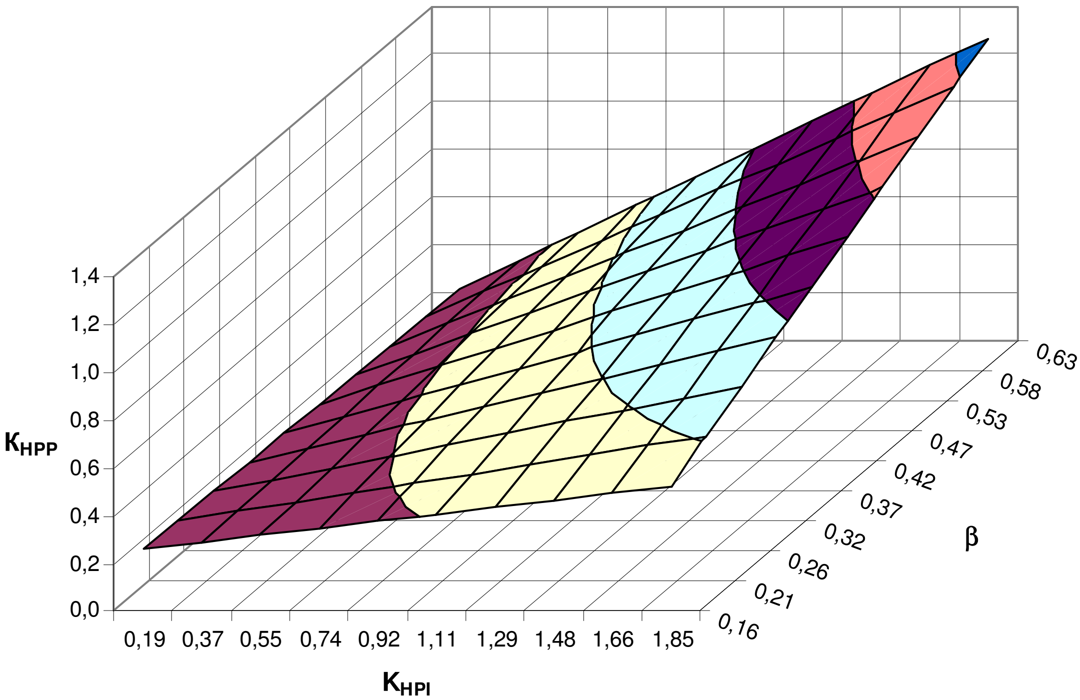

Fig. 9 – Values of dimensionless criterion of energy efficiency of small capacity HPP with electric drive for optimal values of HPI load share, on condition of electric energy consumption from GTI

Fig. 10 shows the values of dimensionless criterion of energy efficiency of large capacity HPP with electric drive for optimal values of HPI β load share, on condition of electric energy consumption from energy system of Ukraine. The given research, according to [6], takes into account: averaged value of efficiency of electric power plants in Ukraine η_{EPP} = 0,383 and the value of total efficiency of generation, supply and conversion of electric energy to large capacity HPI with electric drive $\eta_{EP} = 0{,}301$.

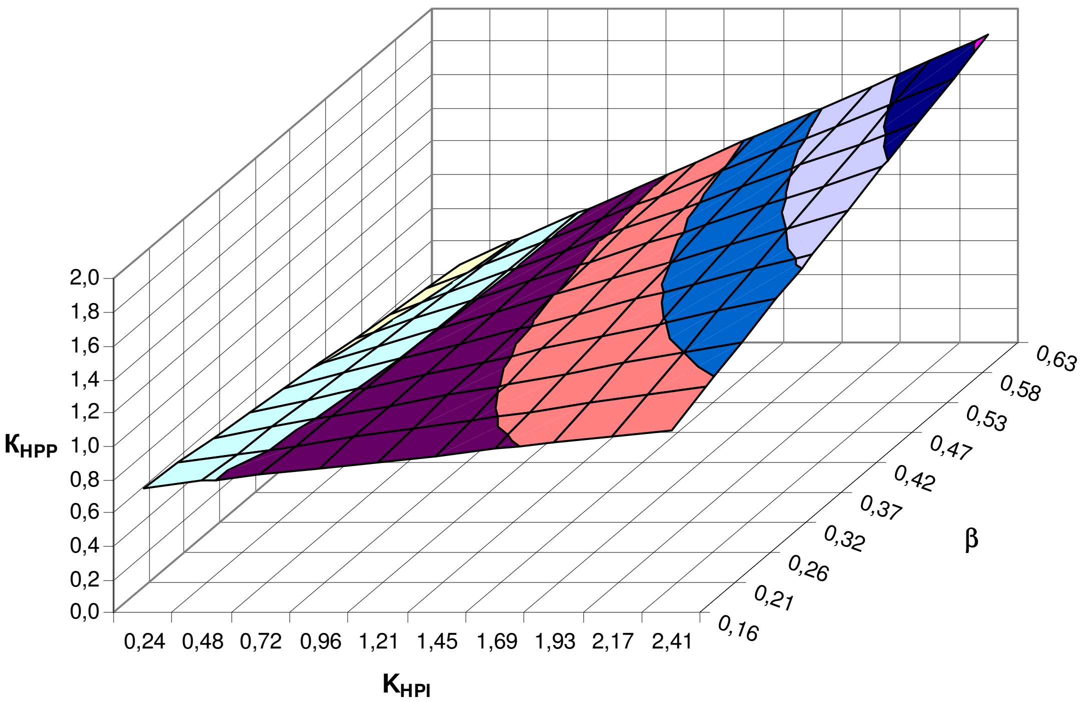

Fig. 10 – Values of dimensionless criterion of energy efficiency of large capacity HPP with electric drive for optimal values of HPI load share, on condition of electric energy consumption from energy system of Ukraine

Fig. 11 shows the values of dimensionless criterion of energy efficiency of large capacity HPP with electric drive for optimal values of HPI β load share, on condition of electric energy consumption from SGI. According to [6], this research takes into account: value of SGI efficiency η_{EPP} = η_{SGI} = 0,55 and the value of total efficiency of generation, supply and conversion of electric energy to large capacity HPI with electric drive $\eta_{EP} = 0{,}433$.

Fig. 12 shows the values of dimensionless criterion of energy efficiency of large capacity HPP with electric drive for optimal values of HPI β load share, on condition of electric energy consumption from GTI. The given research, according to [6], takes into account: value of GTI efficiency η_{EPP} = η_{GTI} = 0,33 and the value of total efficiency of generation, supply and conversion of electric energy to large capacity HPI with electric drive $\eta_{EP} = 0{,}26$.

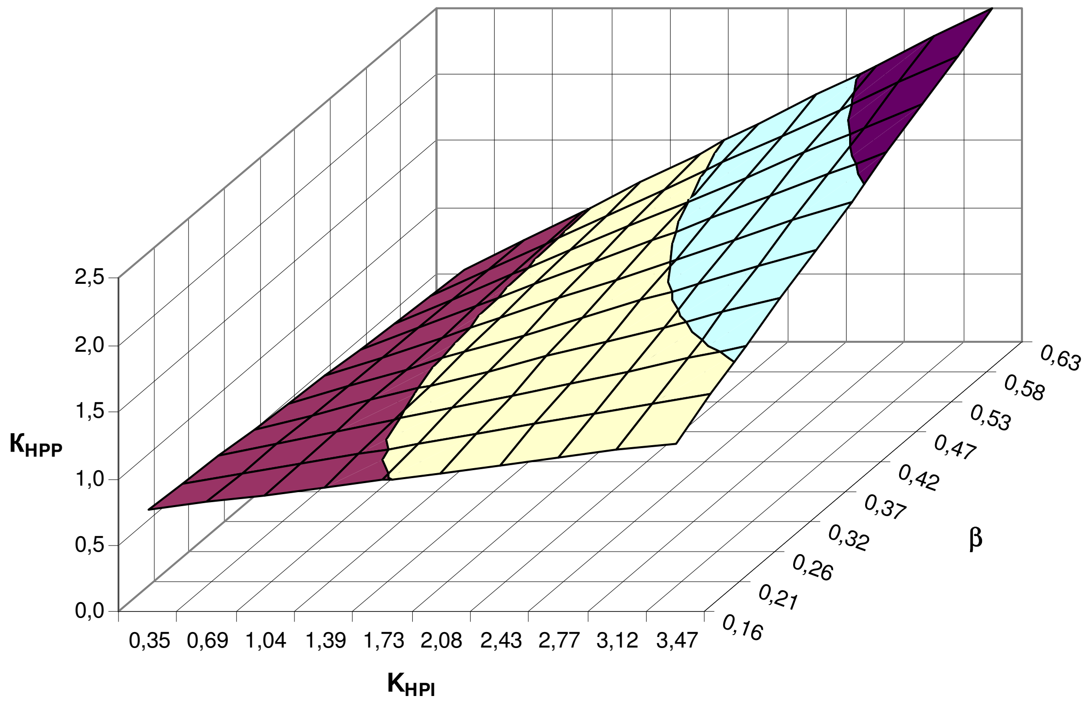

Fig. 11 – Values of dimensionless criterion of energy efficiency of large capacity HPP with electric drive for optimal values of HPI load share, on condition of electric energy consumption from SGI

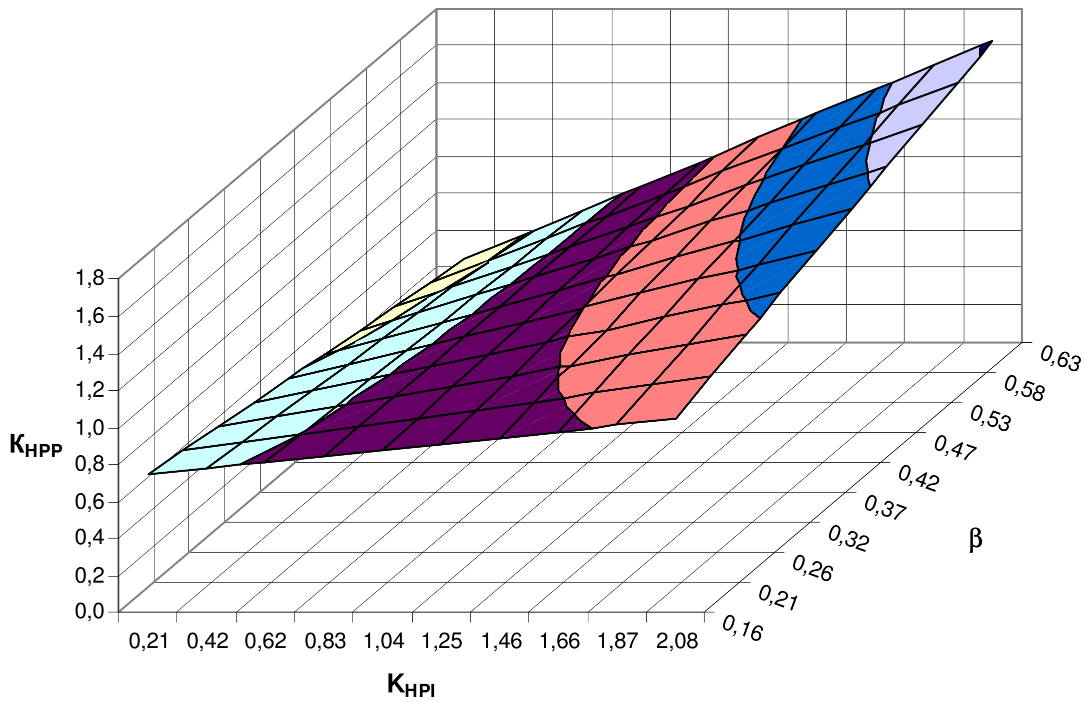

Fig. 12 – Values of dimensionless criterion of energy efficiency of large capacity HPP with electric drive for optimal values of HPI load share, on condition of electric energy consumption from GTI

To perform complex evaluation of energy efficiency of different variants of HPP with electric drive, besides the above-mentioned approaches, we suggest to use the results from the researches [6-12].

Conclusions

The approach, regarding complex evaluation of energy efficiency of steam compressor heat pump plants with electric drive, taking into account complex impact of variable operation modes of HPP, peak sources of HPP heat, sources of drive energy of HPP, with the account of energy losses in the process of generation, supply and conversion of electric energy is suggested.

Methodical fundamentals are developed, complex evaluation of energy efficiency of steam compressor HPP with electric drive, taking into account complex impact of HPP variable operation modes, peak sources of HPP heat, sources of drive energy of steam compressor HPP, with the account of energy losses in the process of generation, supply and conversion of electric energy, is carried out.

The suggested complex approach, aimed at evaluation of energy efficiency of steam compressor HPP with electric drive has several advantages:

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

— it takes into account the operation modes of steam compressor HPI;

— it takes into account variable operation modes of HPP for heat supply during the year with the change of load distribution amony steam compressor HPI and peak source of HPP heat;

— it takes into account the impact of drive energy sourses of steam compressor HPP, with the account of energy losses in the process of generation, supply and conversion of electric energy to HPP;

— it takes into account energy efficiency of steam compressor HPP of various capacity levels with electric drive;

— it takes into account the impact of peak sources of heat of steam compressor HPP and kind of the consumed energy, 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 energy efficiency of electrically-driven HPP, the choice of the most efficient peak source of heat for certain kind of steam compressor HPP can be performed;

— the suggested methodical fundamentals can be applied for evaluation of energy efficiency of steam compressor HPP with different refrigerants and scheme solutions of HPI;

— it allows to evaluate in a complex manner energy efficiency of considerable number of variants of steam compressor HPP with electric drive.

To perform complex evaluation of energy efficiency of different variants of HPP with electric drive, besides the above-mentioned approaches, we propose to use the results from the researches [6-12].

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Ostapenko Olga – Cand. Sc. (Eng.), Assistant Professor with the Department of Heat Power Engineering, olgaost@rambler.ru.

Vinnytsia National Technical University.