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ENERGY EFFICIENCY OF ENERGY SUPPLY SYSTEMS, BASED ON COMBINED COGENERATION HEAT PUMP INSTALLATIONS

Approach to energy efficiency evaluation of energy supply systems (ES), based on combined co-generation heat pump installations (CHPI), taking into consideration complex impact of variable operation modes, sources of drive energy of steam compressor installations (HPI) of various levels of power, taking into account energy losses in the process of generation, supply and conversion of electric energy is suggested.

Key words: *energy efficiency, energy supply system, cogeneration heat pump installation, dimensionless criterion of energy efficiency.*

Introduction

As a result of the shortage and inadequacy in quality of domestic energy resources and high cost of the imported fuel-energy resources in Ukraine, increased demand for electric energy in the peak consumption hours (especially in heating period), because of insufficiency of the existing electric generation power in Ukraine and periodic non-agreement of electric generation and consumption schedules, in order to reduce the load on energy system of Ukraine, in modern conditions the technology of creation of energy generating capacities, based on combined cogeneration and heat pump installations becomes extremely actual.

This technology provides the application of combined cogeneration heat pump installations, that enables to reduce the consumption of natural or alternative gas by 30 – 45 %, as compared with boiler installations of the equivalent capacity [1], and obtain cheaper at cost electric energy, as compared with the grid energy (by 30 – 40 %). Cogeneration drive of HPI compressors can be provided on the base of gas engines-generators, manufactured by Ukrainian enterprises.

Taking into consideration the actuality of the given problem, in recent years a number of investigations, dealing with the efficiency of usage combined cogeneration heat pump installations in thermal schemes of energy supply sources were carried out [1 – 8]. In [1] the authors performed research aimed at increase of energy efficiency of heat supply sources, using HPI with cogeneration drive. In [2] the comparative analysis of promising directions of increasing the efficiency of energy supply systems on the base of small power cogeneration installations is carried out, thermal schemes of integrated systems of complex energy supply are suggested. In research [3] authors evaluated economical efficiency of cogeneration and combined cogeneration heat pump installations with gas-piston and gas-turbine engines. However, in the research [3], authors suggested simplified approach to evaluation of HPI energy efficiency only by the coefficient of performance that does not take into consideration all energy losses, connected with heat generation in HPI. Publication [4] contains the results of the study of the scheme of heat-electric power supply source (mini-TEP) with load regulation, based on the usage of heat pumps. Three variants of the thermal schemes were analyzed in research [4]: scheme with cogeneration and heat pump installations with electric energy supply into the grid, scheme with cogeneration and heat pump installations and tank-accumulator with electric energy supply into the grid, scheme with cogeneration and heat pump installations without electric energy supply into the grid. In the research [4] authors suggested simplified approach to evaluation of HPI energy efficiency, that does not take into consideration all energy losses, connected with heat generation in HPI. Thermal schemes, suggested in [4], can be used only to provide the needs of hot water supply and these schemes can provide only partially the power heating.

Efficient real operation modes of HPI with electric and cogeneration drives, taking into consideration the impact of the sources of steam compressor heat pumps drive energy and energy losses in the process of generation, supply and conversion of electric energy to HPI are determined in [5]. Energy advantages of steam compressor heat pumps with electric and cogeneration drives usage are analyzed in the research [6]. Methodical fundamentals of complex evaluation of energy efficiency of steam compressor heat pump plants (HPP) with electric and cogeneration drives, taking into consideration complex impact of variable operation modes of HPP, peak sources of heat of HPP, sources of HPP drive energy and considering energy losses in the process of generation, supply and conversion of electric energy, are suggested in [7]. In research [8] the complex evaluation of energy efficiency of steam compressor HPP with cogeneration drive, is carried out, taking into consideration complex impact of variable operation modes of HPP, peak sources of heat of HPP, sources of HPP drive energy of steam compressor HPP of various power levels, taking into consideration energy losses in the process of generation, supply and conversion of electric energy.

In [1 – 8] authors did not perform evaluation of energy efficiency of energy supply systems, based on combined cogeneration heat pump installations, efficient operation modes of energy supply systems, based on combined cogeneration heat pump installations, taking into account complex impact of variable operation modes, sources of drive energy of steam compressor HPI of various power levels, taking into consideration energy losses in the process of generation, supply and conversion of electric energy are not determined.

The aim of the research is the evaluation of energy efficiency of energy supply systems, based on combined cogeneration heat pump installations, determination of efficient operation modes of energy supply systems, based on combined cogeneration heat pump installations, taking into account complex impact of variable operation modes, sources of drive energy of steam compressor HPI of various power levels, taking into consideration energy losses in the process of generation, supply and conversion of electric energy.

Main part

The given research contains the evaluation of energy efficiency of energy supply systems, based on combined cogeneration heat pump installations. The efficiency of energy supply systems, based on steam compressor HPI of small (up to 1 MW) and large power with cogeneration drive from gas-piston engine-generator (GPE) was investigated. Usage of cogeneration installations for heat pumps drive allows to avoid additional losses of electric energy in the process of transport and provides recovery of fuel gases heat after gas-fired engine, that provides better energy efficiency. The investigated energy supply systems, based on combined cogeneration heat pump installations can completely or partially ensure installation's needs in electric energy and provide heating and hot water consumers. Schemes of the energy supply systems, based on combined cogeneration heat pump installations are given in [1, 9].

Thermal capacity of ES, based on combined CHPI is determined, taking into consideration the power of HPI and utilization equipment of HPI cogeneration drive $Q_{CHPI} = Q_c + \Sigma Q_{ut}$, where Q_c – capacity of HPI condenser, ΣQ_{ut} – capacity of utilization equipment of HPI cogeneration drive.

Energy efficiency of energy conversion in HPI within CHPI is most frequently evaluated by the coefficient of performance of energy, that equals to the ratio of energy, supplied to the consumer, to the energy, used for cycle realization.

In our research, value of the coefficient of performance of HPI for ES, based on CHPI, according to [1, 5, 9] is determined, taking into consideration the capacity of utilization equipment of cogeneration drive:

$$\varphi_t^{CHPI} = \frac{Q_{CHPI}}{N_{cm}}, \tag{1}$$

where N_{cm} – power of HPI compressor.

The expression of the coefficient of performance of HPI for ES, based on CHPI by the formula (1) may also be presented in the form:

$$\varphi_t^{CHPI} = \varphi_t + K_{GPE}^h, \tag{2}$$

where φ_t – theoretical value of the coefficient of performance of HPI without consideration of GPE utilization equipment power; K_{GPE}^h – thermal coefficient of GPE, that equals the ratio of heat utilization power of GPE to its electric power.

We analyzed the characteristics of a number of gas-piston engine-generators of native production («Pervomayskdizelmach» and state enterprise «V. O. Malyshev plant») and of foreign production (Jenbacher ES (Austria), Wartsilla Disel (Sweden), Ulstein Bergen (Norway), MAN & (Denmark)). It is determined, that the value of thermal coefficient of GPE for the considered gas-piston engine-generators in the range of electric powers of 500…2400 kW is K_{GPE}^h = 1,1…1,44; that corresponds to change range of efficient electric efficiency factor of gas-piston engine η_{EM} = 0,42…0,31. The obtained data perfectly agree with the results from the investigation [3].

Taking into consideration the above-mentioned, the expression of the coefficient of performance of HPI for ES, based on CHPI from the formula (2) will have the form:

$$\varphi_t^{CHPI} = \varphi_t + (1{,}1...1{,}44). \tag{3}$$

As it is seen from the formula (3) the value of the coefficient of performance of HPI with the drive from cogeneration installations will be much higher than the coefficient of performance of HPI φ_t with electric drive.

Real HPI coefficient of performance may be defined as:

$$\varphi_r = \varphi_t \cdot \eta_{hp}, \tag{4}$$

where η_{hp} – energy efficiency of HPI, that takes into consideration all losses of energy in the heat pump.

Real CHPI coefficient of performance may be defined as:

$$\varphi^{CHPI} = \varphi_t^{CHPI} \cdot \eta_{hp}. \tag{5}$$

In our research, we analyzed the energy efficiency of the system «Source of drive energy of CHPI – CHPI – heat consumer from CHPI» on the base of combined cogeneration heat pump installations. The advantage of this approach is taking into consideration of energy losses in the process of generation, supply and conversion of electric energy in CHPI in order to determine the efficient operation modes for ES, based on CHPI.

In research [5] we suggested dimensionless criterion of energy efficiency of steam compressor HPI with cogeneration drive. 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 the 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.

Taking into consideration such an approach, dimensionless criterion of energy efficiency for ES, based on combined CHPI, according to [5] will have the form:

$$K_{ES} = Q_{CHPI} / Q_h = \eta_{EP} \cdot \varphi^{CHPI} \cdot \eta_{hf}, \tag{6}$$

where Q_h – power, spent by gas-piston engine-generator for generation of electric energy for HPI drive, η_{EP} – total efficiency factor of generation, supply and conversion of electric energy from [5], 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.

According to [5], for ES, based on CHPI, total efficiency factor of generation, supply and conversion of electric energy, can be determined:

$$\eta_{EP} = \eta_{EM} \cdot \eta_{ED}, \tag{7}$$

where η_{EM} – efficient factor of gas-piston engine; η_{ED} – efficiency factor of electric motor, taking into consideration energy losses in the control unit of the engine from [5].

With the account of the formula (7) for ES, based on CHPI, dimensionless criterion of energy efficiency from the formula (6) will have the form:

$$K_{ES} = Q_{CHPI} / Q_h = \eta_{EM} \cdot \eta_{ED} \cdot \varphi^{CHPI} \cdot \eta_{hf} . \qquad (8)$$

On condition $K_{ES} = 1$, energy supply system, based on CHPI transports to the consumer the same thermal capacity, as the capacity, that was consumed for generation of electric energy for HPI drive. The greater is the value of this index, the more efficient and competitive energy supply system, based on CHPI will be.

The suggested approach of evaluation of energy efficiency of energy supply systems, based on CHPI has a number of advantages:

— it enables to evaluate the impact of variable operation modes of CHPI, taking into account energy losses in the process of generation, supply and conversion of electric energy;

— it takes into consideration operation modes of steam compressor HPI;

— it takes into consideration the impact of the 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 in CHPI;

— it takes into consideration energy efficiency of energy supply systems, based on CHPI of various power levels;

— the suggested methodical fundamentals may be used for evaluation of energy efficiency of energy supply systems, based on CHPI with various refrigerants, sources of low temperature heat and scheme engineering solutions of HPI.

The application of the suggested approaches, aimed the evaluation of energy efficiency of energy supply systems, based on CHPI we will demonstrate on specific examples.

Fig. 1 shows the values of real coefficient of performance for ES, based on CHPI of small power levels, depending on the real values of the coefficient of performance of HPI and efficient electric efficiency factor of GPE. In the given research, according to [5], the value of electric motor efficiency with the account of energy losses in the motor control unit η_{ED} = 0,8 is taken into consideration. It is seen from Fig. 1, that for the values of real coefficient of performance of HPI in the range φ_r = 0,6…5,4 the values of real coefficient of performance for ES, based on CHPI of small power change in the range of φ^{CHPI} = 1,7…6,84; that is achieved due to the usage of the heat of utilization equipment of HPI cogeneration drive. Such ES, based on CHPI, depending on operation mode, generates 1,7…6,84 units of thermal capacity in HPI and utilization equipment of cogeneration drive relatively to the unit of electric power, consumed by HPI, without the consumption of electric energy from energy system. For comparison, it should be noted, that HPI with electric drive, under these operation modes will generate 0,6…5,4 units of thermal capacity relatively to the unit of the consumed electric power. The obtained high values of real coefficient of performance for ES, based on CHPI of small power affirm high energy efficiency of such combined systems.

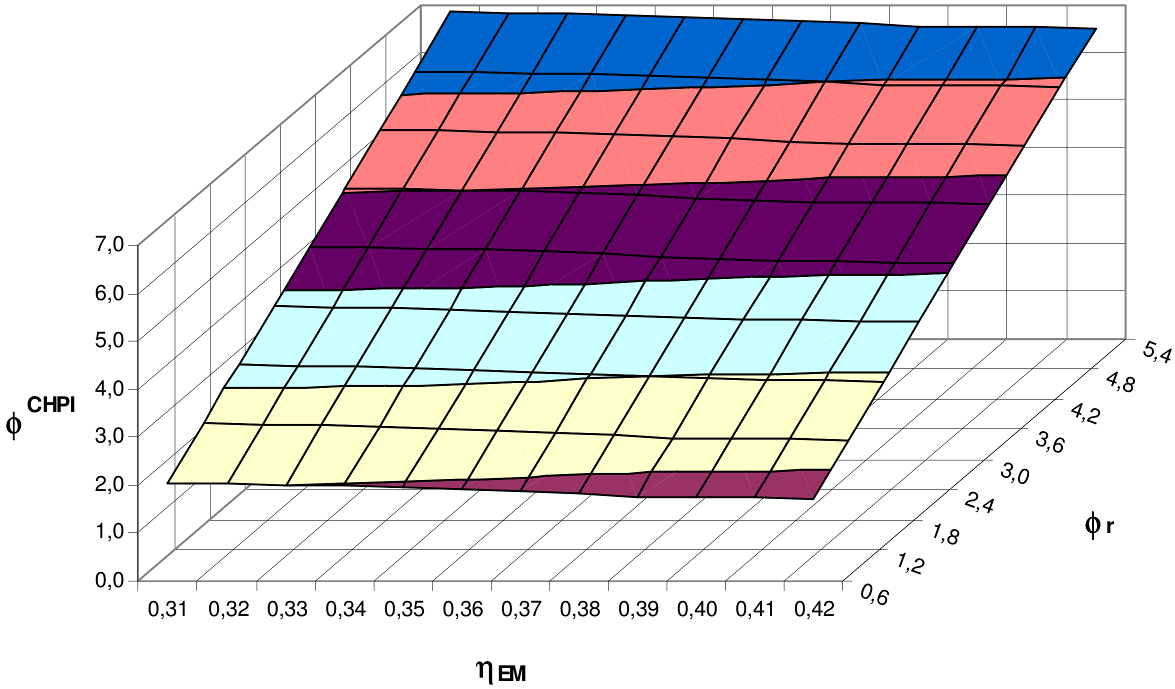

Fig. 1. Values of real coefficient of performance for ES, based on CHPI of small power, depending on the real values of the coefficient of performance of HPI and efficient electric efficiency factor of GPE

Fig. 2 shows values of the dimensionless criterion of energy efficiency for ES, based on CHPI of small power K_{ES}, depending on real values of the coefficient of performance of HPI and efficient electric efficiency factor of GPE. In the study, according to [5], the value of electric motor efficiency is taken into account with the account of energy losses in control unit of the motor $\eta_{ED} = 0{,}8$. As it is seen from Fig. 2, for the values of the real coefficient of performance of HPI in the range of φ_r = 1,8…5,4 the values of dimensionless criterion of energy efficiency for ES, based on CHPI of small power change in the range $K_{ES} = 0{,}66…2{,}04$.

As it was mentioned above, on condition that $K_{ES} = 1$ energy supply system, based on CHPI will transport to the consumer the same thermal capacity, as the capacity, that was consumed for generation of electric energy for HPI drive. The greater the value of this index is, the more efficient and competitive energy supply system, based on CHPI will be.

Thus, efficient operation modes of such ES, based on CHPI of small power will satisfy the condition $K_{ES} > 1$. The obtained high values of dimensionless criterion of energy efficiency for ES, based on CHPI of small power prove high energy efficiency of such combined systems.

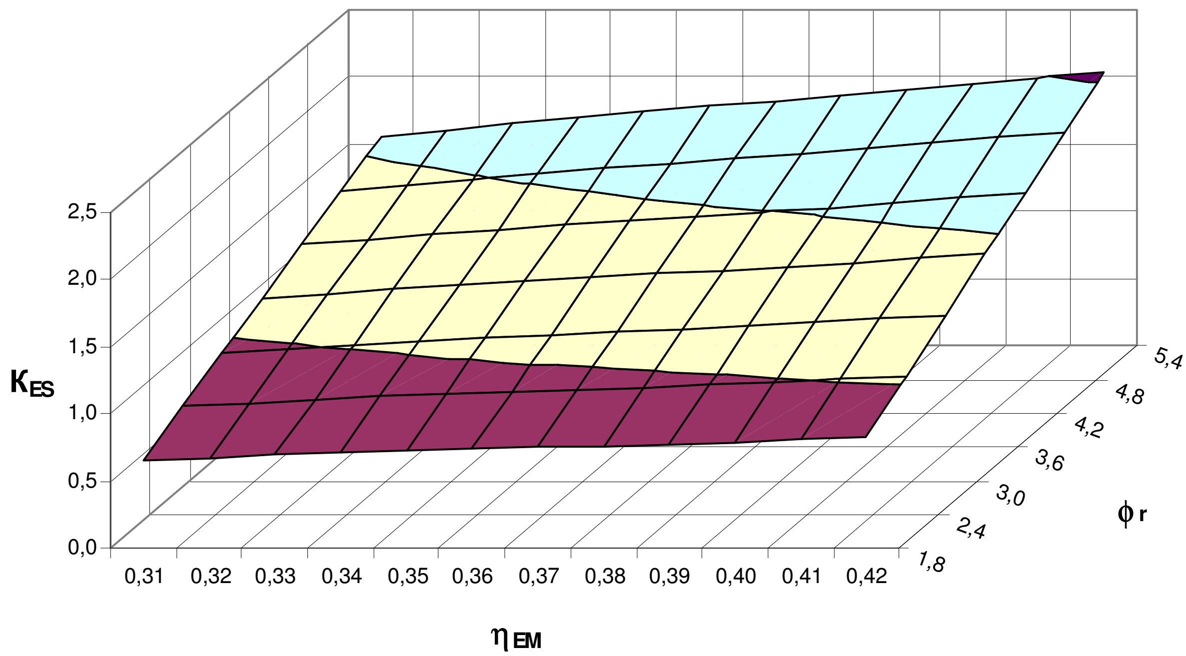

Fig. 2. Values of the dimensionless criterion of energy efficiency for ES, based on CHPI of small power, depending on real values of HPI coefficient of performance and efficient electric efficiency factor of GPE

Fig. 3 shows the values of real coefficient of performance for ES, based on CHPI of large power, depending on real values of HPI coefficient of performance and efficient electric efficiency factor of GPE. In the given research, according to [5], value of electric motor efficiency is taken into consideration, with the account of energy losses in the control unit of electric motor η_{ED} = 0,9. From Fig. 3, it is seen, that for the values of real HPI coefficient of performance within the range φ_r = 0,7…6,1 values of real coefficient of performance for ES, based on CHPI of large power change in the range of $\varphi^{CHPI} = 1{,}78\ldots7{,}72$; this is achieved as a result of using the heat of utilization equipment of HPI cogeneration drive.

Such ES, based on CHPI, depending on operation mode, generates 1,78…7,72 units of thermal capacity in HPI and utilization equipment of cogeneration drive relatively to the unit of electric power, consumed by HPI, without the consumption of electric energy from energy system. For comparison, it should be noted, that electrically-driven HPI under these operation modes will generate 0,7…6,1 units of thermal capacity relatively to the unit of the consumed electric power.

The obtained high values of real coefficient of performance for ES, based on CHPI of large power affirm high energy efficiency of such combined systems that exceeds the efficiency of such systems, based on CHPI of small power.

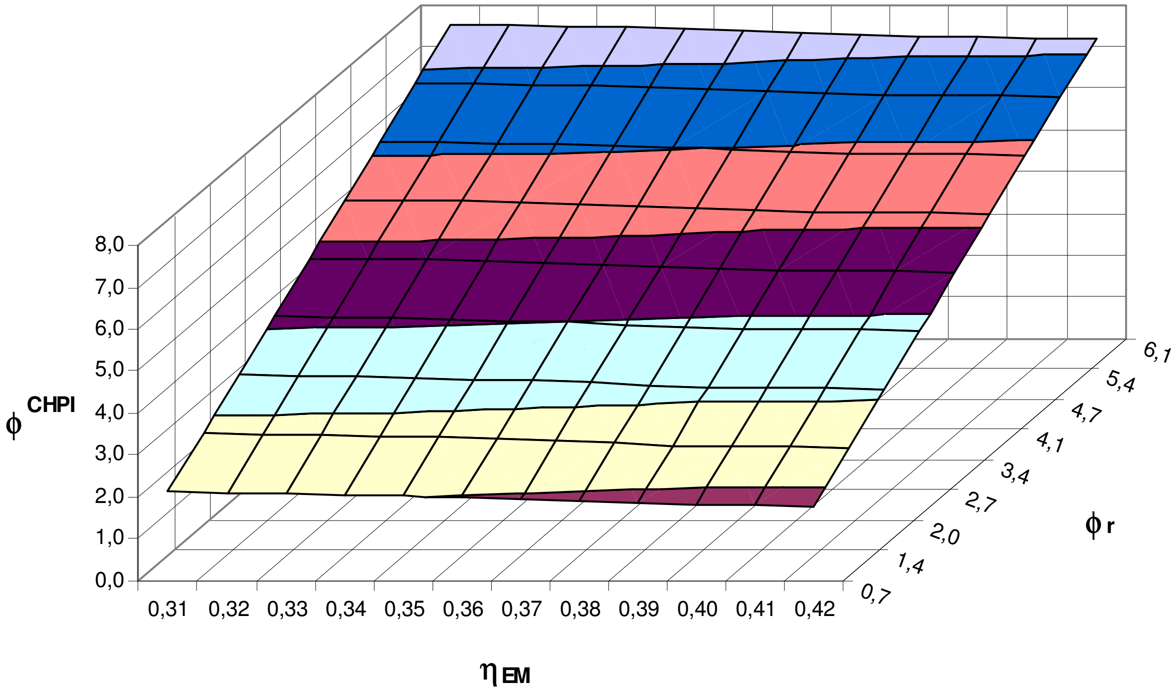

Fig. 3. Values of real coefficient of performance for ES, based on CHPI of large power, depending on real values of HPI coefficient of performance and efficient electric efficiency factor of GPE

Fig. 4 shows values of the dimensionless criterion of energy efficiency for ES, based on CHPI of large power K_{ES}, depending on real values of HPI coefficient of performance and efficient electric efficiency factor of GPE. In the given research, according to [5], the value of electric motor efficiency is taken into consideration, with the account of energy losses in control unit of the motor $\eta_{ED} = 0{,}9$.

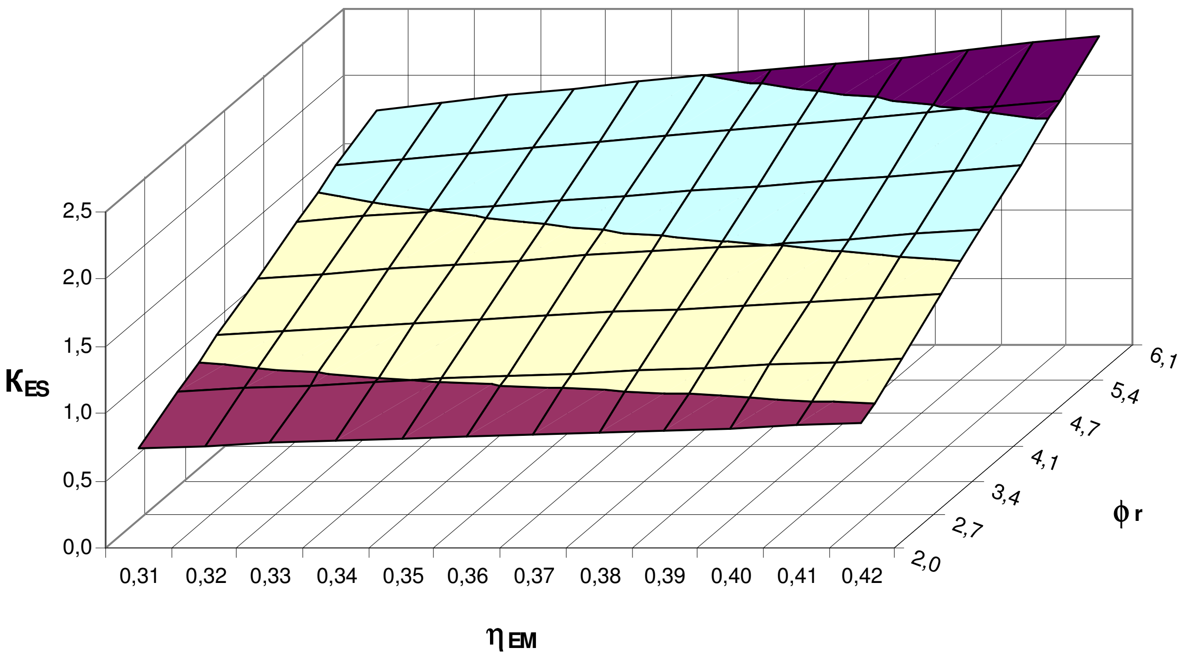

Fig. 4. Values of the dimensionless criterion of energy efficiency for ES, based on CHPI of large power, depending on real values of HPI coefficient of performance and efficient electric efficiency factor of GPE

As it is seen from Fig. 4, for the values of the real coefficient of performance of HPI in the range of φ_r = 2,0…6,1 the values of dimensionless criterion of energy efficiency for ES, based on CHPI of large power change in the range K_{ES} = 0,74…2,29.

As it was mentioned above, on condition that $K_{ES} = 1$ energy supply system, based on CHPI will transport to the consumer the same thermal capacity, as the capacity, consumed for generation of electric energy for HPI drive. The greater the value of this index is, the more efficient and competitive energy supply system, based on CHPI will be. Thus, efficient operation modes of such ES, based on CHPI of large power will satisfy the condition $K_{ES} > 1$

The obtained high values of dimensionless criterion of energy efficiency for ES, based on CHPI of large power prove high energy efficiency of such combined systems that exceeds the efficiency of such systems, based on CHPI of small power.

Comparing the results of research, shown in Figs. 1 – 2 and Figs. 3 – 4, the conclusions can be drawn, that usage of ES, based on CHPI of large power has the advantages as compared with usage of ES, based on CHPI of small power, that is confirmed by greater values of dimensionless criterion of energy efficiency of ES, based on CHPI K_{ES} for various operation modes. Proceeding from the analysis of the results of the research (Figs. 1 – 4) it was determined, that for ES, based on CHPI of large power, the greater values of indexes of energy efficiency are recorded for all investigated operation modes.

To carry out the evaluation of energy efficiency of different variants of ES, based on CHPI, besides the above-mentioned approaches, we propose to use the results of research [1, 5 – 9].

Conclusions

The approach, aimed at evaluation of energy efficiency of energy supply systems, based on combined cogeneration heat pump installations, taking into account complex impact of variable operation modes, sources of drive energy of steam compressor HPI of various power levels, taking into consideration energy losses in the process of generation, supply and conversion of electric energy, is suggested.

Methodical fundamentals have been developed, evaluation of energy efficiency of energy supply systems, based on combined cogeneration heat pump installations, determination of efficient operation modes of energy supply systems, based on combined cogeneration heat pump installations, taking into account complex impact of variable operation modes, sources of drive energy of steam compressor HPI of various power levels, taking into consideration energy losses in the process of generation, supply and conversion of electric energy, has been carried out.

The suggested approach of evaluation of energy efficiency of energy supply systems, based on CHPI has a number of advantages:

— it enables to evaluate the impact of variable operation modes of CHPI, taking into account energy losses in the process of generation, supply and conversion of electric energy;

— it takes into consideration operation modes of steam compressor HPI;

— it takes into consideration the impact of the 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 in CHPI;

— it takes into consideration energy efficiency of energy supply systems, based on CHPI of various power levels;

— the suggested methodical fundamentals may be used for evaluation of energy efficiency of energy supply systems, based on CHPI with various refrigerants, sources of low temperature heat and scheme engineering solutions of HPI.

Proceeding from the analysis of the results of the research it was determined, that usage of ES, on base of CHPI of large power has the advantages as compared with usage of ES, based on CHPI of small power, that is confirmed by greater values of dimensionless criterion of energy efficiency of ES, based on CHPI K_{ES} for various operation modes. It was determined, that for ES, based on

CHPI of large power, the greater values of indexes of energy efficiency are recorded for all investigated operation modes.

To carry out the evaluation of energy efficiency of different variants of ES, based on CHPI, besides the above-mentioned approaches, we propose to use the results of researches [1, 5 – 9].

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