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ENERGY EFFICIENCY OF STEAM COMPRESSOR HEAT PUMPS WITH ELECTRIC AND COGENERATION DRIVE

Energy efficiency of steam compressor heat pumps (HP) with electric and cogeneration drive has been analyzed. Efficient real operation modes of heat pumps with electric and cogeneration drive are determined, taking into account energy losses in the process of generation, supply and conversion of electric energy.

***Key words**: energy efficiency, heat pump, coefficient of performance, electric drive, cogeneration drive.*

Introduction

Modern development of power industry is characterized by substantial cost increase of energy resources, deterioration of the environment and complication of its protection against the impact of heat generating installations. Energy and resource-saving, environment protection are priority directions in the development of fundamental research in the sphere of fuel and energy resources [1]. In industrial complex of Ukraine the share of natural gas consumption still remains rather high more than half of energy problems of the country are solved at the expense of natural gas burning. Problem of efficient consumption of energy resources and introduction of energy-saving technologies becomes very urgent due to energy crisis [2]. Usage of steam compressor heat pumps with electric and cogeneration drive will promote natural gas saving and environment protection due to reduction of thermal pollution and harmful emissions of combustion products.

In recent years a great deal of papers were devoted to the problems of energy efficiency of heat pumps [1 – 7]. In [1] the author carried out the research aimed at efficiency increase, selection of rational parameters and operation modes of heat pumping plants for heating systems and heat supply regarding equivalent fuel consumption. In [2] thermodynamic and exergy analysis of the efficiency of steam compressor cycle of heat pumping plants of heat supply was carried out. The authors in [3] analyze thermodynamic efficiency of heat pumping plants of heat supply. In [4] new approach to the estimation of heat pumps is suggested. However, in research [3 – 4] energy losses during generation, supply and conversion of electric energy from various types of electric power plants are not taken into consideration. The authors [5] performed analysis of HP with electric and cogeneration drive for limited amount of variants. In [6] the estimation of the efficiency of different variants of heat pumps according to the coefficient of primary energy usage is performed. The author in [7] realized thermodynamic analysis of various types of HP.

In [1–7] the authors did not carry out evaluation of energy efficiency of steam compressor heat pumps with electric and cogeneration drive, taking into account energy losses during generation, supply and conversion of electric energy.

Aim of the research is determination of the efficiency of steam compressor heat pumps with electric and cogeneration drive, determination of the efficient operation modes of HP with electric and cogeneration drive, taking into account energy losses during generation, supply and conversion of electric energy.

Main part

In steam compressor heat pumps increase of temperature level of low temperature heat takes place during mechanical compression of refrigerant in the compressor. Heat pumps may have electric and cogeneration drive (from gas-piston engine). Cogeneration drive of heat pumps has advantages as compared with electric one, because it enables to avoid additional losses of electric energy during transportation. Besides, application of HP with cogeneration drive of the compressor from gas engines can be considered as one of important directions of energy and resources-saving, as it provides utilization of fuel gases heat after gas engine, that provides better energy efficiency.

Energy efficiency of heat pumps may be evaluated by several efficiency criteria. Most frequently energy efficiency of energy conversion in heat pump is evaluated by the coefficient of performance of energy φ, that equals to the ratio of energy, obtained by the consumer, to the energy, used by cycle realization.

Energy efficiency of HP may be evaluated by the coefficient of performance, theoretical value of which is defined by the formula

$$\varphi_t = \frac{T_1}{T_1 - T_2}, \tag{1}$$

where T_1 and T_2 – temperatures of high temperature heat-transfer agent at the output and low temperature heat-transfer agent at the input of HP, K; correspondingly.

It should be noted, that coefficient of performance does not take into consideration all losses of energy, connected with heat generation in HP. In real conditions, besides throttling, energy losses take place in pipe-lines and HP equipment.

Real coefficient of performance of HP will be

$$\varphi_r = \varphi_t \cdot \eta_{hp}, \tag{2}$$

where η_{hp} – energy efficiency factor of HP, that takes into consideration all energy losses in heat pump. Value of energy efficiency of modern HP is within the limits of 0,65–0,7 [4].

In home, foreign literature and in practice the efficiency of HP usage is estimated mainly according to real coefficient of performance. For efficient operation of HP with electric drive value of $\varphi_r \geq 2{,}5...3{,}0$ is considered to be acceptable; high energy efficiency of HP is provided at $\varphi_r = 3{,}5...4{,}0.$ Such values of coefficients of performance are proved by statistic data of real coefficients of performance of HP, manufactured by such companies as LG, Mitsubishi, MHPUL, MHPUE, FUJITSU, McQUAY, HPVU, "ENERGY", "TRITON-LTD" [4].

High energy efficiency of HP with cogeneration drive is provided if $\varphi_r \geq 2{,}0$; it is stipulated by the fact, that additional heat power of utilization equipment of HP cogeneration drive is taken into account [6].

We will analyze energy efficiency of the system "Source of drive energy HP – HP – consumer of heat from HP" on the example of steam compressor heat pumps with electric and cogeneration drive. The advantage of such approach is that energy losses during generation, supply and conversion of electric energy to HP is taken into consideration in order to determine efficient real operation modes of HP with electric and cogeneration drive.

Electric energy in Ukraine is generation by thermal power plants (TPP), nuclear power plants (NPP) and hydropower stations (HPS). Energy branch of national economy of Ukraine comprises 44 thermal power plants, 8 hydropower stations and 4 nuclear power plants. Thermal power plants generate 46,3% of the total volume of generated energy, nuclear power plants generate 47%, and hydropower stations – 7% [8, 9].

Let us perform calculation the energy chain from TPP, NPP and HPS to the consumers of electric energy.

Efficiency factor of TPP of electric energy generation depends on the efficiency factor of main elements – steam boiler, turbine plant and pipe lines of steam and water [9, 10].

During generation of electric energy, part of the generated energy (4–6%) is spent on fuel preparation, boiler air supply, flue gases removal from the boilers, cooling water supply, condensate removal and other needs. If electric energy expenditures for TPP auxiliary power are 5%, then final efficiency factor of TPP (energy unit) may be determined

$$\eta_{TPP} = \eta_{sb} \cdot \eta_{pl} \cdot \eta_{tp}(1-0{,}05), \quad (3)$$

where η_{sb} – efficiency factor of steam boiler, η_{pl} – efficiency factor of pipe lines, η_{tp} – efficiency factor of turbine plant.

Efficiency factor of turbine plant that takes into account considerable loss of thermal energy in turbine condenser (45–50% of generated amount of heat energy) has the greatest impact on efficiency factor of power station. Other losses of energy at power station are far less. Assuming η_{sb}=0,9; η_{pl}=0,99; η_{tp}= 0,5, we obtain from the formula (3) the value of $\eta_{TPP} = 0{,}423$, that corresponds to nominal power of electric power station. In case of insufficient load of TPP the value of efficient factor decreases.

If at NPP nuclear reactor is considered to be the primary source of energy, then the value of NPP efficiency factor will depend on the efficiency factor of turbo-generator plant. Turbo-generator plant comprises steam turbine, efficiency factor of which η_{st} (taking into account all losses of thermal energy in nuclear reactor, in heat exchanger, in condenser, in pipe lines) will be approximately 33 – 34%. Efficiency factor of the generator equals approximately 98,5%. Then, the value of NPP efficiency factor may be determined as:

$$\eta_{NPP} = \eta_{st} \cdot \eta_{g} \cdot = 0{,}33 \cdot 0{,}985 = 0{,}325. \quad (4)$$

At HPP energy of water flows is used for generation of electric energy. Prime movers for HPP are hydro turbines that move synchronous hydro generators. Efficiency factor of HPP is $\eta_{HPP} = 90 - 93\,\%$, and, according to this parameter, they are the most economical power stations [9, 10].

Knowing the values of efficiency factors of TPP, NPP and HPP and also shares of electric energy, they generate, we may determine average efficiency factor of electric energy generation in Ukraine.

Averaged value of electric power plants efficiency factor will be:

$$\eta_{EPP} = \frac{\alpha_{TPP} + \alpha_{NPP} + \alpha_{HPP}}{\dfrac{\alpha_{TPP}}{\eta_{TPP}} + \dfrac{\alpha_{NPP}}{\eta_{NPP}} + \dfrac{\alpha_{HPP}}{\eta_{HPP}}}, \quad (5)$$

where α_{TPP}, α_{NPP}, α_{HPP} – shares of electric energy, generated by corresponding electric power plants.

Taking into account that α_{TPP} = 0,463; α_{NPP} = 0,47 and α_{HPP} =0,07, we may obtain from the formula (5) the averaged value of efficiency factor of power plants η_{PP} = 0,383.

If alternative types of electric power plants (on the base of steam-gas installations (SGI) and gas-turbine installations (GTI), solar power plants of thermodynamic cycle (SPP), wind energy plants (WEP)), are involved in energy balance of Ukraine, the averaged value of power plants efficiency factor will be determined in the following way:

$$\eta_{EPP} = \frac{\Sigma\alpha_i}{\Sigma(\alpha_i/\eta_i)}, \quad (6)$$

where α_i – shares of electric energy, generated by corresponding electric power stations;

η_i – efficiency factor of the corresponding electric power station.

From electric power stations electric energy across distributive grids arrives to the consumer. Efficiency factor of distributive grids operation is determined by the level of energy losses while it's transporting.

According to the annual report of National Commission of Energy Branch Regulation of 2010 value of total technological losses of electric energy in Ukraine was 12,5% of the total volume of electric energy, arrived to the grid. Hence, efficiency factor of distributive grids in Ukraine will be

$$\eta_{DG} = 1 - \beta_{los} = 1\text{-}0{,}125\text{=}0{,}875. \quad (7)$$

At the end of energy chain there is a consumer of electric energy – electric motor of HP. Efficiency factor of 55–100 kW electric motor, taking into account losses of energy in motor control unit, will be $\eta_{ED} = 80$–85%. Efficiency factor of large power electric motor will be $\eta_{ED} = 90$–95%.

Thus, having analyzed chain of generation, supply and conversion of electric energy we obtain the value of general efficiency factor of generation, supply and conversion of electric energy to HP

$$\eta_{EP} = \eta_{EPP} \cdot \eta_{DG} \cdot \eta_{ED}, \quad (8)$$

values of which will be:

– for heat pumps of small capacity (up to 1 MW)

$\eta_{EP} = 0{,}383 \cdot 0{,}875 \cdot 0{,}8 = 0{,}268$;

– for heat pumps of large capacity (higher than 1 MW)

$\eta_{EP} = 0{,}383 \cdot 0{,}875 \cdot 0{,}9 = 0{,}302$.

Equation of energy balance for the system "Source of drive energy HP – HP – consumer of heat from HP" on the example of steam compressor heat pumps with electric drive:

$$Q_{hp} = Q_h \cdot \eta_{EP} \cdot \varphi_t \cdot \eta_{hf}, \quad (9)$$

where Q_{hp} – thermal capacity of HP, Q_h – power, spent at electric power station for generation of electric energy of HP drive, η_{EP} – total efficiency factor of generation, supply and conversion of electric energy according to the formula (8), η_{hf} – efficiency factor of heat flow, that takes into account losses of energy and working substance in pipe lines and HP equipment.

For evaluation of energy efficiency of HP with electric drive, we use non-dimensional index

$$Q_{hp} / Q_h = \eta_{EP} \cdot \varphi_t \cdot \eta_{hf}. \quad (10)$$

On condition that $Q_{hp} / Q_h = 1$ heat pump transfers to consumer the same thermal capacity, that was spent for generation of electric energy to HP drive. The greater is the value of this index, more efficient and competitive heat pump will be.

For HP with cogeneration drive energy balance equation for the system "Source of drive energy HP – HP – consumer of heat from HP" will have the form (9). However, in this case, total efficiency factor of generation, supply and conversion of electric energy will be determined by the formula: $\eta_{EP} = \eta_{EM} \cdot \eta_{ED}$, where η_{EM} – efficient factor of gas-piston engine. For HP with cogeneration drive the value of φ_t in the equation (9) will be determined, taking into account the power of utilizing equipment of cogeneration drive $\varphi_t = \dfrac{Q_{hp} + \Sigma Q_{ut}}{N_{cp}}$, where $\mathrm{N_{cp}}$ – theoretical power of HP compressor, ΣQ_{ut} – power of utilizing equipment of HP cogeneration drive.

Energy efficiency of HP with cogeneration drive will be evaluated by non-dimensional index

$$Q_{hp} / Q_h = \eta_{EM} \cdot \eta_{ED} \cdot \varphi_t \cdot \eta_{hf}. \quad (11)$$

Study of HP energy efficiency was carried out applying the method of mathematical modeling of HP operation, using program in Excel. Energy efficiency of HP with electric drive and cogeneration drive of the compressor from gas-piston engine (GPE) was studied. Schemes of the given HP are presented in [11].

Fig. 1 shows the values of non-dimensional index of HP energy efficiency with electric drive for small capacity heat pumps depending on theoretical values of the coefficient of performance. The study was carried out for the cases of usage of electric energy in HP from various types of electric power stations and also for averaged values of electric power stations efficiency factors in Ukraine. Dotted line in Fig. 1 shows the limiting value of HP energy efficiency index. As it was already noted, for the cases $Q_{hp}/Q_h > 1$ usage of HP is expedient.

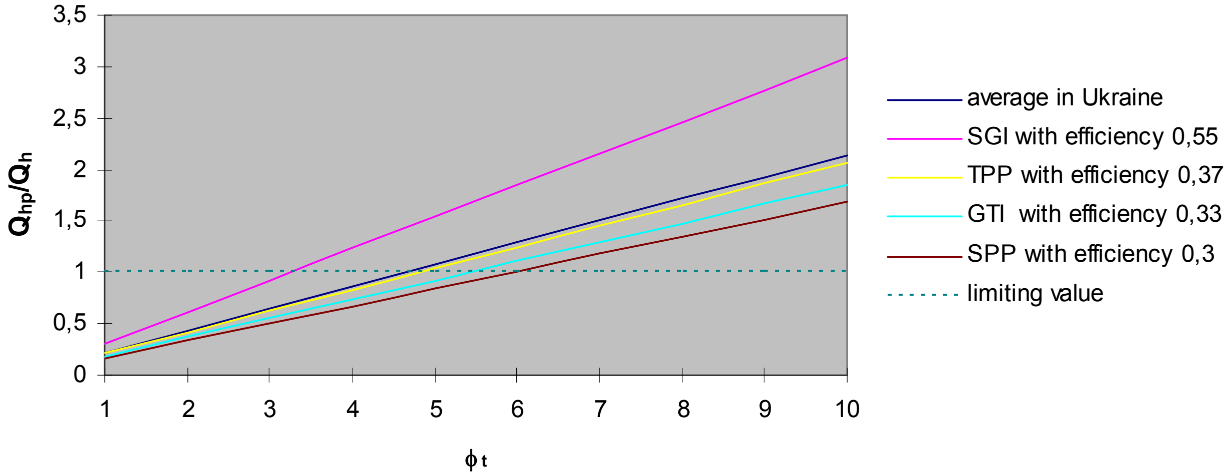

Fig. 1 – Values of non-dimensional index of HP energy efficiency with electric drive for small capacity heat pumps, depending on theoretical values of the coefficient of performance

Fig. 2 shows the values of non-dimensional index of HP energy efficiency with electric drive for heat pumps of large capacity depending on theoretical values of the coefficient of performance. As in the previous case, the study was performed for the cases of usage of electric energy in HP from various types of electric power stations and also for averaged values of electric power stations efficiency factors in Ukraine. Above the dotted line the area of efficient usage of such HP is determined.

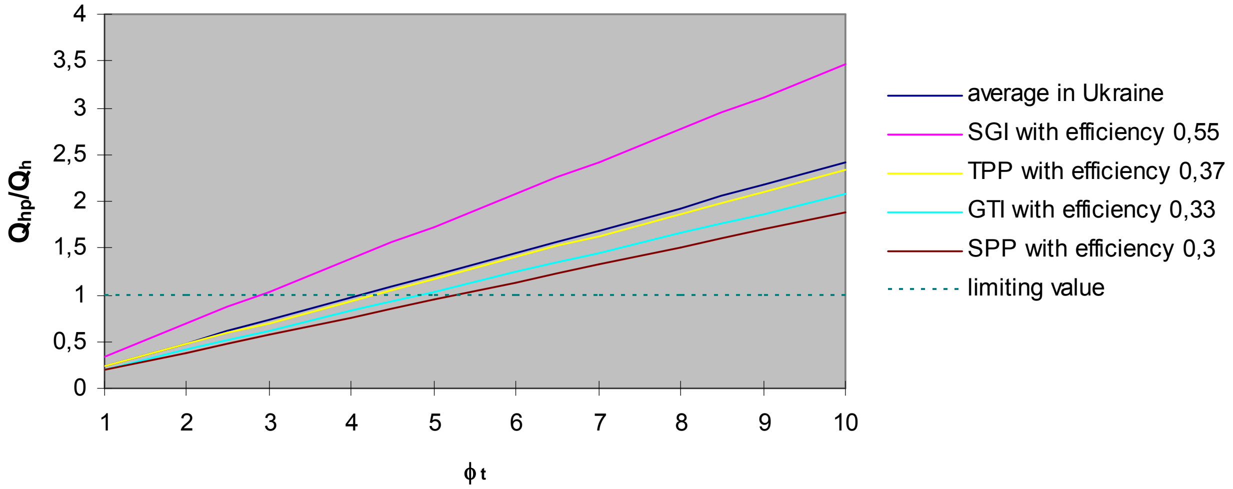

Fig. 2 – Values of non-dimensional index of energy efficiency of HP with electric drive for heat pumps of large capacity, depending on theoretical values of the coefficient of performance

Dependences, shown in Fig. 1 and 2, allow to determine minimal theoretical values of the coefficient of performance of HP, higher of which application of certain type of HP is expedient.

Fig. 3 shows the values of non-dimensional index of energy efficiency of HP with electric drive for small capacity heat pumps depending on the real values of the coefficient of performance. As in the previous cases, in Fig. 3 above the dotted line the area of efficient usage of such HP is determined.

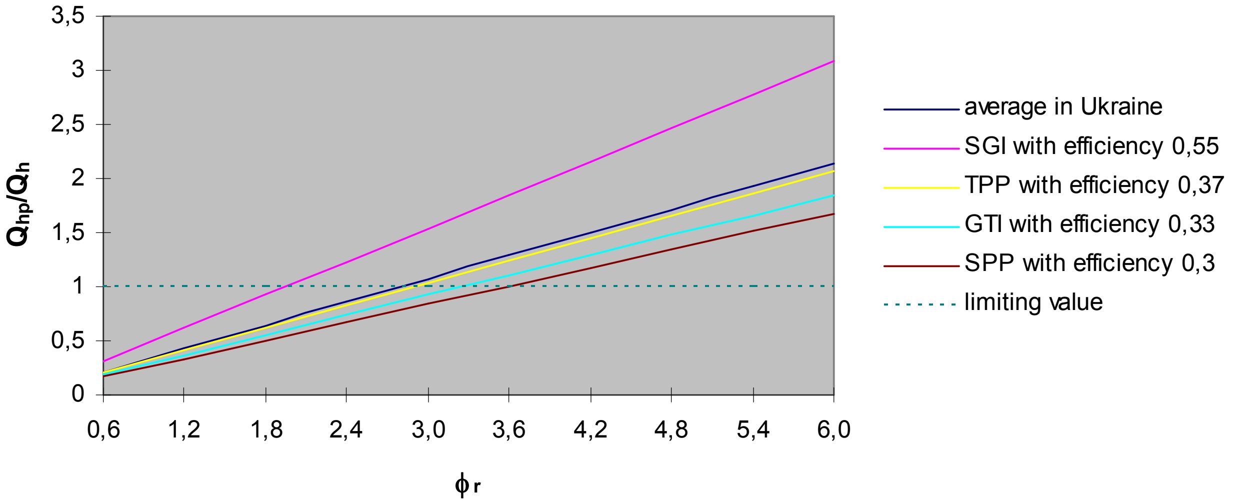

Fig. 3 – Values of non-dimensional index of energy efficiency of HP with electric drive for small capacity heat pumps, depending on real values of the coefficient of performance

Fig. 4 shows the values of non-dimensional index of energy efficiency of HP with electric drive for heat pumps of large capacity, depending on the real values of the coefficient of performance. Above the dotted line the area of efficient usage of such HP is determined.

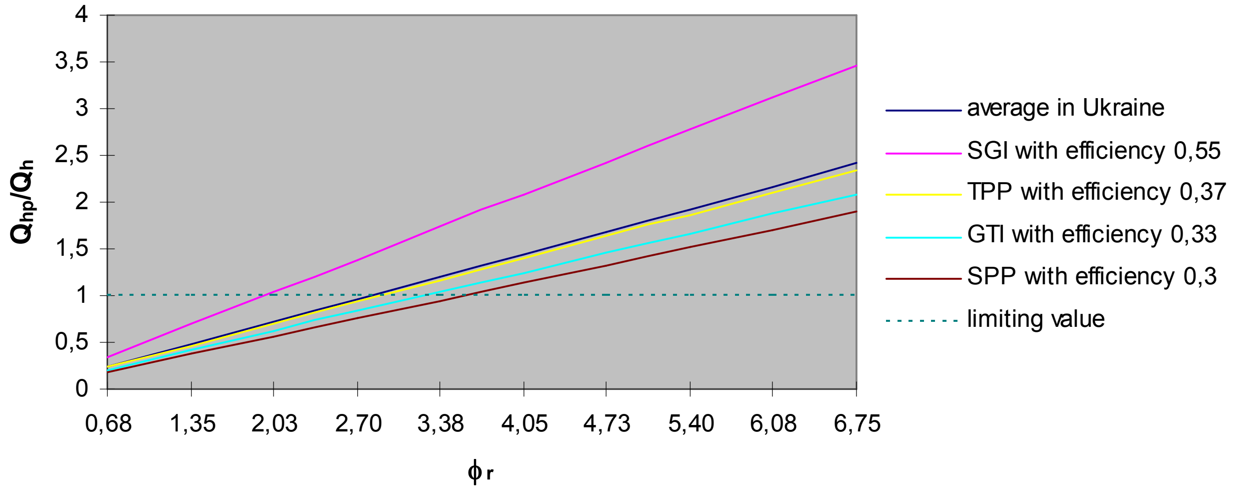

Fig. 4 – Values of non-dimensional index of energy efficiency of HP with electric drive for large capacity heat pumps, depending on real values of the coefficient of performance

Dependences in Fig. 3 and 4 allow to determine minimal real values of the coefficient of performance of HP, above which usage of certain type of HP is expedient.

Fig. 5 shows the values of non-dimensional index of energy efficiency of HP with cogeneration drive for heat pumps of small and large capacity, depending on the theoretical values of the coefficient of performance. As in the previous cases, the dotted line in Fig. 5 shows the limiting value of HP energy efficiency index, above which the area of efficient usage of such HP is determined.

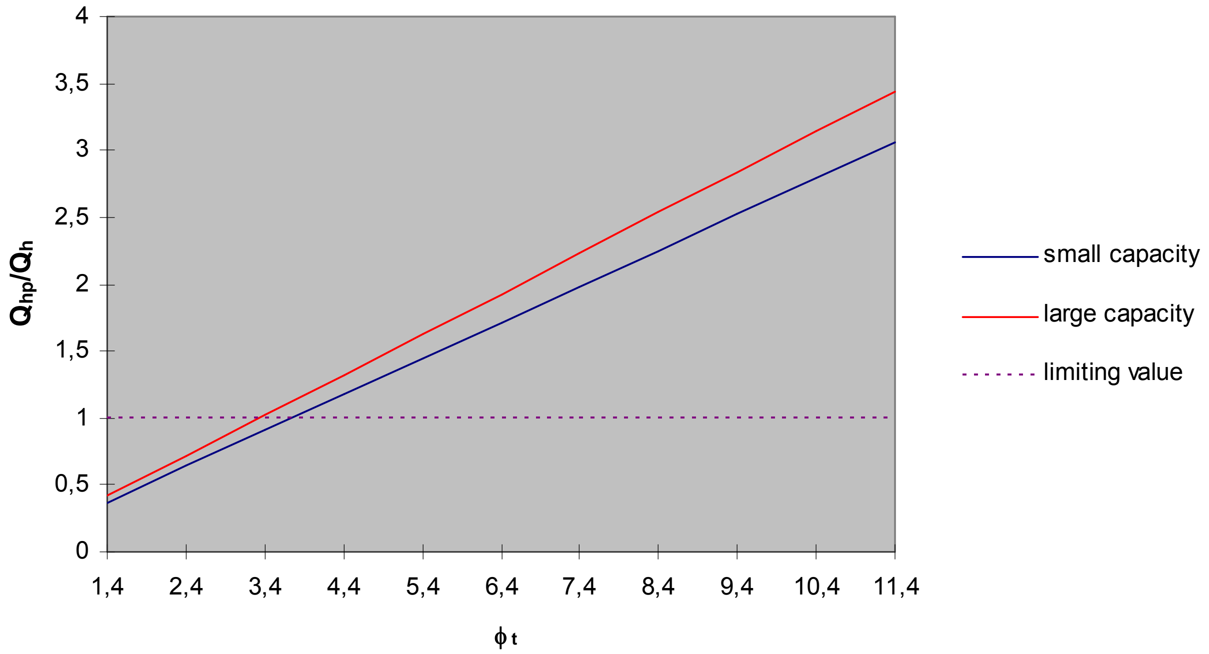

Fig. 5 – Values of non-dimensional index of energy efficiency of HP with cogeneration drive for heat pumps of small and large capacity, depending on theoretical values of the coefficient of performance

Dependences, shown in Fig. 5, allow to determine minimal theoretical values of the coefficient of performance of HP, above which application of certain type of HP is expedient.

Fig. 6 shows the values of non-dimensional index of energy efficiency of HP with cogeneration drive for heat pumps of small capacity, depending on real values of the coefficient of performance. Above the dotted line, the area of efficient usage of such HP is determined.

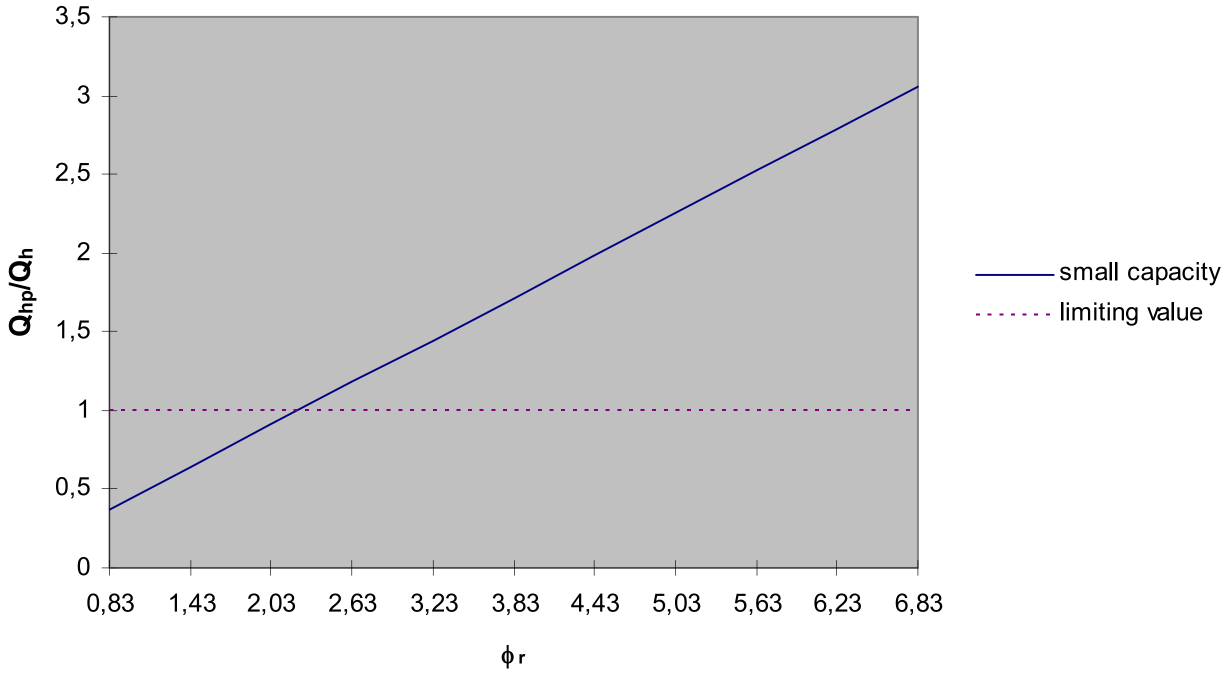

Fig. 6 – Values of non-dimensional index of energy efficiency of HP with cogeneration drive for heat pumps of small capacity, depending on real values of the coefficient of performance

Values of non-dimensional index of energy efficiency of HP with cogeneration drive for heat pumps of large capacity, depending on the real values of the coefficient of performance are shown in Fig. 7. As in previous cases, dotted line in Fig. 7 shows the limiting value of energy efficiency index of HP, above which the area of efficient usage of such HP is determined.

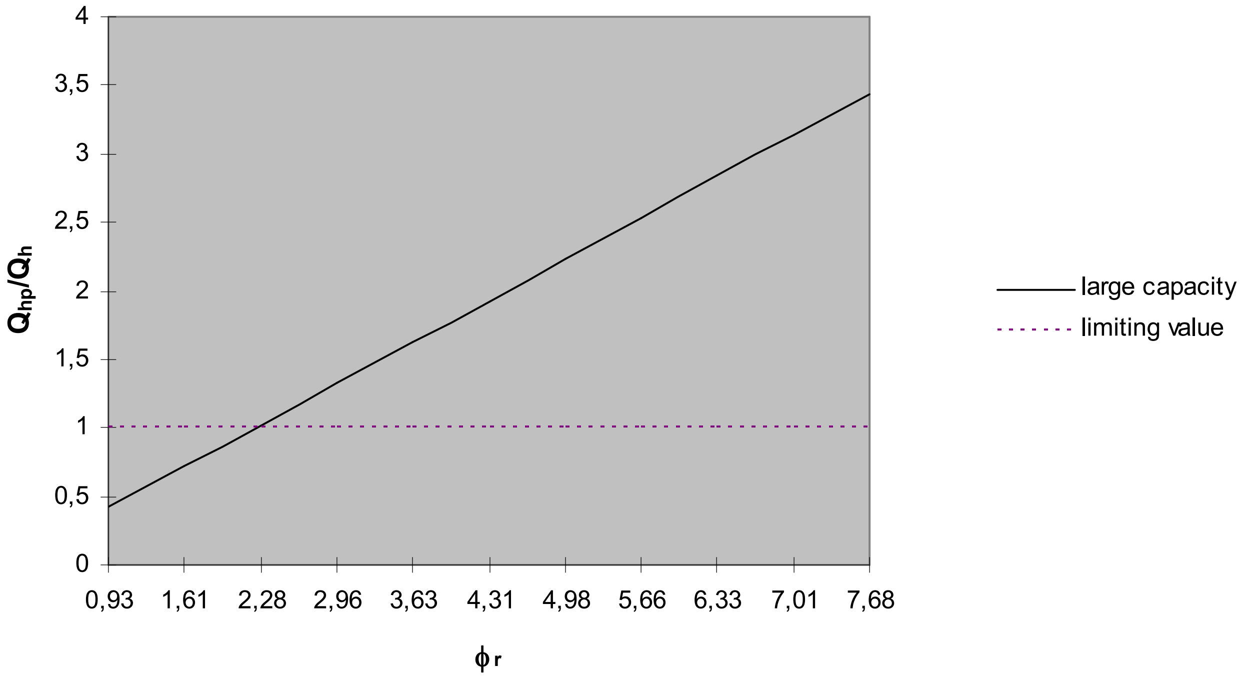

Fig. 7 – Values of non-dimensional index of energy efficiency of HP with cogeneration drive for heat pumps of large capacity, depending on the real values of the coefficient of performance

Dependences, shown in Fig. 6 and 7, allow to determine minimal real values of the coefficient of performance of HP, above which application of certain type of HP is expedient.

Conclusions

Evaluation of energy efficiency of steam compressor heat pumps with electric and cogeneration drive is carried out, efficient real operation modes of HP with electric and cogeneration drive are determined, taking into account energy losses during generation, supply and conversion of electric energy.

Energy efficiency of the system "Source of drive energy HP – HP – consumer of the heat from HP" has been analyzed on the example of steam compressor heat pumps with electric and cogeneration drive. The advantage of such approach is the account of energy losses during generation, supply and conversion of electric energy from various types of electric power stations to HP in order to determine the efficient real operation modes of HP with electric and cogeneration drive.

For steam compressor heat pumps with electric and cogeneration drive areas of their efficient usage according to non-dimensional index of energy efficiency are determined. The analysis for steam compressor heat pumps of small and large capacity has been carried out.

Dependences, suggested in Fig. 1–7, allow to determine minimal theoretical and real values of the coefficient of performance of HP, above which application of certain type of HP is expedient.

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