O. Ostapenko, Cand. Sc. (Eng.), Assis. Professor; V. Leshchenko, R. Tikhonenko

ENERGY ADVANTAGES OF APPLICATION OF STEAM COMPRESSOR HEAT PUMPS WITH ELECTRIC AND COGENERATION DRIVES

Energy advantages of steam compressor heat pumps (HP) with electric and cogeneration drives has been considered. The presented results of research allow to evaluate the economy of equivalent fuel due to application of steam compressor heat pumps (HP) with electric and cogeneration drives for various operation modes of HP and enable to select efficient operation modes of steam compressor HP taking into account the impact of the sources of drive energy of steam compressor HP and taking into consideration energy losses of the process of generation, supply and transformation of electric energy.

Key words*: energy advantages, steam compression heat pump, coefficient of performance, electric drive, cogeneration drive, economy of equivalent fuel.*

Introduction

In Ukraine, modern development of energy sector is characterized by considerable growth of energy resources cost and aggravating of the environment. The solution of problems, dealing with conservation of energy resources and protection of the environment are main directions of research in the sphere of consumption of fuel energy resources [1]. Share of natural gas consumption in the industrial complex of Ukraine still remains at high level. Greater part of energy problems of the country is solved at the expense of natural gas burning. In conditions of energy crisis the problem of efficient consumption of energy resources and introduction of modern energy saving technologies becomes very urgent [2]. Usage of steam compressor heat pumps with electric and cogeneration drives will promote the economy of natural gas and improvement of the environment as a result of decrease of thermal pollution and amount of harmful emissions of combustion products.

Problems, dealing with evaluation of energy efficiency of heat pumps in recent years are considered in numerous publications [1 – 6]. In [1] the author carried out the research aimed at improvement of efficiency and selection of rational parameters and operation modes of heat pumping plants for heating systems and heat supply by the consumption of equivalent fuel. In [2] thermodynamic and exergy analysis of the efficiency of steam compressor cycle of heat pumping plants of heat supply was performed. The authors in research [3] analyze thermodynamic efficiency of heat pumping plants of heat supply. In [4] new approach of heat pumps efficiency evaluation is suggested. However, in studies [1 – 4] energy losses for generation, transportation and conversion of electric energy from power plants of various types are not taken into account. The author [5] performed thermodynamic analysis of various types of HP. In [6] efficient real operation modes of HP with electric and cogeneration drives are determined, taking into account the impact of drive energy sources of steam compressor heat pumps and energy losses for generation, transportation and conversion of electric energy to HP.

In [1–6] the authors did not carry out the evaluation of the volume of energy resources economy as a result of introduction of steam compressor heat pumps with electric and cogeneration drives, taking into consideration energy losses for generation, transportation and conversion of electric energy.

Aim of research is determination of energy advantages of steam compressor HP application and evaluation of the volume of energy resources economy as a result of introduction of steam compressor HP with electric and cogeneration drives, taking into account the impact of drive energy sources of steam compressor HP and taking into consideration energy losses for generation, transportation and conversion of electric energy; determination of the efficient operation modes of steam compressor HP with electric and cogeneration drives.

Main part

In steam compressor HP the increase of temperature level of low temperature heat occurs at mechanical compression of the refrigerant in the compressor. Heat pumps may have electric and cogeneration drive (from gas-piston engine). Cogeneration drive of heat pumps allows to avoid additional losses of electric energy in the process of transportation. Besides, usage of HP with cogeneration drive of the compressor from gas engines may be considered as one of important directions of energy and resources saving since it provides utilization of fuel gases heat after gas engine, that provides better energy efficiency.

Often, 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 that reached the consumer, to the energy, used by cycle realization.

Theoretical value of the coefficient of performance is determined by the formula

$$\varphi_t = \frac{T_1}{T_1 - T_2}, \quad (1)$$

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 account all losses of energy, connected with generation of heat in HP. In real conditions, besides throttling, energy losses occur in pipe-lines and equipment of HP.

Real coefficient of performance of HP will be

$$\varphi_r = \varphi_t \cdot \eta_{hp}, \quad (2)$$

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

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

High energy efficiency of HP with cogeneration drive is provided at $\varphi_r \geq 2{,}0$; it is stipulated by taking into consideration the additional heat power from utilization equipment of HP cogeneration drive [7].

In our research energy efficiency of the system "Source of drive energy HP – HP – consumer of the heat from HP" on the example of steam compressor heat pumps with electric and cogeneration drive is analyzed. The advantage of such an approach is taking into account losses of energy for generation, transportation and conversion of electric energy to HP in order to determine the efficient operation modes of HP with electric and cogeneration drive and evaluation of the volumes of energy resources economy as a result of introduction of steam compressor HP.

Electric energy in Ukraine is generation by thermal power plants (TPP), nuclear power plants (NPP) and hydropower plants (HPP). Knowing the values of efficiency factors of TPP, NPP and HPP and the shares of electric energy, generated by these stations, we can determine the average efficiency factor of electric energy generation in Ukraine.

Averaged value of the efficiency factor of electric power plants will be:

$$\eta_{EPP} = \frac{\alpha_{TPP} + \alpha_{NPP} + \alpha_{HPP}}{\frac{\alpha_{TPP}}{\eta_{TPP}} + \frac{\alpha_{NPP}}{\eta_{NPP}} + \frac{\alpha_{HPP}}{\eta_{HPP}}}, \quad (3)$$

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 from the formula (3) the averaged value of efficiency factor of power plants η_{PP} = 0,383 can be obtained [6].

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 efficiency factor of power plants will be determined in the following way:

$$\eta_{EPP} = \frac{\Sigma\alpha_i}{\Sigma(\alpha_i/\eta_i)}, \quad (4)$$

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 plants the electric energy across distributive grids arrives to the consumers. Efficiency factor of distributive electric grids operation is determined by the level of energy losses in the process of its transportation. In accordance with the annual report of NCER (regulatory organ) for 2010 the value of total technological losses of electric energy in Ukraine was 12,5% from the volume of electric energy, arrived to the grid. Hence, efficiency factor of distributive grids in Ukraine will be η_{DG} =0,875 [6].

At the end of energy chain there is the consumer of electric energy – electric motor of HP. Efficiency factor of 55–100 kW electric motor, taking into account energy losses in motor control unit, will be η_{ED} = 80–85%. Efficiency factor of large power electric motor will be η_{ED} = 90–95% [6].

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

$$\eta_{EP} = \eta_{EPP} \cdot \eta_{DG} \cdot \eta_{ED}. \quad (5)$$

For HP with cogeneration drive general efficiency factor of generation, transportation 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, theoretical value of coefficients of performance is determined, taking into account the power of utilization equipment of cogeneration drive $\varphi_t = \frac{Q_{hp} + \Sigma Q_{ut}}{N_{cp}}$, where N_{cp} – theoretical power of HP compressor, ΣQ_{ut} – power of utilization equipment of HP cogeneration drive.

Efficient integration of steam compressor HP with electric and cogeneration drives in industry and energy sector is substantiated by the need to provide the economy of equivalent fuel as a result of introduction.

Economy of equivalent fuel (in per cent) as a result of usage of steam compressor HP with electric and cogeneration drives is determined in the following way:

$$\Delta B_e = \left(1 - \frac{\eta^n_{s.h.}}{\varphi \cdot \eta_{EP}}\right) \cdot 100, \quad (6)$$

where $\eta^n_{s.h.}$ – netto-efficiency factor of substituted source of the heat, η_{EP} – general efficiency factor of generation, transportation and conversion of electric energy.

Efficient introduction of steam compressor HP with electric and cogeneration drives in industry and energy sector will de achieved on condition:

$$\varphi_r > \frac{\eta^n_{s.h.}}{\eta_{EP}}, \quad (7)$$

where φ_r – real coefficient of performance of steam compressor HP from the formula (2).

Study of HP energy efficiency was performed, applying the method of mathematical modeling of HP operation, using the program in Excel. Energy efficiency of HP with electric drive and cogeneration drive of the compressor from gas-piston engine (GPE) was investigated. The schemes of the above-mentioned HP are given in [8].

The study contains the evaluation of equivalent fuel economy as a result of introduction of steam compressor HP of small (up to 1 MWt) and large powers with electric and cogeneration drive (from GPE). Study was performed for the cases of usage in electrically-driven HP electric energy from various types of electric power stations, and also for averaged values of efficiency factors of electric power stations in Ukraine. The study takes into consideration that netto-efficiency factor of substituted source of the heat is $\eta^n_{s.h.} = 0{,}8$.

In Figs. 1 and 2 values of equivalent fuel economy (in per cent) as a result of usage of steam compressor HP with electric drive for heat pumps of small and large capacity correspondingly, depending on theoretical values of the coefficient of performance, are shown. Studies were conducted for the cases of usage in HP the electric energy from electric power stations of various types of and also for averaged values of efficiency factor of electric power stations in Ukraine. Dependences, shown in Figs. 1 and 2, allow to determine minimal theoretical values of the coefficient of performance of electrically driven HP, above which application of certain type of HP provides equivalent fuel economy and is expedient.

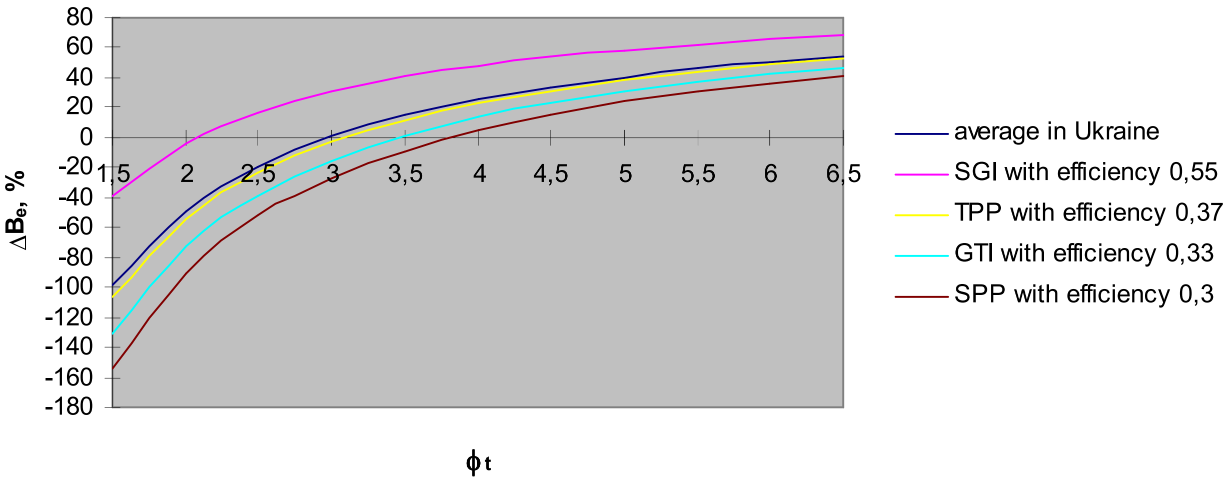

Fig. 1 – Values of equivalent fuel economy (in per cent) as a result of usage of steam compressor HP with electric drive for heat pumps of small capacity, depending on theoretical values of the coefficient of performance

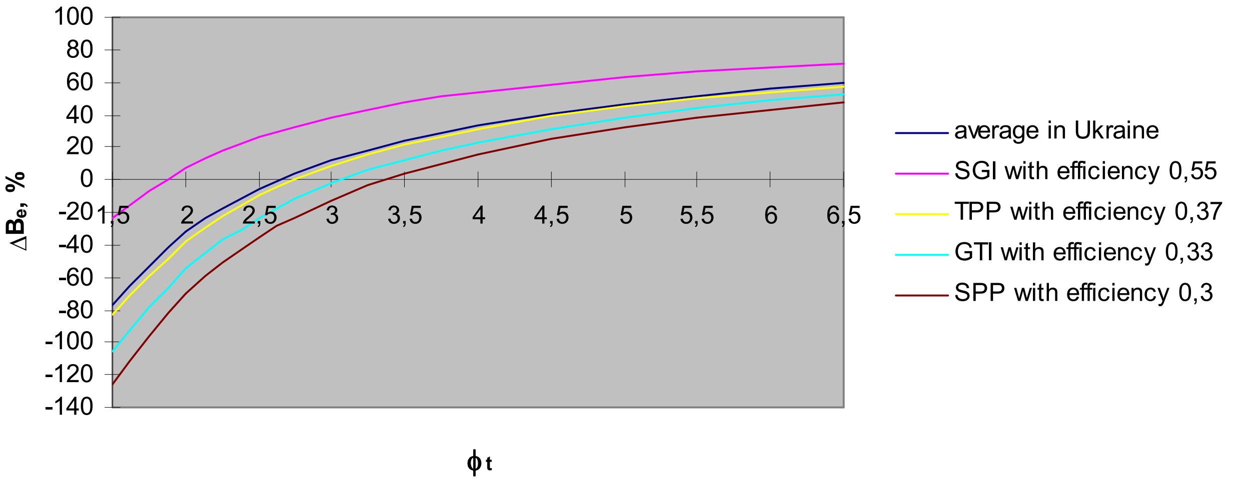

Fig. 2 – Values of equivalent fuel economy (in per cent) as a result of usage of steam compressor HP with electric drive for heat pumps of large capacity, depending on theoretical values of the coefficient of performance

Figs. 3 and 4 show the values of equivalent fuel economy (in per cent) as a result of usage of steam compressor HP with electric drive for heat pumps of small and large capacity, correspondingly, depending on real values of the coefficient of performance. Studies were carried out for the cases of usage in HP the electric energy from various types of electric power stations of and for averaged values of efficiency factor of electric power stations in Ukraine. These dependences allow to determine minimal real values of the coefficient of performance of electrically-driven HP, above which application of certain type of HP provides equivalent fuel economy and is expedient.

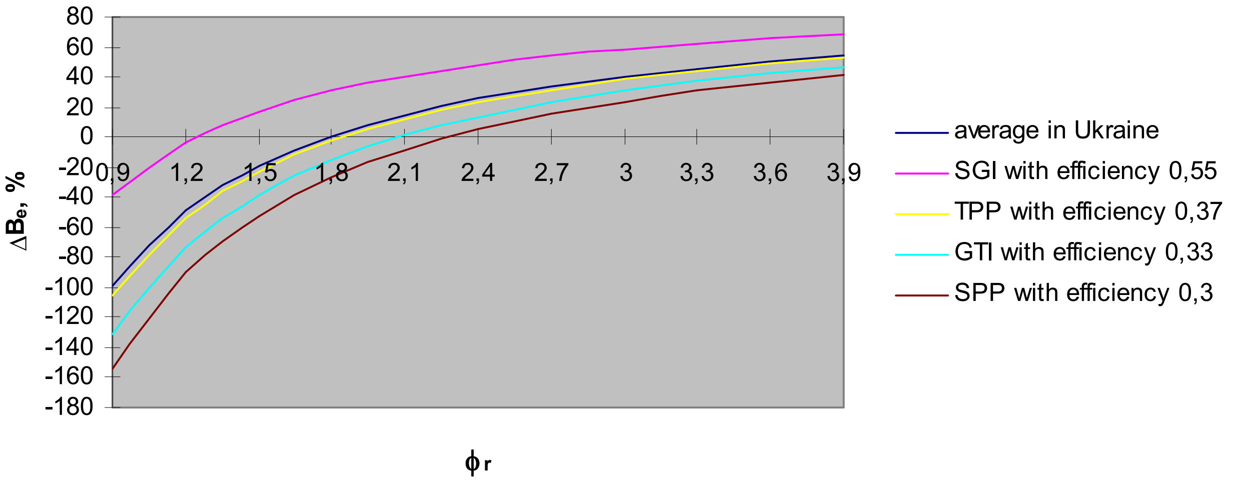

Fig. 3 – Values of equivalent fuel economy (in per cent) as a result of usage of steam compressor HP with electric drive for heat pumps of small capacity, depending on real values of the coefficient of performance

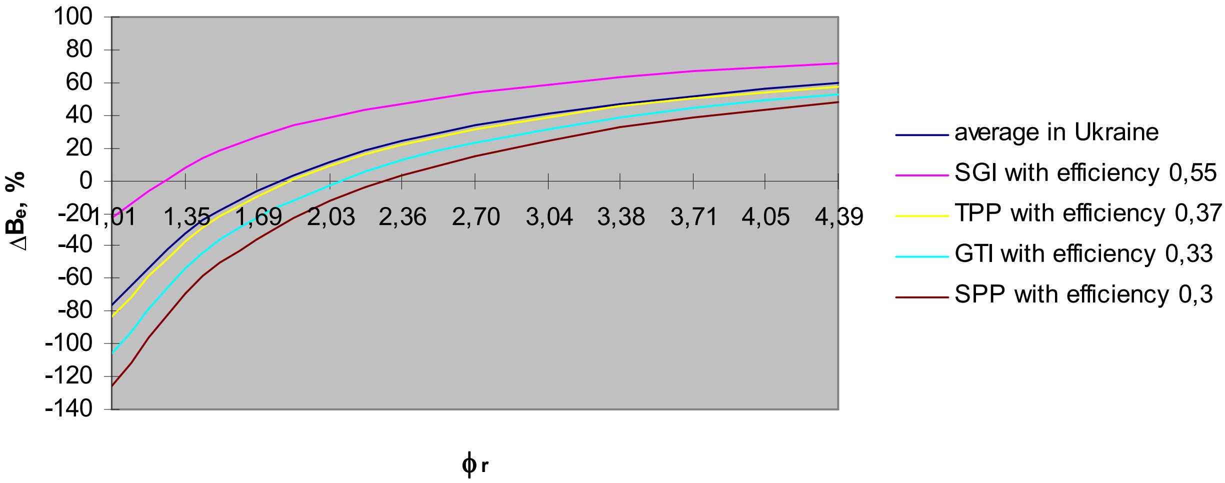

Fig. 4 – Values of equivalent fuel economy (in per cent) as a result of usage of steam compressor HP with electric drive for heat pumps of large capacity, depending on real values of the coefficient of performance

Dependences, suggested in Figs. 1-4, define energy advantages of electrically-driven steam compressor HP application and enable to evaluate equivalent fuel economy as a result of usage of electrically-driven steam compressor HP in case of HP various operation modes and usage of electric energy from different types of electric power stations and for averaged values of efficiency factor of electric power stations in Ukraine.

Fig. 5 shows the values of equivalent fuel economy (in per cent) as a result of usage of steam compressor HP with cogeneration drive for heat pumps of small and large capacity, depending on theoretical values of the coefficient of performance. Dependences, suggested in Fig. 5, allow to define minimal theoretical values of the coefficient of performance of HP, above which application of certain type of cogeneration HP provides equivalent fuel economy and is expedient.

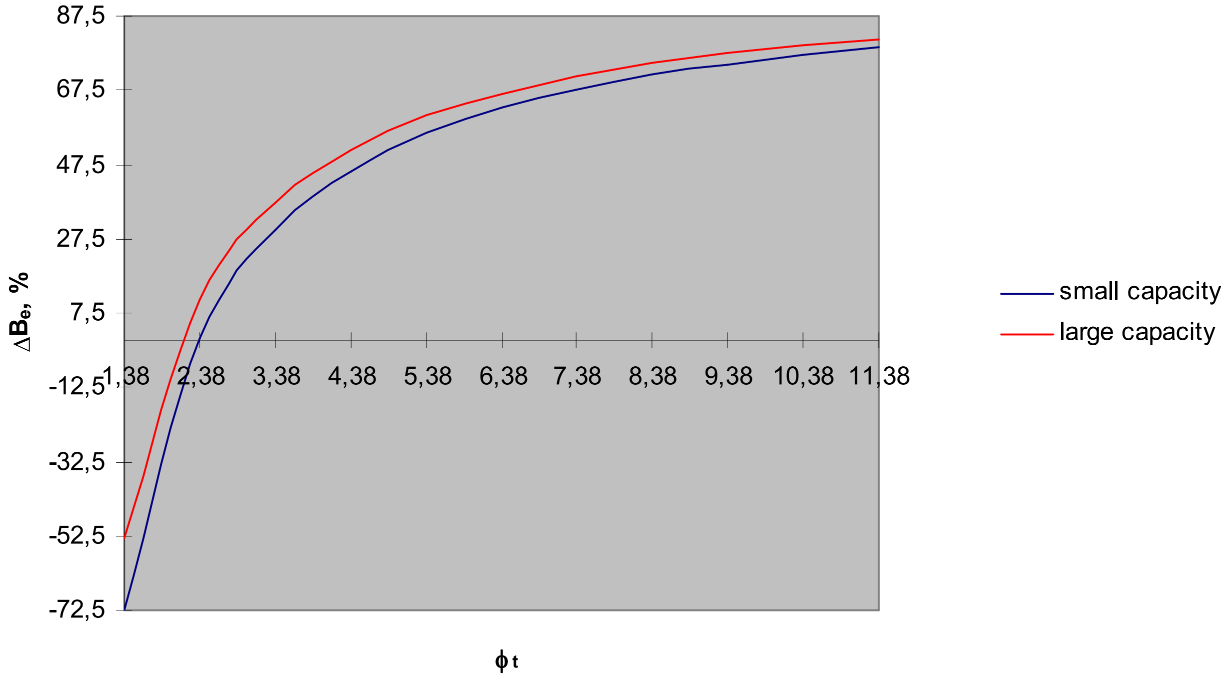

Fig. 5 – Values of equivalent fuel economy (in per cent) as a result of usage of steam compressor HP with cogeneration drive for heat pumps of small and large capacity, depending on theoretical values of the coefficient of performance

Figs. 6 and 7 show the values of equivalent fuel economy (in per cent) as a result of usage of steam compressor HP with cogeneration drive for heat pumps of small and large capacity correspondingly, depending on real values of the coefficient of performance. These dependences allow to define minimal real values of the coefficient of performance of HP, above which application of certain type of cogeneration HP provides equivalent fuel economy and is expedient.

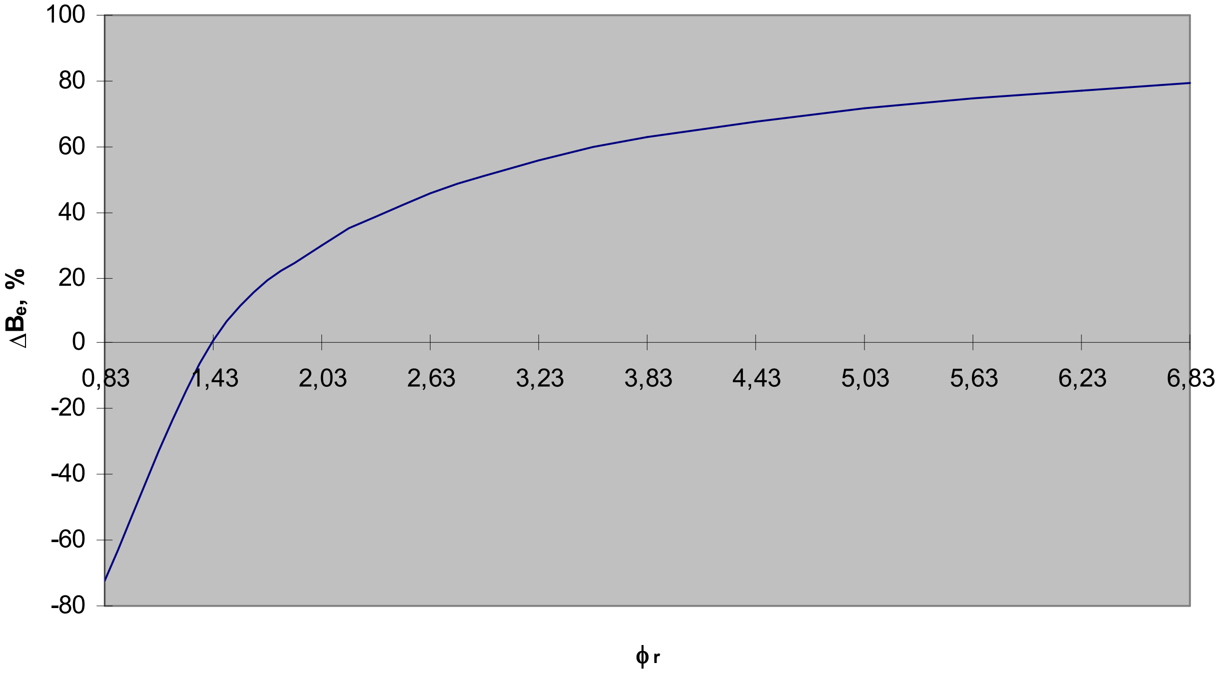

Fig. 6 – Values of equivalent fuel economy (in per cent) as a result of usage of steam compressor HP with cogeneration drive for heat pumps of small capacity, depending on real values of the coefficient of performance

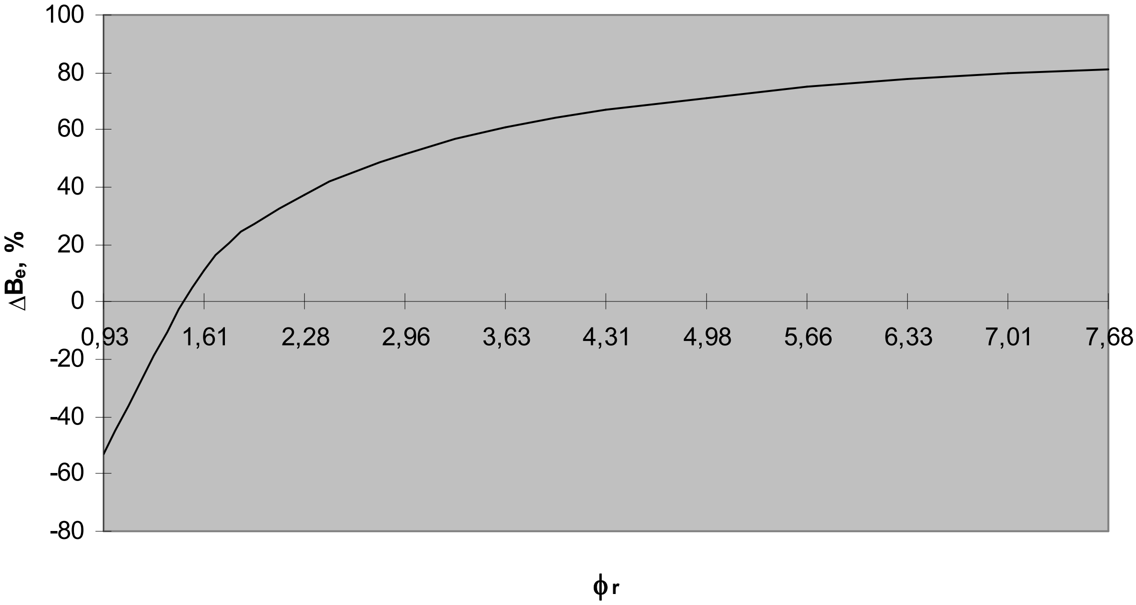

Fig. 7 – Values of equivalent fuel economy (in per cent) as a result of usage of steam compressor HP with cogeneration drive for heat pumps of large capacity, depending on real values of the coefficient of performance

Dependences, suggested in Figs. 5-7, define energy advantages of application of steam compressor HP with cogeneration drive and allow to evaluate equivalent fuel economy as a result of usage of steam compressor HP with cogeneration drive in case of different operation modes of HP.

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

By the results of the research, it has been determined, that sufficient energy efficiency of HP with electric drive for various sources of drive energy of steam compressor HP and with the account of energy losses while generation, transportation and conversion of electric energy is provided if $\varphi_r \geq 2{,}5$. High energy efficiency of electrically-driven HP for various sources of drive energy of steam compressor HP and with the account of energy losses for generation, transportation and conversion of electric energy is provided, if $\varphi_r \geq 3{,}5$. These values of the HP coefficient of performance well agree with statistical data of the research [4] regarding the real coefficient of performance of HP, manufactured by companies LG, Mitsubishi, MHPUL, MHPUE, FUJITSU, McQUAY, HPVU, "ENERGY", "TRITON-LTD".

It has been determined, that high energy efficiency of HP with cogeneration drive, taking into account energy losses for generation, transportation and conversion of electric energy to HP is provided at $\varphi_r \geq 2{,}0$; that well agrees with the data of the research [7].

The presented results of research allow to evaluate equivalent fuel economy as a result of usage of steam compressor HP with electric and cogeneration drive for various operation modes of HP and allow to perform the choice of efficient operation modes of steam compressor HP with the account of the impact of drive energy sources of steam compressor heat pumps and energy losses for generation, transportation and conversion of electric energy.

Conclusions

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 an approach is taking into consideration energy losses for generation, transportation and conversion of electric energy to HP in order to determine the efficient operation modes of HP with electric and cogeneration drives and evaluation of the volumes of energy resources economy as a result of introduction of steam compressor HP.

Dependences, suggested in research (Fig. 1-7) define energy advantages as a result of usage of steam compressor HP and allow to determine minimal theoretical and real values of the HP coefficient of performance, above which application of certain type of HP provides equivalent fuel economy and is expedient.

By the results of studies, it has been determined, that sufficient energy efficiency of HP with electric drive for various sources of drive energy of steam compressor HP and with the account of energy losses for generation, transportation and conversion of electric energy is provided at $\varphi_r \geq 2{,}5$. High energy efficiency of HP with electric drive for various sources of drive energy of steam compressor HP and with the account of energy losses for generation, transportation and conversion of electric energy is provided at $\varphi_r \geq 3{,}5$. It has been determined, that high energy efficiency of HP with cogeneration drive with the account energy losses for generation, transportation and conversion of electric energy to HP is provided at $\varphi_r \geq 2{,}0$. These values of the coefficient of performance well agree with statistical data regarding the real coefficient of performance of HP, manufactured by companies LG, Mitsubishi, MHPUL, MHPUE, FUJITSU, McQUAY, HPVU, "ENERGY", "TRITON-LTD".

The presented results of research allow to evaluate equivalent fuel economy as a result of usage of steam compressor HP with electric and cogeneration drives for various operation modes of HP and allow to perform the choice of efficient operation modes of steam compressor HP, taking into account of the impact of drive energy sources of steam compressor heat pumps and energy losses for generation, transportation and conversion of electric energy.

REFERENCES

1. Исанова А. В. Повышение эффективности и выбор рациональных параметров и режимов работы теплонасосных станций для систем отопления и горячего водоснабжения : автореферат дисс. … канд. тех. наук : 05.23.03 / Исанова Анна Владимировна. – Воронеж, 2011. – 18 с.

2. Денисова А. Є. Аналіз парокомпресійного циклу теплонасосних станцій теплопостачання / А. Є. Денисова., В. Ю. Бірюк // Тр. Одес. политехн. ун-та. – 2012. – Вып. 1 (38). – С. 125 – 128.

3. Безродний М. К. Термодинамічна ефективність теплонасосних схем теплопостачання / М. К. Безродний, Н. О. Притула // Вісник ВПІ. – 2013. – № 3. – С. 39 – 45.

4. Ильин Р. А. Новый подход к оценке эффективности тепловых насосов / Р. А. Ильин, А. К. Ильин // Вестник АГТУ. Сер.: Морская техника и технология. – 2010. – № 2. – С. 83 – 87.

5. Елистратов С. Л. Комплексное исследование эффективности тепловых насосов : дисс. ... докт. техн. наук : 01.04.14 / Елистратов Сергей Львович. – Новосибирск, 2010. – 383 с.

6. Energy efficiency of steam compressor heat pumps with electric and cogener ation drive [Електронний ресурс] / O. P. Ostapenko, V. V. Leshchenko, R. O. Tikhonenko // Scientific Works of Vinnytsia National Technical University. – № 4. – 2014. – Режим доступу до журн.: http://praci.vntu.edu.ua/article/view/3821/5564.

7. Калнинь И. М. Техника низких температур на службе энергетики / И. М. Калнинь // Холодильное дело. – 1996. – № 1. – С. 26 – 29.

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

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

Leshcnenko Vadym – Student of the Institute of Civil Engineering, Heat Power Engineering and Gas Supply.

Tikhonenko Roman – Student of the Institute of Civil Engineering, Heat Power Engineering and Gas Supply.

Vinnytsia National Technical University.