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ENERGY ECOLOGICAL EFFICIENCY OF HEAT PUMPING STATIONS, OPERATING ON NATURAL AND INDUSTRIAL SOURCES OF HEAT AT VARIABLE OPERATION MODES

Evaluation of energy ecological efficiency of heat-pumping stations (HPS) with various types of compressor drive and sources of low-temperature heat, taking into account variable operation modes of heat supply systems in wide range of capacity change of heat-pumping installation (HPI) is carried out. The results obtained enable to evaluate the energy efficiency and reduction of CO_2 emissions. The suggested results of the research allow to perform the selection of HPS operation modes and sources of low temperature heat in order to reach the set values of energy ecological efficiency of HPS operation. The given recommendations can be used to forecast rational operation modes of HPS of different power in energy supply systems.

Key words*: heat pumping station, low temperature source of heat, energy ecological efficiency, fuel consumption, economy of equivalent fuel, economy of operation fuel, reduction of CO_2 emission.*

Introduction

Reduction of energy consumption and application of non-traditional and renewable energy resources of natural and industrial origin are important conditions to achieve energy independence of Ukraine. It is expedient to develop and introduce in Ukraine modern technologies, aimed at usage of renewable and non-traditional sources of energy, particularly, introduction of heat-pumping installations. In accordance with "Energy strategy for the period till 2030" (adopted by the decision of the Cabinet of ministers of Ukraine №145-p of March 15, 2006) the development of heat supply system is planed to be realized by means of gradual increase of heat generation on the basis of electric thermal generators (mainly – heat pumps). Till 2030 the volume of generation of thermal energy by electric thermal generators (using heat pumps) will increase up to 180 mil GCal compared with 1.7 mil GCal in 2005. Thus, "Energy strategy" defined new conceptual approach to heat-supply of housing municipal complex of the country [1].

Application of heat pumps, besides energy advantages, provides the reduction of environment (also thermal pollution) and decrease of harmful emissions in the atmosphere. Involvement of financial resources obtained as a result of selling of CO_2 emission quotas, according to Kyoto protocol, allows to improve economic efficiency of HPS implementation and reduce the term of their recoupment.

Greater energy conservation effect than from HPI, should be expected as a result of introduction of heat-pumping stations, where heat pump is combined with peak source of heat. For efficient operation of heat-pumping stations, natural or industrial source of low-temperature heat with rather high temperature during the whole year, is required. Heat, generated by heat-pumping stations, can be used for heating and hot water supply of residential buildings, industrial and public buildings as well as, for technological needs [2 – 4].

Sources of low temperature heat for heat-pumping stations can be conventionally divided into two groups. The first group – natural sources of heat: water (surface water, deep water and thermal water), air, soil, solar radiation, etc. The second group comprises the industrial sources of heat – secondary low temperature resources: exhaust air of aeration stations; water to be cooled in the systems of process water supply of industrial enterprises; waste heat of the cooling systems of mechanisms (hydrogenerators, transformers, etc); heat, removed in technological process for cooling, is also used.

In [5], possibilities of application and energy efficiency of heat-pumping stations in Ukraine have been evaluated, taking into account the available sources of low-temperature heat (air, sea waters, river waters, soil, water storage reservoirs, mine water, thermal waters, sewage waters and secondary energy resources (SER) of integrated iron and steel works), volume of energy resources economy and reduction of technogenic impact on the environment as a result of heat-pumping stations introduction has been evaluated. The given research investigated and analyzed 108 projects of heat-pumping stations operated on natural and industrial sources of heat in Ukraine. In [5] it was determined that greatest fuel economy is achieved at HPS, using the heat of thermal and sewage waters (58.17% and 56.09% correspondingly). The smallest fuel economy is observed at HPS, using the heat of air (20.41%). In Ukraine the heat of sewage waters and river water is planned to be used in HPS, that will allow to save 235.864 and 164.920 mil m^3 per year of natural gas, correspondingly. Introduction of HPS, operating on sea water, will provide the economy of natural gas in the volume of 96.350 mil m^3 per year. Introduction of heat-pumping stations in Ukraine, using the sources of low temperature heat, available in the regions, will allow to save 614.650 mil m^3 of natural gas per year and provide the reduction of CO_2 emissions in the volume of 732.263 tons per year.

Introduction of heat-pumping stations with natural or industrial sources of low temperature heat will allow to reduce the consumption of natural gas, decrease the cost of thermal energy and reduce technogenic impact on the environment. This stipulates the importance of research aimed at investigation of energy ecological efficiency of heat-pumping stations.

Main part

A number of research, dealing with the study of HPS efficiency in thermal circuits of energy supply sources has been carried out in resent years [3, 5 – 12]. Evaluation of HPS efficiency was performed by the following criteria: coefficient of performance, economy of operating and equivalent fuel as compared with the existing scheme, by economic indices.

In the analyzed research, the authors did not carry out the evaluation of energy ecological efficiency of HPS with different types of drive and varied operation modes of heat supply systems in wide range of HPI power change.

The aim of the research is the evaluation of energy ecological efficiency of HPS with different types of the compressor drive at various sources of low temperature heat, taking into account changing operation modes of heat supply systems in wide range of HPI power change; realization of optimization research in order to determine rational modes of HPS of different power operation in heat supply systems.

The research was carried out, applying the method of mathematical modeling of HPS operation, using the program in EXCEL environment. The program is used for modeling of operation of heat-pumping stations with various types of the compressor drive for heat supply. The program is of block structure and consists of the following computation modules: calculation of thermal circuit of equivalent water heating boiler house, calculation of heat-pumping installation, calculation of internal combustion engine and the system of heat utilization, calculation of energy ecological efficiency of heat-pumping stations. Module of the selection of source of low temperature heat for HPS and its temperature level, depending on operation mode of HPS is provided.

Energy efficiency of heat-pumping stations, with maximum power of 10 MW in heating period, was investigated; maximum power of HPS in operation mode for hot water supply was 2 MW. The variant of water heating boiler house operation of the same power was taken as a comparative variant. The efficiency of HPS with electric drive and compressor drive from gas-piston engine (GPE) was investigated. The schemes of the above-mentioned HPS are presented in [3]. The power of the condenser of heat pump varied from 500 to 2000 KW, according to the type of heat pumps, of industrial manufacture. The sources of low-temperature heat for HPS were: surface waters, water from system of circulating water supply, ground waters, geothermal waters, air, secondary energy resources, sewage water and ground heat.

Energy efficiency of HPS operation is mainly determined by optimal distribution of load between heat-pumping installation (unit) and hot-water boiler combined in HPS. Load distribution between the elements of HPS is characterized by the portion of HPI load within HPS β, which is determined as the relation of power of the HPI condenser to the power of HPS $\beta = Q_{hpi} / Q_{hps}$.

Power and temperature modes of heat-pumping stations in the system of heat supply are determined by temperature graph depending on the temperature of ambient air and necessary power of consumers.

Proceeding from the analysis of the results of research carried out, optimal values of β index for HPS at different sources of heat with various kinds of HPI compressor drive at changing modes of heating system operation. Certain value of HPS, HPI thermal capacities and portion of HPI β load corresponds to one of these modes.

For the cases of variable operation modes and variable thermal load of HPS during a year, average annual value of HPI load portion within HPS can be determined in such a way:

$$\beta_{av.an.} = \frac{\sum_i \beta_i \cdot \tau_i}{\tau_{annual}}, \tag{1}$$

where β_i – is a portion of HPI load for i^{th} operation mode of HPS; τ_i – is the duration of i^{th} mode of HPS operation; τ_{annual} – is the annual duration of HPS operation.

Saving of equivalent fuel as a result of HPS introduction is determined by optimally selected operation mode of HPS, rational distribution of loading between hot-water boiler and HPI, thus – by optimal value of the portion of HPI load within HPS β. On the basis of the determined values of the portion of HPI β load, the economy of the equivalent fuel of HPS is determined for certain operation more of heat supply system.

For the cases of variable operation mode and variable heat loading of HPS during a year, average annual value of equivalent fuel economy at HPS can be determined in the following way:

$$\Delta B^e{}_{av.an.} = \frac{\sum_i \Delta B^e{}_i \cdot \tau_i}{\tau_{annual}}, \tag{2}$$

where ΔB_i^e – is the economy of equivalent fuel as a result of introduction for i^{th} operation mode of HPS %.

Average annual value of economy of HPS fuel can be determined as:

$$\Delta B^w{}_{av.an.} = \frac{\sum_i \Delta B^w{}_i \cdot \tau_i}{\tau_{annual}}, \tag{3}$$

where ΔB_i^w – is the economy of working fuel as a result of HPS introduction for i^{th} operation mode of HPS, %.

As it has already been noted, besides energy advantages, the application of the heat pumps stipulates the reduction of the environment pollution (also thermal) and reduction of harmful emission.

Reduction of CO_2 emissions (in per cent) while using HPS of 10 MW of varying operation modes is evaluated as compared with the operation of hot water boiler house of the same power, using natural gas. CO_2 emissions while gas burning in boilers and CO_2 emissions while electric energy generation at power stations were taken into account.

Values of annual reduction of CO_2 emissions, as a result of HPS usage can be defined as:

$$\Delta CO_{2annual.} = \frac{\sum_i \Delta CO_{2i} \cdot \tau_i}{\tau_{annual.}}, \quad (4)$$

where $\Delta CO_{2\,i}$ – is CO_2 emissions reduction as a result of HPS introduction for i-th mode of HPS operation, as compared with hot water boiler house of the same capacity, operating on natural gas, %. The suggested criteria allow to evaluate energy and ecological efficiency of TCS operation during the year , at different operation modes.

Tables 1-7 show the results of investigation of HPS operation efficiency at different sources of heat with different drives on conditions of varying operation modes of HPS. Tables 1 and 2 contain the indices of the efficiency of HPS with electric drive and GPE drive, operating on the heat of sewage, on conditions of variable operation modes. In Tables 1 and 2 there are designations: HM heating mode. IHM-inter heating mode.

Powers of HPI, values of HPI loading portions are indicated in Tables 1 and 2. Values of equivalent and operation fuel of HPS are indicated for heating and interheating modes, depending on the portion of HPS loading. Annual reduction of CO_2 emissions, depending on the portion of HPI loading is also shown. Analogous results have been obtained for HPS with other sources of heat.

Table 1

Indices of HPS efficiency, operating on sewage waters heat with electric drive, on condition of variable operation modes

Power of HPI, KW		Saving of equivalent fuel by HPS with electric drive, %		Saving of operation fuel by HPS with electric drive, %		Reduction of CO_2 emissions from HPS with electric drive, %	Portion of thermal power of HPI in HPS		
HM	IHM	HM	IHM	HM	IHM		HM	IHM	Сред. за год
500	500	-22.92	4.73	6.126	24.32	1.010	0.061	0.25	0.158
1000	500	-14.98	4.73	14.07	24.32	1.481	0.121	0.25	0.187
1500	500	-7.04	4.73	22.01	24.32	1.953	0.182	0.25	0.2165
2000	500	0.901	4.73	29.95	24.32	2.425	0.243	0.25	0.246
1000	1000	-14.98	9.46	14.07	48.64	2.019	0.121	0.5	0.315
1500	1000	-7.04	9.46	22.01	48.64	2.491	0.182	0.5	0.344
2000	1000	0.901	9.46	29.95	48.64	2.963	0.243	0,5	0.374
1500	1500	-7.04	14.19	22.01	72.95	3.029	0.182	0.75	0.472
2000	1500	0.901	14.19	29.95	72.95	3.501	0.243	0.75	0.502
2000	2000	0.901	18.92	29.95	97.27	4.038	0.243	1	0.629

Table 2

Indices of HPS efficiency, operating on sewage waters heat with GPE drive for variable operation modes.

Power of HPI, KW		Saving of equivalent fuel by HPS with GPE drive, %		Saving of operation fuel by HPS with GPE drive, %		Reduction of CO_2 emissions from HPS with GPE drive, %	Доля тепловой мощности ТНУ в ТНС		
HM	IHM	HM	IHM	HM	IHM		HM	IHM	Сред. за год
500	500	1.93	11.32	1.678	9.842	3.721	0.0609	0.25	0.158
1000	500	6.11	11.32	5.312	9.842	6.409	0.121	0.25	0.187
1500	500	10.8	11.32	9.39	9.842	9.425	0.182	0.25	0.2165
2000	500	16.1	11.32	13.998	9.842	12.833	0.243	0.25	0.246
1000	1000	6.11	24.35	5.312	21.171	9.263	0.121	0.5	0.315
1500	1000	10.8	24.35	9.39	21.171	12.279	0.182	0.5	0.344
2000	1000	16.1	24.35	13.998	21.171	15.687	0.243	0.5	0.374
1500	1500	10.8	39.88	9.39	34.673	15.681	0.182	0.75	0.472
2000	1500	16.1	39.88	13.998	34.673	19.089	0.243	0.75	0.502
2000	2000	16.1	59.26	13.998	51.523	23.334	0.243	1	0.629

Values of average annual economy of equivalent fuel (in percent) for HPS with various sources of low temperature heat and GPE drive depending on the portion of HPI loading are shown in Table 3. As it is seen from Table 3, for all sources of low temperature heat and investigated HPS operation modes the economy of equivalent fuel is observed, its values increase with the growth of HPI loading portion β.

Table 3

Values of average annual economy of equivalent fuel of HPS with different sources of low-temperature heat and GPE drive, depending on the portion of HPI loading, %

Portion of HPI loading β	Source of low-temperature heat							
	Surface waters	Circulating water	Ground waters	Geothermal waters	Air	Secondary energy resources	Sewage waters	Ground
0.158	6.66	9.21	5.92	7.935	5.67	14.32	6.71	4.06
0.187	8.64	11.72	7.91	10.18	7.43	17.91	8.73	6.06
0.2165	10.88	14.4	10.14	12.64	9.47	21.53	10.99	7.84
0.246	13.41	17.29	12.67	15.35	11.86	25.18	13.55	10.02
0.315	15.3	20.07	13.91	17.685	13.43	29.66	15.38	11.43
0.344	17.53	22.85	16.14	20.19	15.48	33.27	17.64	13.22
0.374	20.06	25.64	18.67	22.85	17.86	36.93	20.2	15.39
0.472	25.45	31.99	23.57	28.72	22.9	45.16	25.56	20.14
0.502	27.98	34.88	26.09	31.43	25.28	48.82	28.12	22.32
0.629	37.87	45.52	35.07	41.695	34.89	60.93	38	31.16

Table 4 show values of average annual economy of equivalent fuel (in percent) for HPS with various sources of low temperature heat and the drive, depending on the of HPI loading.

Table 4

Values of average annual economy of equivalent fuel of HPS with different sources of low-temperature heat and electric drive, depending on the portion of HPI loading, %

Portion of HPI loading β	Source of low-temperature heat							
	Surface waters	Circulating water	Ground waters	Geothermal waters	Air	Secondary energy resources	Sewage waters	Ground
0.158	-8.69	-1.7	-9.8	6.98	-11.53	12.39	-8.39	-14.99
0.187	-4.84	2.15	-5.95	12.31	-7.68	16.52	-4.55	-11.15
0.2165	-0.99	6	-2.11	16.17	-3.83	20.09	-0.69	-7.29
0.246	2.86	9.85	1.74	20.02	0.016	23.93	3.15	-3.44
0.315	-2.42	7.53	-4.67	20.57	-6.38	27.54	-2.12	-10.94
0.344	1.43	11.38	-0.8	24.42	-2.53	31.4	1.72	-7.09
0.374	5.27	15.23	3.04	28.27	1.31	35.24	5.57	-3.24
0.472	3.95	16.76	0.49	32.68	-1.23	42.69	4.19	-6.89
0.502	7.7	20.61	4.34	36.53	2.62	46.54	8	-3.06
0.629	10.12	26	5.64	44.49	3.92	57.84	10.41	-2.84

As it seen from Table 4, for HPS with the electric drive, over expenditure of equivalent fuel is observed for the member of heat sources (air, ground, ground waters, sewage waters, surface waters). For the investigated sources of low temperature heat rational modes of HPS operation at which the economy of equivalent fuel is provided are determined.

For HPS with GPE drive for all investigated operation modes, greater values of equivalent fuel economy than for HPS with electric drive are provided.

Table 5 show the value of average annual economy of operation fuel (in percent) for HPS with electric drive and GPE drive, depending on the portion of HPI loading for various sources of low temperature heat.

As it is seen from Table 5, in this case for HPS, operating on all sources of heat and types of drive the saving of operation fuel is observed. For HPS with electric drive the saving of operation fuel is higher than for HPS with GPE drive.

Table 6 presents the values of annual reduction of CO_2 emissions (in per cent) for HPS with electric drive. As it is seen from Table 6, for HPS using the heat of the ground and air the growth of CO_2 emissions is observed.

Table 7 shows the values of annual reduction of CO_2 (in per cent) for HPS with GPE drive. For all investigated operation modes of HPS with GPE drive the reduction of CO_2 emissions is observed.

Table 5

Values of average annual economy of working fuel of HPS with electric and GPE drive, depending on the portion of HPI loading, for various sources of low temperature heat %

Portion of HPI loading β	GPE drive of HPI								Electric drive of HPI
	Source of low-temperature heat								
	Ground	Air	Ground waters	Surface waters	Sewage waters	Circulating water	Geothermal waters	Secondary energy resources	All sources of low-temperature heat
0.158	4.01	4.95	5.16	5.81	5.85	8.03	15.19	12.49	15.42
0.187	5.28	6.49	6.89	7.54	7.61	10.22	18.22	15.63	19.27
0.2165	6.84	8.27	8.84	9.49	9.59	12.25	21.28	18.78	23.12
0.246	8.73	10.34	11.05	11.70	11.82	15.08	24.40	21.97	26.96
0.315	9.97	11.73	12.13	13.34	13.41	17.50	22.38	25.87	31.71
0.344	11.53	13.51	14.09	15.29	15.39	19.53	25.44	29.03	35.56
0.374	13.42	15.58	16.29	17.50	17.62	22.37	28.56	32.22	39.41
0.472	17.56	21.15	20.56	22.20	22.30	27.60	34.63	39.40	48.01
0.502	19.47	23.22	22.76	24.41	24.53	30.44	37.74	42.59	51.86
0.629	27.61	30.44	31.15	33.04	33.16	39.71	47.65	53.16	64.31

Table 6

Values of annual reduction of CO_2 emissions from HPS with electric drive, %

Portion of HPI loading β	Source of low-temperature heat							
	Air	Ground	Ground waters	Surface waters	Sewage waters	Circulating water	Secondary energy resources	Geothermal waters
0.158	-0.35	-1.04	0.79	1.09	1.01	4.22	11.86	7.95
0.187	-1.21	-1.89	1.07	1.36	1.48	6.06	12.39	11.45
0.2165	-2.06	-2.75	1.36	1.63	1.95	7.90	16.03	14.94
0.246	-2.91	-3.60	1.65	1.90	2.43	9.75	19.67	18.43
0.315	-0.71	-2.08	1.57	1.88	2.02	8.44	17.50	15.91
0.344	-1.56	-2.94	1.86	2.15	2.49	10.29	21.14	19.40
0.374	-2.41	-3.79	2.15	2.42	2.96	12.13	24.78	22.89
0.472	-1.06	-3.13	2.36	2.67	3.03	12.67	26.24	23.86
0.502	-1.92	-3.98	2.65	2.94	3.50	14.51	29.88	27.36
0.629	-1.42	-4.17	3.15	3.46	4.04	16.89	34.99	31.82

Table 7

Values of annual reduction of CO_2 emissions for HPS with GPE drive, %

Portion of HPI loading β	Source of low-temperature heat							
	Air	Ground	Ground waters	Surface waters	Sewage waters	Circulating water	Secondary energy resources	Geothermal waters
0.158	3.01	2.24	3.34	3.66	3.72	5.29	8.56	9.78
0.187	5.36	4.18	5.98	6.30	6.41	8.62	13.34	14.39
0.2165	8.08	6.56	8.96	9.28	9.43	11.72	18.16	19.07
0.246	11.24	9.45	12.33	12.65	12.83	16.05	23.03	23.83
0.315	7.94	6.48	8.56	9.15	9.26	12.21	18.38	16.44
0.344	10.66	8.86	11.54	12.13	12.28	15.30	23.20	21.12
0.374	13.82	11.76	14.91	15.50	15.69	19.63	28.07	25.88
0.472	14.42	11.84	14.72	15.53	15.68	19.28	28.31	25.64
0.502	17.58	14.73	18.09	18.90	19.09	23.60	33.18	30.40
0.629	21.13	18.74	22.22	23.15	23.34	28.17	38.38	35.27

It should be noted that for HPS with GPE drive for all investigated operation modes better energy ecological indices are provided than for HPS with electric drive.

Conclusions

Energy ecological efficiency of HPS with various types of the compressor drive and sources of low-temperature heat (surface waters, water from system of circulating water supply, ground waters, geothermal waters, air, secondary energy resources, sewage water and ground heat), is evaluated, taking into account variable operation modes of heat supply systems in wide range of HPI power change.

For all sources of low-temperature heat and investigated operation modes of HPS with GPE drive equivalent fuel economy is observed, its values increase with the increase of HPI loading portion. For HPS with electric drive for the number of heat sources (air, ground, ground waters, sewage, surface waters) overexpenditure of equivalent fuel for certain operation modes is observed. For investigated sources of low temperature heat, rational operation modes of HPS, providing the economy of equivalent fuel are determined. For HPS with GPE drive for all investigated operation modes greater values of equivalent fuel economy than for HPS with electric drive are provided.

At different operation modes of HPS on all investigated sources of heat and types of drive the economy of operation fuel is observed. For HPS with electric drive the economy of operation fuel is higher than for HPS with GPE drive.

For HPS with electric drive the reduction of CO_2 emissions is provided at all investigated sources of heat, except the usage of ground heat and air, for which the increase of CO_2 emissions is observed. For all investigated operation modes of HPS with GPE drive the reduction of CO_2 emissions is observed.

For HPS with GPE drive for all investigated operation modes better energy ecological indices than for HPS with electric drive are provided.

The obtained results enable to evaluate energy efficiency and reduction of CO_2 emissions for HPS with various types of compressor drive and sources of low temperature heat on condition of variable operation modes of heat supply systems. The suggested results of the investigations enable to perform the selection of HPS operation modes and sources of low temperature heat in order to obtain the preset values of the indices of energy ecological efficiency of HPS operation.

The given recommendations can be used for the forecast of rational operation modes of HPS of different power in heat supply systems.

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