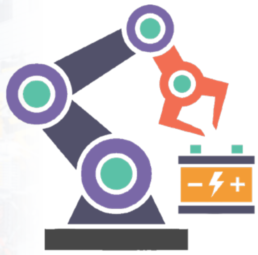

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Theoretical Studies of Determining the Efficiency Indicators of Heat Pump Installations Under Climatic Conditions of the Northern Region of Kazakhstan Kostanay Region

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Abstract. *The purpose of the work is the formation of target indicators of the technological efficiency of the use of a heat pumping unit in the design and climatic conditions of Northern Kazakhstan on the example of the Kostanay region. The result of the proposed solutions are piecemeal studies of exergy losses of the real thermodynamic cycle of a heat pump installation in the climatic conditions of the Kostanay region. The calculations have shown that the main source of exergy loss is the condensate cooler and the condenser. The exergy losses in the remaining elements of the thermodynamic cycle were found to be insignificant. The main way to reduce exergy losses in the further study of scientific and technical problems of using thermal pumps in the Kostanay region is the correct choice of architecture of heat exchange equipment, which allows to reduce the relative level of their losses in the overall exergy balance to a minimum.*

Keywords: *heat pump, heat exchanger, geothermal energy, exergy energy conservation, renewable energy sources, ecology.*

Introduction

In the modern world, including in the Republic of Kazakhstan, the problem of energy saving is becoming more and more urgent. The conditional problem is that the republic has significant reserves of many energy resources that are inexpensive and affordable. As a consequence, this may reduce the activity in the scientific and technological development of the energy industry to increase its competitiveness [1].

However, a number of adopted programs, regulatory documents, laws, guidelines still contribute to the development of energy conservation and renewable energy sources, such as: wind, solar, biomass, geothermal and low-potential energy sources, etc. [2].

A special position here is occupied by heat pump installations that use low-potential heat from the ground, air, water, municipal, agricultural and industrial secondary energy sources, in various power supply systems [3, 4].

The most well-known modifications of heat pumps in the world use the air space as a source of low-potential heat, as well as the heat of the soil [3, 4, 6, 8]. In the conditions of Northern Kazakhstan and, in particular, the Kostanay region, their use can be effective and technically and economically justified, only taking into account the indicators of specific design and climatic conditions (the estimated temperature difference of the source-consumer system, the depth of freezing of the soil, as well as the structure of the soil, etc.).

The purpose of scientific research is the formation of target indicators of technological efficiency of the use of a heat pumping unit in the design and climatic conditions of Northern Kazakhstan on the example of the Kostanay region.

Research methods

To determine the ways to improve the efficiency of heat pump installations in the conditions of the Kostanay region of the northern region of the Republic of Kazakhstan, it is necessary to identify in which elements most of the exergy is lost.

Exergy, as a measure of measurement, is the limiting amount of work in a thermodynamic system that is necessary when using a given amount of heat in a nonequilibrium system.

As the initial heat pump installation, we will take a heat pump installed in an office center. The functional diagram and general view of this heat pump installation are shown in Figure 1.

The installation functions by implementing a thermodynamic cycle of a steam compression heat pump with single-stage compression in various coordinates. A closed cycle of operation is realized by bringing low-potential heat from the heat exchanger 2 to the working substance in the evaporator 1 with cooling of its coolant from the temperature T_{S1} to T_{S2}. Further, through the drive device, mechanical energy is supplied to the working substance in the compressor during compression. There is a process of transferring electrical energy to mechanical energy, to the drive shaft of the compressor unit.

The implementation of the set goals and objectives allows an exergetic method of evaluating the operation of a heat pump [2].

Results and their discussion

In accordance with the calculated climatic conditions of Kostanay region and adjacent areas, the climate is characterized by pronounced aridity and a high degree of continentality. The average temperature in January ranges from –12.9°C to –22.2°C., the absolute minimum temperature ranges from –40.5°C to –43.2°C Starting from November 15 to March 27, persistent frosts persist, in April the air temperature reaches positive values, and in May they already exceed +10°C. The depth of soil freezing in Kostanay and the surrounding areas reaches from 109 cm to 155 cm (Dievskaya). The average height of the snow

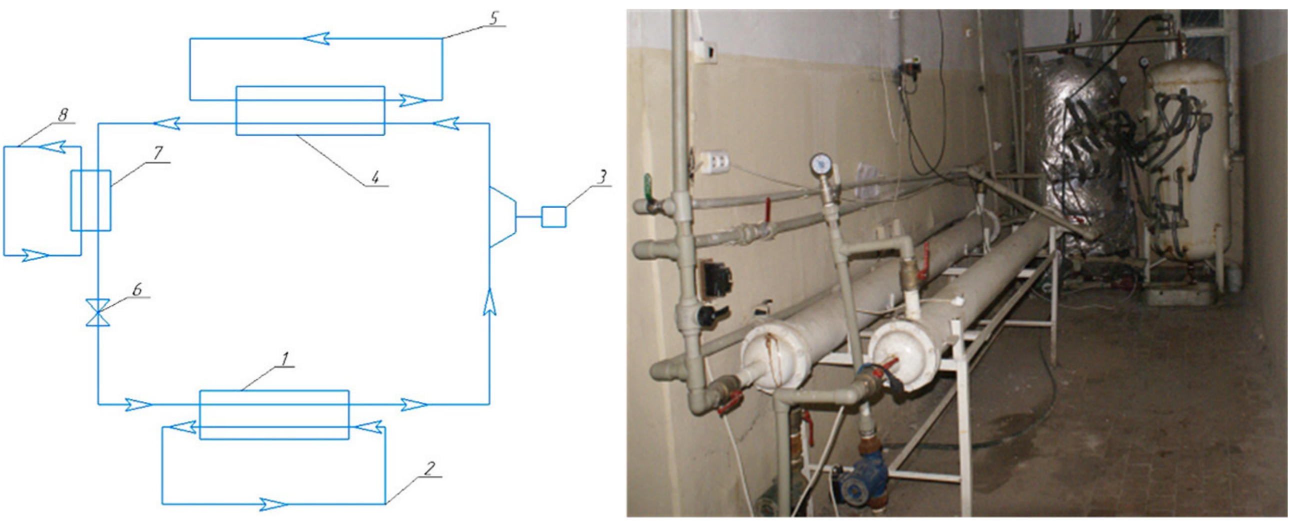

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Figure 1 – Combined functional diagram (a) [3] and industrial (b) telepumping unit

cover of the largest decadal for the winter ranges from 29.8-74 cm. The beginning of the heating season ranges from 01.10 to 24.04. [5].

According to the research results, the exergetic estimation method for a low-potential coolant takes the value $T_{S1}=276°K$ (+3°C), $T_{S2}=274°K$ (+1°C), and for a heating system coolant $T_{W2}=335°K$ (+62°C).

At the outlet of the heat exchangers, finite temperature differences are taken: in the evaporator $\Delta T_{ev}=T_{S2}-T_0=3°K$; in the condenser $\Delta T_c=T_K-T_{W1}=5°K$.

In accordance with the technical data of the manufacturer, the following values of indicators are accepted for the semi-hermetic reciprocating compressor of the Bitzer 4G-30.2 (Y)-40P brand: the coefficient of harmful space of the compressor $c=0{,}03$; the volume theoretical capacity of the compressor $V_0=84{,}5$ m³/h, the electromechanical efficiency of the compressor $\eta_c=0{,}95$. The ozone-safe refrigerant R422D is used as a working substance.

Studies of the thermodynamic cycle of a steam compression heat pump with single-stage compression of the ground-air system, in the coordinates «temperature T – entropy S» with heat carriers of low-potential heat source systems, heating and hot water systems have shown that the temperature of the saturated vapor of the working fluid at the outlet of the evaporator is $T_0=271°K$, the condensation temperature of the working body is $T_K=340°K$. Parameters of the working fluid state at characteristic points of the thermodynamic cycle (Figure 2).

The parameters, in accordance with the specified climatic conditions in the Kostanay region, are as follows:

Point 1: $T_0=T_1=271°K$; $P_1=P_0=0{,}2722$ MPa; $v_1=0{,}0739$ m³/kg; $T_0=271°K$; $P_1=P_0=0{,}2722$ MPa; $h_1=396{,}04$ kJ/kg; $S_1=1{,}723$ kJ/·°K, $x=1{,}000$.

Point 2: $T_2=285°K$; $p_2=p_0=0{,}272$ MPa; $v_2=0{,}0792$ m³/kg; $h_2=408{,}74$ kJ/kg; $S_2=1{,}768$ kJ/·°K.

Point 3*: $T_{3*}=358°K$; $P_{3*}=P_k=1{,}977$ MPa; $v_{3*}=0{,}0111$ m³/kg; $h_{3*}=453{,}00$ kJ/kg; $S_{3*}=S_2=1{,}7689$ kJ/°K.

Point 3: $h_3=463{,}45$ kJ/kg.

Point 4*: At this point, the process of 3-4* cooling is completed at this point, the process of 3-4* cooling of compressed vapors of the working fluid to a saturation state is completed at a temperature of $T_{4*}=T_{k*}=340°K$ and a pressure of $P_{4*}=1{,}977$ MPa, for which $S_{4*}=1{,}6967$ kJ/°K; $v_{4*}=0{,}0094$ m³/kg; $h_{4*}=427{,}81$ kJ/kg.

Point 4: $T_4=T_k=340°K$; $P_4=P_k=1{,}977$ MPa; $V_4=0{,}985$ m³/kg; $P_k=1{,}977$ MPa; $v_4=0{,}985$ m³/kg; $h_4=299{,}12$ kJ/kg; $S_4=1{,}3183$ kJ/·°K; $x=0.00$.

Thermal loads with a choice of volumetric output with a choice of volumetric compressor capacity in the design mode, $V=0{,}0155$ m³/s are investigated. With the mass flow rate of the working substance $G_{ws}=0{,}195$ kg/s, the thermal load of the evaporator was $Q_{ev}=36{,}36$ kW.

The thermal load of the condensate cooler was $Q_{cc}=14{,}93$ kW, and as a result, the electric power of the electric drive $N_{ed}=11{,}25$ kW.

The estimation of the external and internal calculated losses of exergy in the elements of the heat pump installation is carried out, which makes it possible to determine the magnitude of these losses in each of its constituent elements, their specific weight in the total amount of losses.

The values of the specific values of the exergies of the working substance are determined by the well-known Huy-Stodola theorem [6, 7]:

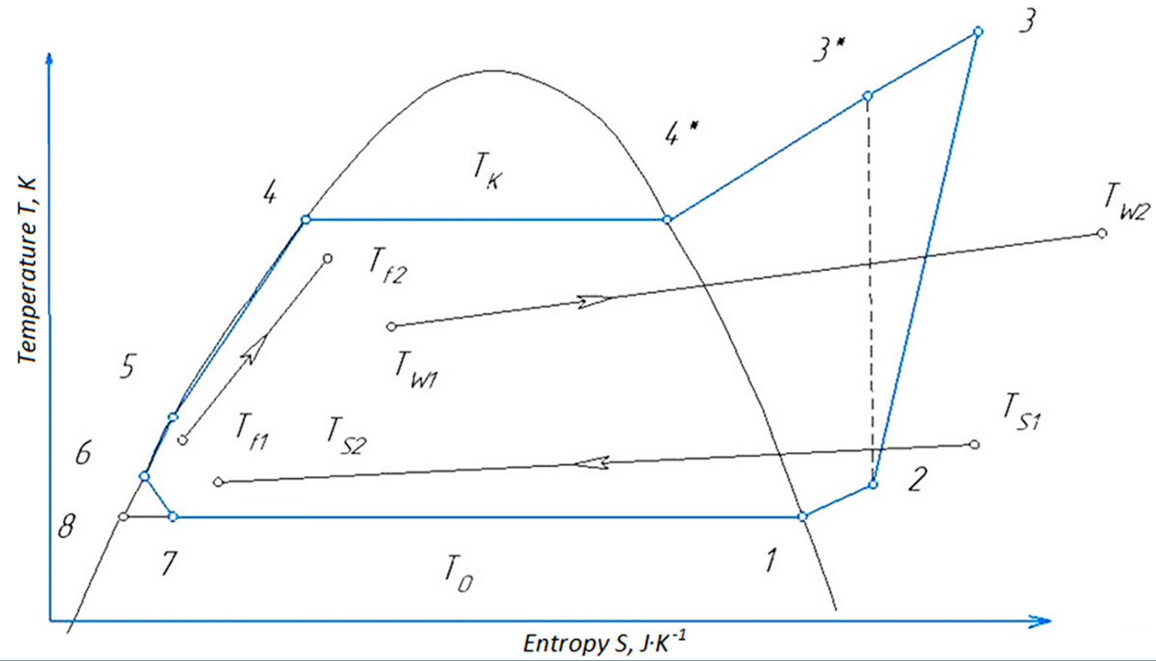

Figure 2 – Typical thermodynamic cycle of a steam compression heat pump with single-stage compression in the coordinates «temperature T – entropy S of the steam compression cycle» [3]

$$e_i = h_i - h_{ev} - T_{ev} \cdot (S_i - S_{ev}), \quad (1)$$

where T_{ev}, h_{ev} and S_{ev} – are the temperature, enthalpy and entropy of the working substance under environmental conditions;

h_i, S_i – enthalpy and exergy of the working substance R-422D at characteristic points of the thermodynamic cycle.

Further, the specific electromechanical losses of exergy di in each element of the heat pump unit (drive unit, compressor, condenser, etc.)

Are determined, the exergetic efficiency is determined [6, 7]:

The exergetic efficiency η_i^e is determined by [6, 7]:

$$\eta_i^e = (e_{en} - d_i) \cdot e_{en}, \quad (2)$$

где e_{en} – the specific amount of exergy (electricity).

The results of the studies are summarized in Table 1.

In order to take further practical measures to reduce energy costs in the components of the system, the own and technical losses of exergy in each of the components were also investigated. The costs that are constantly associated with the physical content of a certain thermodynamic work are assumed to be exergy's own losses [8]. By performing studies of these losses, as a result, it is possible to identify the directions and boundaries of reducing the values of exergetic losses in general throughout the heat pumping unit.

To carry out this analysis, the following restrictions and conditions were introduced:

- it is allowed to exclude extremes of temperature differences in the condenser (process 4* – 4 on the graph) and evanotransporation of the working fluid in the heat exchanger (process 1-7 on the graph), while the values $\Delta T_c = T_c - T_{W2} = 0{,}0$ °K and $\Delta T_{ev} = T_{S2} - T_0 = 0{,}0$ °K;
- it is allowed to exclude extremes of temperature differences in the heating zone of the heat transfer fluid in the condensate cooler (process 4-5), that is $\Delta T_{cc} = 0{,}0$ °K;
- it is allowed to exclude hydraulic losses and losses to the environment through thermal insulation in all elements of the heat pump installation;
- it is allowed that there is no volume of dead space (linear gap), pressure losses and friction losses in the compressor cylinders.

The amount of technical losses of exergy is determined by the formula [6, 7]:

$$d_i^T = d_i - d_i^{ow}, \quad (3)$$

где d_i, d_i^{ow} и d_i^T – total, own and technical losses in the i-th element of the system.

The boundary limit value of the exergetic efficiency is calculated [7]:

$$\eta_{ei}^{\lim} = \frac{e_i^{in} - d_i^{ow}}{e_i^{in}}, \quad (4)$$

где e_i^{in} – the exergy value at the input to the i-element of the system.

Studies and calculations were carried out in the following nodes of the heat pump system: compressor, condenser (compressed vapor cooling zone, condensation zone), condensate cooler, throttle device, evaporator.

The results of the conducted studies are presented in Tables 2 and 3.

Conclusion

Piecemeal studies of the exergy losses of the real thermodynamic cycle of a heat pump unit with a Bitzer 4G-30.2(Y)-40P compressor were carried out, where reftorite R 422D was taken as the working substance. The calculations have shown that the main source of exergy loss is the condensate cooler (0.1046 e^{in}) and the condenser (0.046 e^{in}). The exergy losses in the other elements of the thermodynamic cycle of the evaporator (0.037 e^{in}); compressor (0.025 e^{in}); throttle (0.0 e^{in}) are not so significant. The main way to reduce exergy losses, due to the fact that their own exergy losses cannot be eliminated by technical methods, is the correct choice of the architecture of heat exchange equipment, which allows to reduce the relative level of their losses in the overall exergy balance to a minimum. As a consequence, it is proposed that in order to increase the efficiency of the heat pump in the climatic conditions of the Kostanay region, it is necessary to improve the condensate cooler and modernize some units of the existing heat exchange equipment.

Table 1 – Absolute and relative exergy losses in a heat pump installation

Name of the element	Exergy losses				η_i^e
	External		Internal		
	d_i, kJ/kg	d_i / e_{en}	d_i, kJ/kg	d_i / e_{en}	
Electric drive	2,884	0,052	-	-	0,952
Compressor	-	-	7,933	0,138	0,854
Condensate cooler	-	-	5,143	0,089	0,571
Throttle device	-	-	6,002	0,106	0,853
Vaporizer	-	-	0,302	0,002	0,894
Total exergy losses in the installation, $\sum_1^n d_i$, kJ/kg and ($\sum_1^n d_i / e_{en}$)	25,191 (0,438)				

Table 2 – Internal irreversible exergy losses in the main elements of the installation

Element of the heat pump system	Total		Own		Technical		η_{ei}^{lim}
	d_i, kJ / kg	d_i / e_i^{in}	d_i^{ow}, kJ / kg	d_i^{ow} / e_i^{in}	d_i^T, kJ / kg	d_i^T / e_i^{in}	
Compressor	7,930	0,138	6,51	0,113	1,424	0,025	0,884
Capacitor	5,141	0,089	2,453	0,043	2,692	0,046	0,941
Condensate cooler	6,002	0,104	0,00	0,00	6,002	0,104	1,00
Throttle device	0,304	0,005	0,302	0,005	0,000	0,000	0,8514
Vaporizer	2,585	0,045	0,463	0,008	2,125	0,037	0,822
Total:	22,314	0,388	9,895	0,172	12,423	0,216	
* – The value of exergy at the inlet to the compressor e_{en} = 57,543 kJ / kg							

Table 3 – Values of own and technical losses in some elements of the heat pump installation

Element of the heat pump system	Own			Technical		
	$d_i^{ow} / \sum d_i$	$d_i^{ow} / \sum d_i^{in}$	d_i^{ow} / d_i^{in}	$d_i^T / \sum d_i$	$d_i^T / \sum d_i^{in}$	d_i^T / d_i^{in}
Compressor	0,254	0,292	0,820	0,055	0,063	0,180
Capacitor	0,096	0,110	0,477	0,105	0,118	0,523
Condensate cooler	0	0	0	0,234	0,264	1,0
Throttle device	0,012	0,013	1,00	0	0	0
Vaporizer	0,017	0,020	0,178	0,083	0,093	0,822
Total:	0,393	0,443		0,493	0,556	

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Қостанай облысы Қазақстанның солтүстік өңірінің климаттық жағдайларында жылу сорғы қондырғылары тиімділігінің көрсеткіштерін айқындауды теориялық зерттеу

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Аңдатпа. *Жұмыстың мақсаты – Қостанай облысының мысалында Солтүстік Қазақстанның есептік-климаттық жағдайларында жылу сорғы қондырғысын пайдаланудың технологиялық тиімділігінің нысаналы көрсеткіштерін қалыптастыру. Ұсынылған шешімдердің нәтижесі Қостанай облысының климаттық жағдайларында жылу сорғы қондырғысының нақты термодинамикалық циклінің шығындарын элементтік зерттеу. Есептеулер көрсеткендей, эксергияны жоғалтудың негізгі көзі конденсат салқындатқышы мен конденсатор болып табылады. Термодинамикалық циклдің басқа элементтеріндегі эксергияның жоғалуы маңызды емес. Қостанай облысындағы жылу сорғыларын пайдаланудың ғылыми-техникалық міндеттерін одан әрі зерттеуде эксергия шығынын азайтудың негізгі тәсілі жалпы эксергетикалық баланста, олардың шығындарының салыстырмалы деңгейін минимумға дейін төмендетуге мүмкіндік беретін жылу алмасу жабдығының архитектурасын дұрыс таңдау болып табылады.*

Кілт сөздер: *жылу сорғысы, жылу алмастырғыш, геотермалдық энергия, эксергия, энергия үнемдеу, жаңартылатын энергия көздері, экология.*

Теоретические исследования определения показателей эффективности теплонасосных установок в климатических условиях северного региона Казахстана Костанайской области

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Аннотация. *Цель работы – формирование целевых показателей технологической эффективности использования тепловой насосной установки в расчетно-климатических условиях Северного Казахстана на примере Костанайской области. Результатом предлагаемых решений являются поэлементные исследования потерь эксергии реального термодинамического цикла теплонасосной установки в климатических условиях Костанайской области. Проведенные расчеты показали, что основным источником потери эксергии являются охладитель конденсата и конденсатор. Потери эксергии в остальных элементах термодинамического цикла выявлены не существенными. Основным способом снижения потерь эксергии в дальнейшем исследовании научно-технических задач использования тепловых насосов в Костанайской области является правильный выбор архитектуры теплообменного оборудования, позволяющий свести относительный уровень их потерь в общем эксергетическом балансе к минимуму.*

Ключевые слова: *тепловой насос, теплообменник, геотермальная энергия, эксергия, энергосбережение, возобновляемый источник энергии, экология.*

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