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DEVELOPMENT OF A CONJUGATE ANALYSIS METHOD FOR THE EFFECTIVE USE OF HEAT PUMPS IN THE CLIMATIC CONDITIONS OF KOSTANAY REGION

The article discusses the issues of effective use of heat pumps in the northern region of Kazakhstan, Kostanay region. The purpose of this article is to study the physical and technological characteristics of various types of refrigerants for the effective use of heat pumps in the climatic conditions of Northern Kazakhstan, using the «Water – Water» coolant system, taking into account the external and internal parameters of the system's interaction. An analysis of the estimated climatic and soil characteristics of the Kostanay region was carried out, and priority methods for designing heat pump systems were determined. The results of a computational experiment performed on the basis of a model and a developed algorithm for the conjugate calculation of the Water-Water heat pump system are presented, taking into account external and internal factors affecting the system. As a result of the research, it turned out that the efficiency of a heat pump when installed in the Kostanay region depends on internal (thermodynamic parameters of the installation system and refrigerant characteristics) and external (temperature *characteristics of the external environment). and groundwater, operating conditions of the installation, depth of water resources, etc.) factors.*

The thermodynamic cycle of a heat pump has been determined depending on the refrigerant pressure P and refrigerant enthalpy h, heat conversion coefficients and their changes when the pump reaches its nominal operating mode. It has been proven that the best thermodynamic characteristics for the design and climatic conditions of the Kostanay region with internal influencing factors is the use of R513A refrigerant. The obtained research data can be used as the basis for calculating a joint analysis of the heat balance of rooms with heating equipment and technologies based on the use of heat pumps of the «Water-Water» system for the Kostanay region.

Keywords: heat pump, climate, ecology, renewable energy sources, heating of buildings. heat supply, enthalpy, thermodynamics.

Introduction

With a significant increase in thermal energy consumption in Kazakhstan, there is high wear and tear on the equipment of existing thermal power plants, boiler houses and heating networks, the modernization and repair of which, due to changes in consumer tariffs, cannot fully ensure their uninterrupted operation. operation [1]. Therefore, several options are proposed for overcoming the crisis with uninterrupted heat supply in winter - this is attracting additional investments with subsequent updating of heating equipment or a systematic partial transition to renewable energy sources, in particular, to heat pumps [2].

To form an effective method for determining the parameters of a heat pump based on the thermodynamic and soil-climatic characteristics of the Kostanay region [3], many scientific works were studied. Thus, in a scientific article [4], the authors propose an interesting method of accumulating heat at night with subsequent release of heat by bypassing hot gas by changing the rotation speed of the outdoor unit fan during daylight hours.

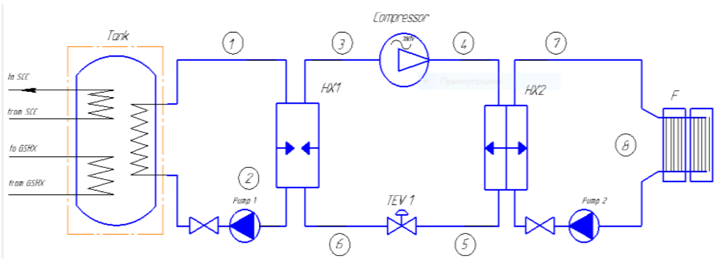
Also, in scientific work [5], an effective method was developed to bypass hot gas in a heat pump installation of an air-to-air system by changing the rotation speed of the outdoor unit fan. A similar method was proposed by the authors in article [6]. The use of a large array of data to control and regulate the thermodynamic cycles of a heat pump is proposed in the articles of the authors

[7;8]. Changes in design parameters when directly using heat pumps in various industries are presented in articles [9;10;11].

Materials and methods

To study the thermodynamic parameters of the refrigerant when designing a prototype of a ground heat pump with a vertical ground heat exchanger, a modeling method was used with a description of mathematical and computer algorithms of action.

To test various modes of operation of the ground source heat pump according to the «Water – Water» scheme, the licensed software «Engineering Equation Solver (EES)» was used. Figure 1 shows an image of a heat pump of the "Groundwater - Water" system in the room heating mode, which was isolated from the general diagram. When carrying out calculations, the following input data are indicated: water temperature in the tank +5^{0}C, temperature of the heating circuit in the fan coil +40 ^{0}C.



Tank – reservoir; Fan coil (F) – heating / air conditioning system; HX1 – evaporator; HX2 – capacitor; Pump – pumps; TEV1 – valve (shut-off valve); Compressor – heat pump.

Figure 1 – Component of the heat pump model of the «Water-Water» system

In general, the heat pump installation system is divided into circuits [12]: circuit 1 – heat source supply system 1-HX1; Circuit 2 – heat absorption system with evaporation circuit pump; Circuit 3 – compression of the coolant and gas supply from the evaporator to the HX1-Cmpr compressor; 4th circuit – compression of the coolant when gas is supplied to the Cmpr-HX2 condenser; Circuit 5 – branch of the chain of the process of thermal expansion and supply of coolant with excess pressure to the throttle valve; Circuit 6 – branch of the pressure relief circuit; 7th circuit – condensate supply system to the HX2-F heating system; Circuit 8 – heating system.

For the design and climatic conditions of the Kostanay region, six refrigerants were identified [13], the characteristics of which are presented in Table 1.

Table 1 – Refrigerants and their physical and environmental characteristics

Refrigerant	Molecular mass	Temperature (0^0C)	Pressure (MPa)	Boiling point (^{0}C)	ASHRAE Code	ODP R11 = 1	GWP 100 year
R-22	52,03	78,2	5.72	-51,7	A1	-	550,0
R-142	100,50	136,45	4.15	-26,5	A1	-	1410,0
R-500	93,48	80,0	4,88	-46,1	A1	-	1890,0
R-502	97,6	62,0	4,07	-46,3	A1	0,34	3750,0
R-152	44,1	96,7	4,52	-42,2	A3	-	20,0
R-513A	109,0	104,4	4,06	-23,1	A1	-	547

In the table, the parameters GWP is a coefficient that determines the degree of impact of various greenhouse gases on global warming, the ASHRAE parameter is a safety classification code and ODP R11 (Dichlorofluoromethane) is ozone depletion potential.

The mathematical model used to determine the thermal performance of the Water-Water heat pump is based on the following assumptions:

- A stationary process is assumed throughout the system;
- pressure losses in the suction and discharge areas are neglected;
- the mechanical efficiency of the compressor is assumed to be 95 %, and the isothermal efficiency is 80-85 %.
- it is assumed that there is 1-2 ^{0}C subcooling in the condenser, and 1-2^{0}C overheating in the evaporator;
- for heat exchangers, the «Closest Approach Temperature» parameter is set to 3;

- mass flow is considered constant at each stage of the thermodynamic work cycle.

The characteristics of the system with given parameters are calculated. According to the presented conditions, a mathematical algorithm has been developed for determining the parameters of a heat pump installation when operating in the climatic conditions of the Kostanay region. In this case, the first parameter, the thermal power in the «Cmpr-HX2-F» circuit of the model in Figure 1, can be estimated using the following formula [14]:

$$Q_{hx2} = m_r \cdot (\Delta h_5 - \Delta h_4) \quad (1)$$

where: Δh_4, Δh_5 – input and output enthalpy of the capacitor (heat exchanger 2 – HX 2, kJ).

m_r – mass flow rate of liquid, kg

The electrical energy consumption of the compressor, as well as the energy transferred to the refrigerant by the compressor, is the second most important indicator in the mathematical model, and is assessed using the following relationships [14]:

$$N_{cmpr} = \frac{m_r \cdot (h_4 - h_3)}{\eta_t \cdot \eta_{mch}} \quad (2)$$

$$W_{cmpr} = m_r \cdot (\Delta h_4 - \Delta h_3) \quad (3)$$

where: Δh_3, Δh_4 – enthalpy of the refrigerant at the inlet and outlet of the compressor (kJ),

η_t, η_{mch} – isothermal and mechanical efficiency of the compressor (%).

The transformation coefficient COP_{el} and the coefficient of the installation system $COPS_{el}$ are determined by the expressions [12;14]:

$$COP = \frac{Q_{hx2}}{W_{cmpr}} \quad (4)$$

$$COP_{el} = \frac{Q_{hx2}}{N_{cmpr}} \quad (5)$$

$$COPS_{el} = \frac{Q_{hx2}}{N_{tot}} \quad (6)$$

where: N_{tot} is the total amount of electrical energy consumed by the HPI installation, kW (circulation pumps, compressor, etc.).

Heat collection by the heat exchanger (evaporator) of the «1–HX1» circuit of the model in Figure 1 is determined by:

$$Q_{1-HX1} = m_{r0} \cdot (h_3 - h_6) \tag{7}$$

where: h_3, h_6 is the enthalpy of the refrigerant at the inlet and outlet of the evaporator of the 1–HX1-Cmpr" circuit, kJ.

As a result, it is necessary to calculate the Energy Balance equation, while the indicator of absorbed heat from the heat source of the "Water-Water" system should be considered as the boundary condition:

$$Q_{w-w} = Q_b + \Delta Q_a + W_{cmpr} \tag{8}$$

where: Q_{w-w} – absorbed heat from a source (ground water, underground river);

Q_b – heat that is transferred from the refrigerator to the building or structure (heat from the condenser);

ΔQ_a – heat loss from the installation to the atmosphere;

W_{cmpr} – heat pump compressor operation.

As a result of the developed mathematical algorithm for a given model of the heat pump of the "Water-Water" system, further studies of the operating modes of the system are determined taking into account external characteristics: soil and climatic conditions of the Kostanay region, and internal characteristics: physical and thermal properties of various refrigerants that are most effective for climatic conditions. conditions of the city of Kostanay (northern region of Kazakhstan).

Results and discussion

The conditions for choosing the power of the heat pump compressor are given for the climatic conditions of the city of Kostanay, with the following external characteristics of the heat pump system:

average outdoor temperature in winter $t_{oa} = -18 \ldots -20^0C$, heat pump start temperature at 8 ^{0}C;

depth of groundwater is 2...5 meters with the temperature of groundwater entering the evaporator $tt_{w1} = 3 \ldots 11^0 C$, and at its outlet $t_{w2} = 1 \ldots 8^0 C$;

average heated room area – 50 m^2 with sectional radiators.

Internal characteristics of the system:

temperature graph of the heating system 95÷55^{0}C, with a cut-off temperature 40÷80^{0}C

electromechanical efficiency of the compressor η_{mech}= 0.9…0.95, isothermal efficiency on average η_i= 0.5…0.65;

the estimated heat load of the HPP is Q_{tn} = 1.4 kW.

Figure 2 shows a schematic illustration of the calculation results for the R-513A refrigerant, using the formulas of the method (1)-(5).

As a result of using the mathematical model algorithm, the coefficient of performance (COP) values of the heat pump were obtained. The system COP was also calculated, taking into account the energy costs of the circulation pumps and compressor, which turned out to be 30% lower than COP_{cmpr}. For a visual representation of heat pump cycles, a p-h diagram was constructed, depending on the refrigerant proposed for use, as well as to determine the properties of the substance at a given point in the cycle. Moreover, it is necessary to take into account all the parameters and values of the critical upper point of the diagram, the range of refrigerant in the liquid phase of the system, in the vapor-liquid phase and also in the superheated vapor phase.

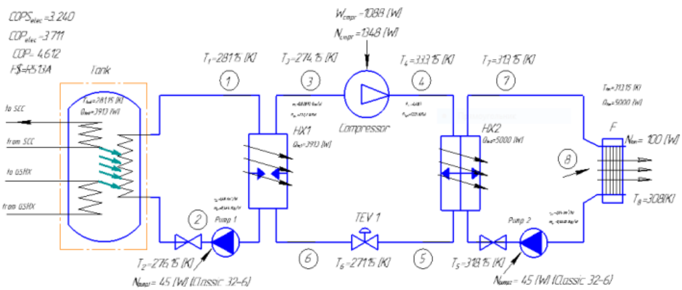
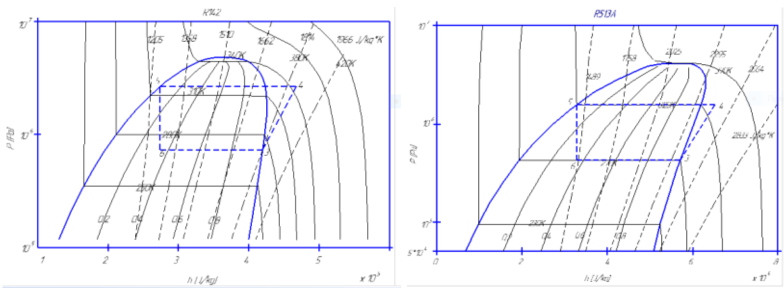


Figure 2 – Model of a heat pump system taking into account all internal thermodynamic parameters using the example of using R513A refrigerant

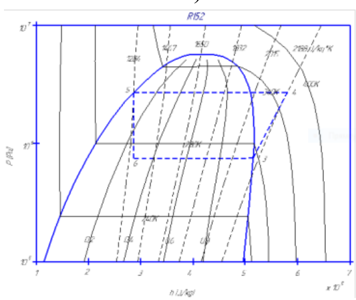
To analyze the phase composition and concentration of dissolved refrigerant compounds, only three refrigerants were selected: R-142, R-152 and R-513A.

These ozone-safe refrigerants have the most suitable characteristics for their use in the climatic conditions of the Kostanay region. Figure 3 shows the results of calculations and plotting of P-h diagrams. Analysis of the diagrams shows that the process of refrigerant evaporation due to the supply of heat from the cooled medium of the "Water-Water" system is most acceptable in terms of specific enthalpy for R513A, and is 3.1-6.2 (kJ/kg) at a constant pressure of 18.4 mPa. During the process of isobaric condensation (section 3-5) and heat transfer to the heating system, the R513A refrigerant also has the most optimal characteristics. The flow of a mixture of liquid and vapor into the evaporator (point 6) is better in terms of indicators for R152, but the enthalpy level is more effective for R513A, and is constant 3.1 kJ/kg.

Figure 4 shows some calculated coefficient of performance (COP) and compressor compression ratio data for the specified refrigerants. According to the calculation results, refrigerants R142, R500 and R513A demonstrate high COP values. However, R152 is a flammable gas, and its use in heat pumps is recommended in small quantities, that is, for low-power HPs.



b)

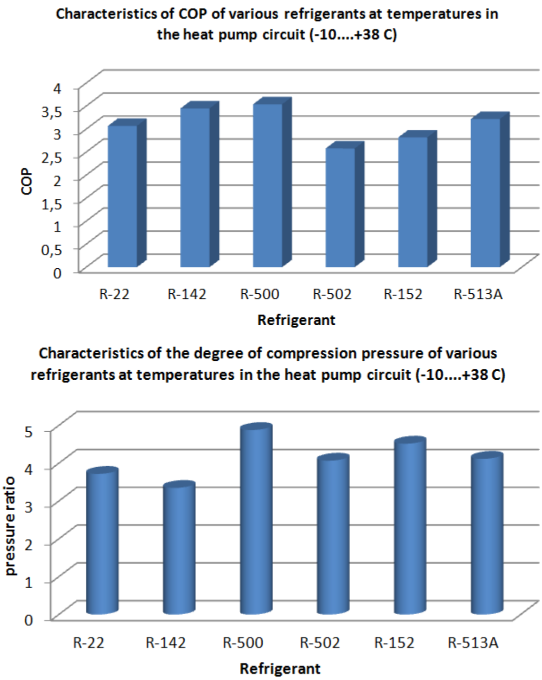


c)

a) R142 refrigerant, b) R513A refrigerant c) R152 refrigerant

Figure 3 – Results of the P-h diagram for the heat pump of the "Water-Water" system

According to Figure 4, R502 refrigerant has a low COP of 2.48 and the highest COP has R500 of 3.46. Under different conditions, an analysis of the global warming potential (GWP) was carried out, where the highest refrigerant was R500 with a value of 3750.



a) b)

Figure 4 – Conversion coefficient for various refrigerants in the temperature range from +5^{0}C in the tank to +40^{0}C in the heating circuit

At the same time, the refrigerant R513A has a lower GWP of 690, and this refrigerant belongs to the 4th generation and meets the requirements Paris Protocol. The theoretical compression ratio (pressure ratio) of the compressor for all considered refrigerants, according to calculated data, does not exceed 5:1, which is acceptable for the system.

The diagrams show that as the refrigerant temperature in the storage tank increases at a fixed heating circuit temperature of +40 ^{0}C, the coefficient of performance (COP) increases and the compressor load decreases. On the other hand, when the temperature of the working fluid in the fan coil increases at a fixed tank temperature of +5^{0}C, the COP coefficient decreases and the compressor compression ratio increases.

Conclusion

The article presents the results of a computational experiment performed on the basis of a model and a developed algorithm for the conjugate calculation of the «Water-Water» heat pump system in relation to the soil and climatic conditions of the Kostanay region and the energy characteristics of the heat pump refrigerants. As a result of the study, the following conclusions were made: The efficiency of the heat pump depends on internal (thermodynamic parameters of the installation system and characteristics of the refrigerant) and external (temperature characteristics of the external environment and groundwater, operating conditions of the installation, depth of water resources, etc.) factors; as a result of the study, the thermodynamic cycle of the heat pump was determined depending on the refrigerant pressure P and refrigerant enthalpy h, heat conversion coefficients and their changes when the pump reaches its nominal operating mode; it has been proven that the best thermodynamic characteristics for the structural and climatic conditions of the Kostanay region with internal influencing factors is the use of R513A refrigerant; changes in the temperature of the low-grade heat source (ground and underground water) during the heating season have a significant impact on the characteristics of the heat pump, while its heating capacity changes approximately twice in inverse proportion to the heat demand.

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ҚОСТАНАЙ ОБЛЫСЫНЫҢ КЛИМАТТЫҚ ЖАҒДАЙЫНДА ЖЫЛУ СОРҒЫЛАРЫН ТИІМДІ ПАЙДАЛАНУ ҮШІН КОНЪЮГАТТЫҚ ТАЛДАУ ӘДІСІН ЖАСАУ

Мақалада Қазақстанның солтүстік өңірінде, Қостанай облысында жылу сорғыларын тиімді пайдалану мәселелері қарастырылған. Бұл мақаланың мақсаты Солтүстік Қазақстанның климаттық жағдайында жылу сорғыларын тиімді пайдалану үшін «Су – Су» салқындатқыш жүйесін пайдалана отырып, сыртқы және ішкі салқындатқыш агенттердің физикалық және технологиялық сипаттамаларын зерттеу болып табылады. жүйенің өзара әрекеттесуінің параметрлері. Қостанай облысының есептік климаттық және топырақ ерекшеліктеріне талдау жүргізілді, жылу сорғы жүйелерін жобалаудың басым әдістері анықталды. Жүйеге әсер ететін сыртқы және ішкі факторларды ескере отырып, «Су-Су» жылу сорғысы жүйесінің конъюгаттық есептеуінің моделі мен әзірленген алгоритмі негізінде орындалған есептеу экспериментінің нәтижелері берілген. Зерттеу нәтижесінде Қостанай облысында орнатылған жылу сорғысының тиімділігі ішкі (қондыру жүйесінің термодинамикалық параметрлері және салқындатқыштың сипаттамалары) және сыртқы (сыртқы ортаның температуралық сипаттамалары) тәуелді екендігі анықталды.

және жер асты сулары, қондырғының жұмыс жағдайлары, су ресурстарының тереңдігі және т.б.) факторлар.

Жылу сорғысының термодинамикалық циклі хладагенттің қысымы P және хладагенттің энтальпиясы h, жылу түрлендіру коэффициенттері және олардың сорғының номиналды жұмыс режиміне жеткендегі өзгеруіне байланысты анықталды. Ішкі әсер етуші факторлары бар Қостанай облысының конструктивтік және климаттық жағдайлары үшін ең жақсы термодинамикалық сипаттамалар R513A хладагентін пайдалану болып табылатыны дәлелденді. Алынған зерттеу деректері Қостанай облысы үшін «Су-Су» жүйесінің жылу сорғыларын пайдалануға негізделген жылыту жабдығы мен технологиялары бар үй-жайлардың жылу балансын біріктірілген талдауды есептеу үшін негіз ретінде пайдаланылуы мүмкін.

Кілтті сөздер: жылу сорғысы, климат, экология, жаңартылатын энергия көздері, ғимараттарды жылыту. жылумен қамтамасыз ету, энтальпия, термодинамика.

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РАЗРАБОТКА МЕТОДА СОПРЯЖЕННОГО АНАЛИЗА ДЛЯ ЭФФЕКТИВНОГО ИСПОЛЬЗОВАНИЯ ТЕПЛОВЫХ НАСОСОВ В КЛИМАТИЧЕСКИХ УСЛОВИЯХ КОСТАНАЙСКОЙ ОБЛАСТИ

В статье рассматриваются вопросы эффективного использования тепловых насосов в условиях северного региона Казахстана Костанайской области. Целью данной статьи заключается исследование физико-технологических характеристик различных видов хладагентов для эффективного использования тепловых насосов в климатических условиях Северного Казахстана, по системе теплоносителя «Вода – Вода» с учетом внешних и внутренних параметров взаимодействия системы. Проведен анализ расчетно-климатических и почвенных особенностей Костанайской области, определены приоритетные методы для проектирования теплонасосных систем. Представлены результаты вычислительного эксперимента, выполненные на основе модели и разработанного алгоритма сопряженного расчета теплонасосной системы «Вода-Вода» с учетом внешних и внутренних факторов влияния на систему. В результате исследований выяснилось, что эффективность теплового насоса при установке в Костанайском регионе, зависит от внутренних (термодинамических параметров системы установки и характеристики хладагента) и внешних (температурных особенностей внешней среды и подземных вод, *условия эксплуатации установки, глубины залегания водных ресурсов и др.) факторов.*

Определены термодинамический цикл теплового насоса в зависимости от давления хладагента P и энтальпии хладагента h, коэффициенты трансформации теплоты и их изменение в процессе выхода насоса на номинальный режим работы. Доказано, что наилучшими термодинамическими характеристиками для расчетно-климатических условий Костанайской области при внутренних влияющих факторах, является использование хладагента R513A. Полученные данные исследований могут быть положены в основу методики расчета сопряженного анализа теплового баланса помещений с отопительным оборудованием и технологиями, основанными на применении тепловых насосов системы «Вода-Вода» для Костанайской области.

Ключевые слова: тепловой насос, климат, экология, возобновляемые источники энергии, отопление зданий, теплоснабжение, энтальпия, термодинамика.

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