DOI 10.52209/1609-1825_2023_1_405 UDC 621.577.012

Mathematical Modeling of a Heat Pump Unit in the Climatic Conditions in the Northern Region of Kazakhstan

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Abstract. *Currently, the use of heat pumps in the Republic of Kazakhstan is becoming popular. However, there is no introduction of low-potential thermal resources from renewable sources together with the use of heat pumps, which is important in the area of energy conservation and also deemed nature-friendly for the country. The purpose of this work to form a mathematical model of the optimal choice of the working units and calculation of thermodynamic parameters of a heat pump installation, taking into account the design and climatic conditions of the Kostanay region situated in the northern region of Kazakhstan. The conditions of efficiency and the choice of a specific source of thermal energy are considered, which depends on climatic conditions, especially if the source of heat extraction is atmospheric air and earth. The mathematical model of the heat pump unit is formed by studying arithmetic relations in the function of temperature indicators of external and internal environments, which characterizes its effective use in the climatic conditions of the Northern region of Kazakhstan. Based on the developed algorithm of the model's calculations of heat consumption, the thermal power of the heat pump was made.*

Keywords: *heat exchanger, temperature, compressor, refrigerant, circuit, heat pump, thermal energy, efficiency, mathematical modeling.*

Introduction

The significant use of technically and economically sound systems of low-potential heat sources in the design is one of the promising areas of renewable energy development in the world, as well as in the Republic of Kazakhstan [1, 2].

The tasks and goals for the energy development of the republic are relevant at the present time, and all the tasks of regulating and organizing efficient energy consumption systems are being solved in Kazakhstan at the legislative and legal levels.

In accordance with the Law of the Republic of Kazakhstan «On Energy Conservation and Energy Efficiency Improvement», it is recommended to support technological regulation in the areas of generation and consumption of electric and thermal energy, and also regulates the stimulation of energy conservation, energy efficiency of equipment, in order to increase all technological procedures, including the use of certain classes of energy-saving equipment and materials [2, 3].

Several scientific and technical enterprises have been created for the development, production and implementation of heat pumps – Ust-Kamenogorsk Heat Pump Plant «SanDyu» LLP (Ust-Kamenogorsk Heat Pump Plant). Therefore, it should be noted in principle that the problem of studying methods and devices for improving the performance of heat pump systems and installations is relevant, and should occupy priority positions in solving the established tasks of energy saving in industry and agriculture.

Methodology

To compile a mathematical model that allows calculating and predicting the thermal engineering parameters for the efficiency of the heat pump installations for the specified design and climatic conditions of the Kostanay region, it is necessary to form a methodology that allows obtaining the most reliable result, considering the features of the equipment of the energy system for the use of earth's heat [1, 4, 5].

Various sources were analyzed to select the research method. So, in the article [4], a method is proposed to increase the productivity of cascade dryers with a heat pump, taking into account changes in ambient temperature, flow parameters of low and high stages of the operation cycle. Also of interest is the authors' research in [5], which shows ways to achieve an increase in the efficiency of heat pumps in a cold climate. The authors in the article [6] propose the operation of a heat pump in cold climates and the exclusion of its icing, a combined heat supply system using exhaust gases. Also, in [7, 8], interesting ways are proposed to increase the efficiency of heat pumps using local climatic features of the soil and the environment.

However, the studied methods do not take into account the parameter of the average outdoor temperature for the entire heating period of the heat pump, as well as other parameters characteristic of the climatic conditions of the northern region of Kazakhstan.

The calculated climatic parameters of the region are presented according to datas from long-term observations of meteorological stations of the branch of Republican State Enterprise «Kazhydromet» in the Kostanay region. The observation periods used for research depend on the time resolution of the parameter, in addition to the specific values of the specified observation periods which are specified for each calculated meteorological parameter [6].

The modeling system of qualitative regulation of a heat pump is reduced to determine the temperatures of «direct» and «reverse» water in the heating network. This allows you to maintain the internal temperature in heated rooms at the required level. The methodology for mathematical modeling of a heat pump, considering the conditions of the temperature conditions of our climate for the heat supply system, includes initial data at a conditional design load (heating capacity) Q_r^T в 100 kW, such as:

t_{start} is the temperature of the low-potential heat source (equals to 8°C);

$t_{out.c}^{dir}$ is the temperature of the refrigerant in the «direct» mains line (70°C);

$t_{out.c}^{rev}$ is the temperature of the refrigerant in the «reverse» mains line (40°C);

$t_{calc.out.}$ is an average parameter that is fixed depending on the value of the temperature outside the room, during the entire heating season (on average equal to $t_{calc.out.} = -11°C \div -26°C$);

$t_{calc.ind.}$ the fixed value of the air temperature inside the building,, during the entire heating season (on average equal to $t_r = 16°C \div 25°C$, taken from the Kazakhstan standards).

Results and their discussion

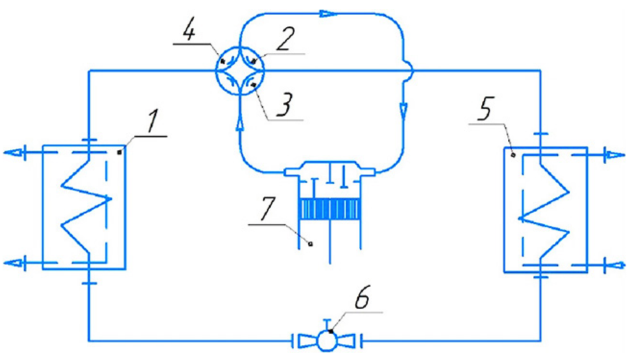
Figure 1 shows a typical model of a heat pump installation that uses the heat of the earth and takes into account the temperature conditions of the environment. [1, 9]. The system is reversible and provides heat and cold generation modes. To operate the heat pump in the air conditioning mode, the valve «4» of the compressor unit moves to the opposite position, while the coolant, bypassing the compressor, enters the energy distribution radiators and absorbs excess heat from the room. Energy savings are achieved by eliminating the operation of the compressor from energy consumption when using only the capabilities of pumps and instrumentation.

Typical modes of steam compression systems using heat pumps are as follows. In the heating mode of the building (structure), the coolant enters the external heat exchanger with low pressure. Then the refrigerant is heated by transferring heat from a more heated coolant, which gives heat to the heated room by further compressing and heating it in the compressor. In the reverse mode (cooling), steam passes in the opposite direction through an internal heat exchanger (condenser), which reduces overheating and condenses steam into liquid at a constant temperature and pressure in the circuit. Further, when passing through the control valve, the pressure drops sharply, causing cooling of a small part of the liquid [2, 7, 8].

To form a mathematical model of heat production in the conditions of the northern region of Kazakhstan, it is necessary to set the initial data.

Based on the conducted studies of the climatic conditions of the northern region of Kazakhstan on the example of the Kostanay region, Table 1 shows the average time periods of the heating season and the estimated air conditioning inside buildings and structures, depending on the value of the ambient temperature $t_{calc.out.}$.

The parameters of the ambient air temperature in winter and summer are taken from the analysis of data for the period from 2010 to 2020 according to [3], the minimum and maximum temperatures are taken from the standards of the Republic of Kazakhstan. As can be seen from the table, the average heating period for energy consumers in the northern region of Kazakhstan is 4479 hours, and the summer period of high temperatures is 1986 hours. The remaining duration of the temperature values in the year fell to



1 – external heat exchanger; 2 – the direction of movement of the refrigerant when cooling the room; 3 – the direction of movement of the refrigerant when heating the room; 4 – four-way tap switch; 5 – internal heat exchanger; 6 – control valve; 7 – compressor

Figure 1 – Functional diagram of the heat pump operation in the modes of heat generation and cooling supply

Table 1 – The time of the heating season and the time of the need for cooling of the objects of the design of the heat pump installation, for the climatic conditions of the northern region of Kazakhstan

Heating season								
$t_{calc.out.}$, °C	-28,0...-25,0	-24,9...-20	-19,9...-15,0	-14,9...-10,0	-9,9...-5,0	-4,9...0,0	+0,10...+5,0	+5,1...+8,0
τ, h	270,0-274,0	436,0-438,0	346,0-350,0	465,0-470,0	725,0-730,0	600,0-605,0	1200,0-1220	388,0-392,0
Summer air conditioning								
$t_{calc.out.}$, °C	+8,0 – 20,0				20,0 – 30,0			
τ, h	1246,0				740,0			

values below –28°C(–30°C) and above +30°C, they can be considered as temperatures that are not included in the task of determining the range of mathematical ranking factors.

Next, it is necessary to determine the heat consumption for heating Q^T, associated with the outdoor air temperature and the indoor air temperature $t_{calc.ind.}$. The dependence is:

$$Q^T = Q_r^T \cdot \frac{t_{calc.ind.} - t_{calc.out.}}{t_{calc.ind.} - t_{calc.real}}, \tag{1}$$

where Q_r^T is the estimated heating capacity of the system, (kW);

$t_{out.real}$ is the real outdoor temperature (valid), (°C).

The temperatures (°C) of the «direct» and «reverse» water in the heat pipe are determined by equations [2]:

$$t_w^{dir} = t_{calc.ind.} + \Delta t' \cdot \bar{Q}^{0.8} + \bar{Q} \cdot \frac{\theta'}{2}, \tag{2}$$

$$t_w^{owt} = t_{calc.ind.} + \Delta t' \cdot \bar{Q}^{0.8} - \bar{Q} \cdot \frac{\theta'}{2}, \tag{3}$$

where $\Delta t'$ is the arithmetic mean difference of the calculated air temperatures outside and inside the room and is defined as

$$\Delta t' = \frac{t_{out.c}^{dir} + t_{out.c}^{rev}}{2} - t_{calc.ind.},$$

where θ' this is the energy consumption of heat for heating at a fixed average value of the temperature inside the building (structure) and the temperature of the external environment, (J/h); $Q^{0.8}$ is the reduced value of heat exchange at critical ambient temperatures, J/(kg K).

The estimated water consumption (kg/h) is determined taking into account the design load and the temperature difference in the forward and reverse pipelines of the heat pump system of the building (facility) [2, 9]:

$$G_w^h = \frac{Q_{calc}^T}{c_w \cdot \left(t_{wp}^k - t_{wp}^{out}\right)}. \tag{4}$$

The amount of heat Q^{hp} (thermal power) of the heat pump must be calculated according to [2]: is determined by, (kW) [2]:

$$Q^{hp} = G_w^h \cdot c_w \cdot \left(t_w^k - t_w^{owt}\right), \tag{5}$$

where t_w^k is the value of the temperature of the coolant at the outlet of the condenser of the heat pump system, (°C);

c_w is the heat capacity of a unit of coolant in a heating system with a heat pump unit (J/(kg·°C).

The value of the coolant temperature in the system circuit after the condenser, (°C), is:

$$t_w^k = t_k - \frac{t_k - t_w^{out}}{e^m - 1}, \tag{6}$$

where m is the heat transfer coefficient, calculated by the formula $m = \frac{k_k \cdot F_k}{G_w^k \cdot c_w}$.

The algebraic product $k_k F_k$ describe the convective heat transfer in the condenser of the system, at the highest value of thermal power, (W/K).

The condensation temperature is determined by the expression, (°C):

$$t_k = \frac{e^m \cdot t_w^{dir} - t_w^{out}}{e^m - 1}. \tag{7}$$

The maximum performance of the peak heating system is determined by the equation:

$$Q^p = G_w^k \cdot c_w \cdot \left(t_w^{dir} - t_w^{out}\right). \tag{8}$$

The effective capacity of the heat pump compressor N is determined by the conditions of the Carnot thermodynamic cycle.

$$N = G_w^h \cdot l_s, \tag{9}$$

where l_s is the specific operation of the compressor and is selected according to the cycle of operation of the heat pump in p-i coordinates, (J/kg) [2].

The mathematical model resulting from the construction of the algorithm of the conceptual model of the heat-carrying system, taking into account the design and climatic conditions of the northern region of Kazakhstan, can be considered a complete set of tasks. According to the specified algorithm, studies were conducted for a room with an area of 100 m² and a recommended maximum heating capacity of 125 kW with heat extraction from the ground. The obtained data on the climatic and natural features of the region were used in the calculation. The results of the quantitative study are presented in Table 2.

The analysis of calculated indicators of tabular parameters allows us to draw conclusions about the

Table 2 – Calculation results of the heat pump in the heating load mode

Parameter	Outdoor air temperature $t_{o.a.}$, °C								
	–30	–25	–20	–15	–10	–5	0	+5	+10 (+8)
Parameters of the heat pump compressor									
Q^T, kW	125	112	100	87,5	75,0	62,5	50,0	37,5	25,0
Q^{hp}, kW	63,8	57,3	53,9	52,59	54,74	51,6	50,0	37,5	25,0
t_w^{dir}, °C	80,6	75,33	70,0	64,6	59,05	53,4	47,6	41,5	35,2
t_w^{out}, °C	43,1	41,58	40,0	38,3	36,55	34,6	32,6	30,3	27,7
t_w^k, °C	62,4	58,9	56,3	34,2	53,1	50,2	47,6	41,5	35,2
G_w^h, kg/s	0,79								
Parameters of the heat pump condenser									
t_k, °C	43,0	41,0	400	40	40,0	37,2	35,0	33,2	30,4
θ_k, °C	2,8	3,2	4,0	6,0	7,0	8,0	7,5	5,6	3,2
K_kF_k, W/K	7820,0	7820,0	7820,0	7820,0	7820,0	7820,0	7820,0	7820,0	7820,0
Parameters of the heat pump evaporator									
G_w^i, kg/s	7,3	7,3	7,3	7,3	7,3	7,3	7,3	7,3	7,3
K_iF_i, W/K	9400,0	9400,0	9400,0	9400,0	9400,0	9400,0	9400,0	9400,0	9400,0
Results of the heat pump parameters									
Q^p, kW	61,2	54,7	46,1	34,9	20,26	10,9	0	0	0
N, kW·h	26,5	20,8	19	11,4	11,2	9,9	8,7	6,7	4,4

features of the seasonal performance of a heat pump in the conditions of the northern region of Kazakhstan on the example of the city of Kostanay, in which the dependencies of compressor power consumption on outdoor air temperature are obtained (Figure 2 (a)). It is revealed that the maximum power consumption of 26.5 (kW·h) is observed at a temperature of –30°C. Figure 2 (b) shows the dependences of heating capacity on the duration of the heating season.

The main variable design parameters of the conceptual mathematical model included the values of the temperatures of «direct» and «reverse» water in the heating network of the object. All design parameters of the model depend on the heat load required in the given natural and climatic conditions. This makes it possible to maintain the internal temperature in the heated premises at the required level, which is specified in the regulatory documents of the Republic of Kazakhstan.

According to the results of the formalization of the data presented in Table 2, in Figure 3, the dependences of temperatures in the «forward» and «reverse» pipelines of the heating system using a heat pump on the value of external ambient temperatures are plotted.

As a result of the analysis of the dependencies in Figure 3, it can be assumed that at the minimum design temperatures of the winter heating period (–30°C), it is necessary to maintain the temperature in the «direct» pipeline of the order of 80.6°C, with an estimated compressor load of 26,5 (kW·h).

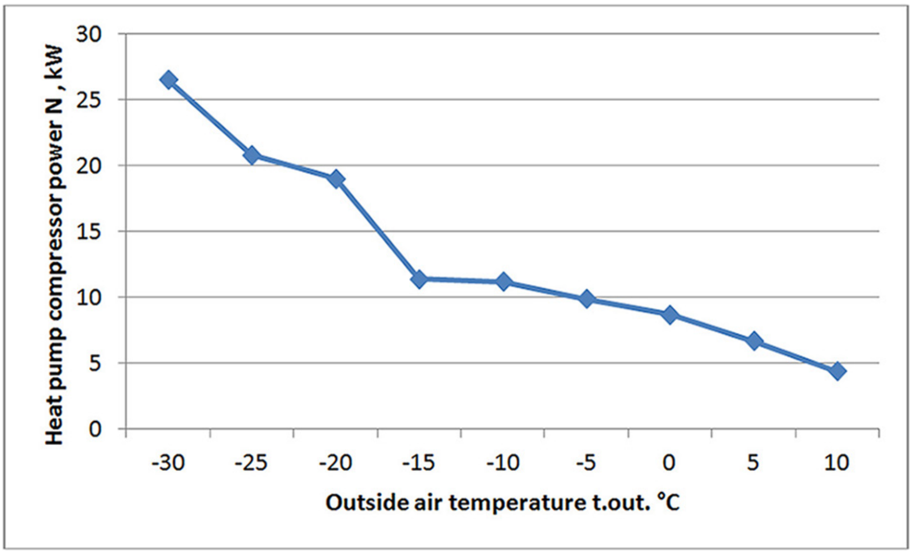
In the future, calculations based on the simulation algorithm, you can choose a heat pump, as well as its power equipment: compressor, circulation pump, evaporator pump and much more.

Conclusion

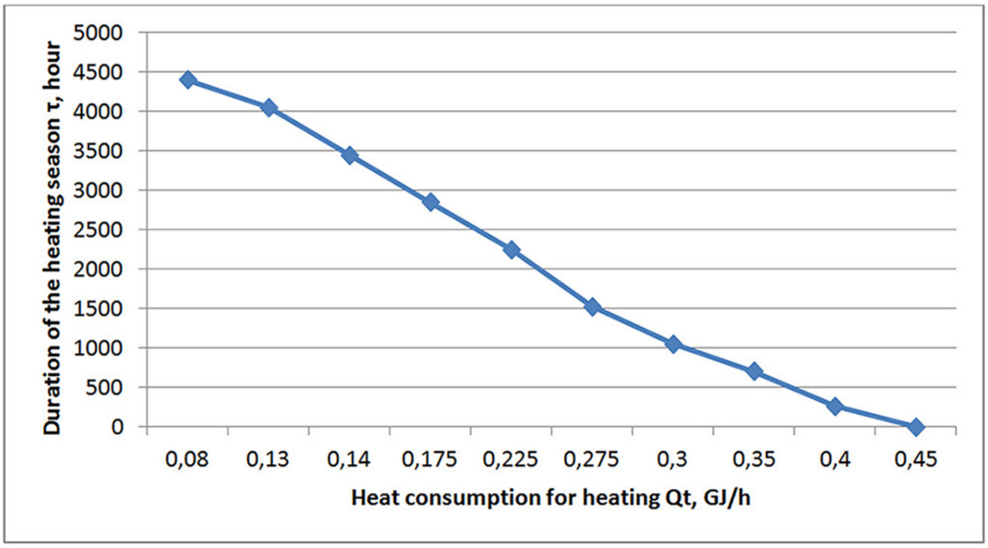
The article proposes a set of mathematical rules and approaches to calculating the parameters of the thermodynamic heat supply system of a building (structure) using a heat pump in the natural and climatic conditions of northern Kazakhstan on the example of the city of Kostanay. A survey of the technological chain of heating systems using a heat pump was carried out, the correctness of the model was assessed, a solution method was chosen, and a mathematical algorithm of the study was developed. The theoretical use of the mathematical model was made on the example of a room in the city of Kostanay, preliminary results of the analysis were obtained.

The calculation of the thermal performance of the heating system was carried out in the temperature range inherent in the Kostanay region during the heating season from –30(–28)°C to +10(8)°C. It was found that at the lowest possible temperatures, heat consumption reaches 26.5 (kW·h), the characteristic temperature of the «direct» pipeline is +80.6°C.

It is assumed that in the climatic conditions inherent in the Kostanay region, in order to cover peak thermal loads at low temperatures, there is a need to use new circuit solutions involving the use of additional energy sources.



(a) The dependence of the compressor power on the external ambient temperature during the heating period



(b) The dependence of the heating capacity of the heat pump system on the duration of the heating season

Figure 2 – Heat and power characteristics of the design parameters of the heating system using a heat pump with heat extraction from the ground, in the conditions of the northern region of Kazakhstan

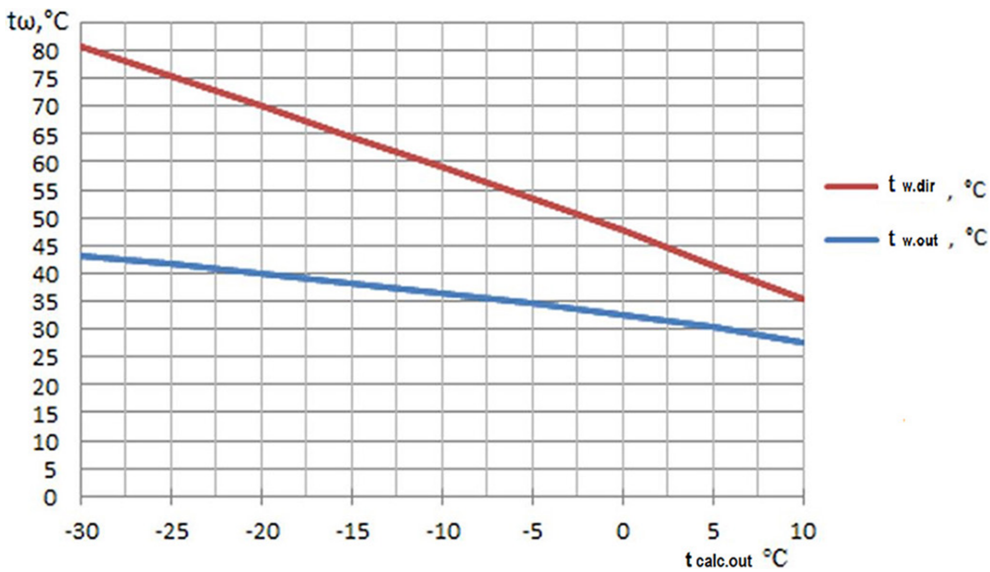


Figure 3 – Temperature schedule of qualitative regulation of heating load

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Қазақстанның солтүстік аймағының климаттық жағдайында жылу сорғы қондырғысын математикалық модельдеу

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Аңдатпа. *Қазіргі уақытта Қазақстан Республикасында жылу сорғыларын пайдалану барған сайын танымал бола түсуде, бірақ әзірге ол тиісті түрде тараған жоқ. Дегенмен, жаңартылатын көздерден төмен потенциалды жылу ресурстарын енгізу және жылу сорғыларын пайдалану біздің еліміздегі энергияны үнемдеу мен табиғатты қорғаудың маңызды саласы болып көрінетініне күмән жоқ. Ғылыми мақаланың мақсаты Қазақстанның солтүстік өңірінің Қостанай облысының конструкциясы мен климаттық жағдайларын ескере отырып, жұмыс тораптарын оңтайлы таңдаудың математикалық моделін қалыптастыру және жылу сорғы қондырғысының термодинамикалық параметрлерін есептеу болып табылады. Мақалада тиімділік шарттары мен климаттық жағдайларға байланысты жылу энергиясының нақты көзін таңдау қарастырылады, әсіресе жылу алу көзі атмосфералық ауа мен жер болса. Жылу сорғы қондырғысының математикалық моделі сыртқы және ішкі ортаның температуралық көрсеткіштерінің функциясындағы арифметикалық қатынастарды зерттеу арқылы қалыптасты, бұл оны Қазақстанның солтүстік аймағының климаттық жағдайында тиімді пайдалануды сипаттайды. Модельдің әзірленген алгоритміне сәйкес жылу шығыны, жылу сорғысының жылу қуаты есептелді.*

Кілт сөздер: *жылу алмастырғыш, температура, компрессор, салқындатқыш, контур, жылу сорғысы, жылу энергиясы, тиімділік, модельдеу.*

Математическое моделирование тепловой насосной установки в климатических условиях северного региона Казахстана

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Аннотация. *В настоящее время использование тепловых насосов в Республике Казахстан становится все более популярным, но пока не получило должного распространения. Однако нет никаких сомнений в том, что внедрение низкопотенциальных тепловых ресурсов из возобновляемых источников вместе с использованием тепловых насосов, по-видимому, является важной областью энергосбережения и охраны природы в нашей стране. Целью научной статьи является формирование математической модели оптимального выбора рабочих узлов и расчета термодинамических параметров теплонасосной установки с учетом конструкции и климатических условий Костанайской области северного региона Казахстана. Рассматриваются условия эффективности и выбор конкретного источника тепловой энергии, которые зависят от климатических условий, особенно если источником отбора тепла является атмосферный воздух и земля. Математическая модель теплонасосной установки была сформирована путем изучения арифметических соотношений в функции температурных показателей внешней и внутренней сред, что характеризует ее эффективное использование в климатических условиях северного региона Казахстана. В соответствии с разработанным алгоритмом модели были произведены расчеты расхода тепла на отопление, тепловой мощности теплового насоса.*

Ключевые слова: *теплообменник, температура, компрессор, хладагент, контур, тепловой насос, тепловая энергия, КПД, моделирование.*

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