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Assessment of heat pump efficiency for microclimate formation in a greenhouse

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Abstract. The article provides information about the ring heating system comprising heat pumps. The system is designed as a closed loop, which includes a pump, a thermal energy battery, and a heat pump. The evaporator is connected to the system of water intake from the well and the cooling system of air inside the greenhouse. The resulting thermal energy is consumed for the needs of heating and watering the greenhouse complex. We present a method for determining the dependence of the net present value on the temperatures in supply and return pipelines and temperature of low-potential heat source. The main economic indicators of the implementation of this system on a typical block greenhouse in the city of Tyumen are determined.

1 Introduction

In greenhouses, temperature control is carried out at lower temperature by turning on the heating, and at elevated temperature by forced or natural ventilation (through a transom) [1]. Mamedov, Magulaev and Kolomiets proposed a method for controlling the greenhouse temperature and a device for its implementation [2,3] which consists in pumping heat energy from a low-potential heat source to a heating system by a heat pump. In [4] the authors propose a method of heating plants in hydroponic installations of the greenhouse, which includes heating trays and useful volume of a greenhouse, and the trays are heated with a hydroponic solution. Aminov and Astafurova proposed a method of greenhouse air heating [5]. Also there exist a heating system which is a system of irradiation of plants with radiation sources, heat exchange circuits and pipelines [6]. A group of authors headed by Sharupich and Mazurov [7, 8] developed a heating system in which the above-ground heating circuit is divided into several independent heating systems. The ring system of heat supply was developed (the system of Kozhukhov and Semenova was adopted as a prototype).

The heat supply system consists of a pipeline, a heat accumulator, a heat pump. Heat pump is the main source of heat for water and air heating and watering systems. As a source of low-potential heat, water from wells and the greenhouse cooling system are used. The battery tank is an element of automation, as it regulates the temperature of water supplied to the circuit. When water temperature in the heat accumulator falls below 30 degrees, the pump

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is turned on and draws water from well to evaporator of the heat pump. Some part of the well water is used for irrigation (through the storage tank and the irrigation water tank), another part is discharged or given to outside consumers.

During the warm period, to prevent overheating of the plants, the air from the greenhouses is cooled in the air heater by giving up its heat to the cooling water, and the heat pump is turned on, using this heat to heat the water in the closed heating system. The heated water enters the heat accumulator where it can be stored for a long time.

When the temperature in the greenhouse decreases, the water heating system, which uses the coolant from the storage tank, turns on. In winter, when there is a shortage of water heating system power, the air heating system is activated. With prolonged frosts it is possible to use electric water heating in the batter [9].

The purpose of our research is to develop a methodology for assessing the technical and economic efficiency of using a ring system of heating irrigation water, heating and air conditioning of greenhouses to ensure the established parameters of the microclimate [10].

To achieve the goal of the research, the following tasks were formulated:

1. To analyze and develop a methodology for assessing the energy-saving heating system for irrigation water, heating and air conditioning of an industrial winter greenhouse using renewable energy sources.
2. To conduct an engineering experiment based on computer modeling in order to determine the optimal parameters of the recommended heating system, air conditioning and heating of irrigation water at which the maximum values of economic efficiency are achieved.
3. To carry out analysis of the obtained dependence to determine the indicator of the optimal operation of the heat pump and the calculation of the main economic indicators.

2 Methods

The utilized methods were: analytical summary of known scientific and technical results; computer simulation of the studied system; engineering experiment based on computer simulation.

Technical and economic indicators of application of the heat supply system based on heat pump depend on the cost of electricity and capital investments for the heat supply system. Further, the cost of electricity decreases with a decrease in temperature of the heat pump condenser and with an increase in temperature of evaporator, but this increases capital costs in the heating system, as the area of heat exchangers, radiators and heaters increases [11].

$$\mathrm{NPV} = \mathrm{f}(\mathrm{t}_{\mathrm{dir}}, \mathrm{t}_{\mathrm{ret}}, \mathrm{t}_{\mathrm{LPHS}}\ )$$

We develop a mathematical model and determine the dependence of the net present value on the temperature of hot water at the heat pump outlet $\mathrm{t}_{\mathrm{dir}}$, the temperature of water in the return pipline $\mathrm{t}_{\mathrm{ret}}$and the temperature of the low-potential heat source $\mathrm{t}_{\mathrm{lphs}}$.

Consider the methods of calculating some of indicators that are included in the mathematical model.

2.1 The method of determining the cost of electricity

The dependence of the conversion coefficient of the heat pump μ_{hp} on the temperature difference between the evaporator and the condenser Δt can be averagely expressed by the formula [12, 21]:

$$\varphi_{hp} = 42.3 \cdot \Delta t^{-0.62} \tag{1}$$

On the other hand, the coefficient of conversion of heat pump unit is the ratio of the generated heat energy to the cost of electricity.

$$\varphi = \frac{\mathrm{Q_{ph}}}{\mathrm{Ne}} = 1 + \frac{(1-\mathrm{X})\mathrm{Q_{npi}}}{\mathrm{Ne}} \tag{2}$$

From equations (1-2) we obtain

$$\frac{\mathrm{Q}_{HPU}}{\mathrm{Ne}} = 42.3 \cdot \Delta t^{-0.62} \tag{3}$$

$$\mathrm{Ne} = \frac{\mathrm{Q}_{HPU}}{42.3 \cdot \Delta t^{-0.62}},\ \mathrm{kW} \tag{4}$$

The amount of heat taken from the well can be defined as

$$\mathrm{Q}_{well} = (1-\mathrm{X})\mathrm{Q_{npi}} = (\varphi - 1)\mathrm{Ne}, \mathrm{kW} \tag{5}$$

$$G_{well} = \frac{\mathrm{Q}_{well}{}^{\mathrm{year}}}{4180 \cdot \Delta \mathrm{t_{isp}}}, m^3 \tag{6}$$

$\mathrm{Q}_{well}{}^{\mathrm{year}}$, kJ is the amount of heat taken from the well water for the needs of heating and water supply in winter and transition period [13].

2.2 Calculating the cost of water heating system

The surface area of the heating system, S (m^2):

$$S = \frac{\mathrm{Q}_{ot}}{\mathrm{k_p}\ (\mathrm{t_{av}} - \mathrm{t_n})} \tag{7}$$

where $\mathrm{k_p}$ is the heat transfer coefficient of pipes, W/m^2 ^{0}C

$\mathrm{t_{av}}$, °C is the average temperature of the coolant

$$\mathrm{t_{av}} = \frac{\mathrm{t_{dir}} + \mathrm{t_{ret}}}{2} \tag{8}$$

The length of pipes with a diameter of 57 mm under the trays is 1344 m^2.

The area of pipes under the trays can be defined as:

$$S_p = \frac{0.057 \cdot \pi}{L_{pt}} \tag{9}$$

$$S_p = \frac{0.057 \cdot 3.14}{1344} = 240.67\ m^2$$

Then the area of the heating plates under the trays is:

$$S_l = S - S_p \tag{10}$$

The cost of the heating system will be:

$$\mathrm{C}_{tr} = 1.1\left(S_l \cdot P_m + S_p \cdot P_p\right), \tag{11}$$

where P_m, P_p are prices per 1 m^2 of steel plate, and the price per 1 m^2 of pipe with a diameter of 57 mm; 1.1 is coefficient taking into account the cost of fittings, regulators, connecting elements and system installation works [14].

2.2.1 Calculation of heaters

We determine the flow rate of heated air, kg/hour

$$G = \frac{Q}{c(t_{init} - t_{fin})} \tag{12}$$

Q, W is load of the heating system

G is mass air flow, kg/h

c is specific heat of air, J/(kg·K)

t_{init} is air temperature at the inlet to the heat exchanger, °C

t_{fin} is the temperature of the heated air at the outlet of the heat exchanger, °C

We determine L which is the volume amount of heated air, m^3/h:

$$L = G / p \tag{13}$$

We find the frontal section for the passage of air (m^2):

$$f = G / v \tag{14}$$

where *v* is mass air velocity. For ribbed air heaters it is taken in the range of (3–5) kg/m^2·s [15].

Valid values are up to 7-8 kg/m^2·s.

We set the speed of water in the tubes.

We calculate the coolant flow:

$$Gw = \frac{Q}{c_w \cdot (t_{in} - t_{out})}, kg/s \tag{15}$$

c_w is specific heat of water, J/(kg·K)

t_{in} is water temperature at the inlet to the heat exchanger, °C

t_{out} is water temperature at the outlet of the heat exchanger, °C

2.2.2 Calculation of the heat transfer coefficient (heat efficiency) for the selected heater

The heat transfer coefficient of the selected heat exchanger can be taken from Table 1 [16, 17].

$$К = А \cdot V^n \cdot W^m, W/(m^2 \cdot °С) \tag{16}$$

V is actual mass air velocity, kg/m^2·s, *W* is water velocity in pipes, m/s, *A, n, m* are values of modulus and powers from Table 1.

Table 1. Tabular values of the coefficients A, n, m

Calculated values for calculating heat transfer coefficients			
The heater index	A	n	m
KSk2 (two-row model)	33.3	0.383	0.175
KSk3 (three-row model)	29.3	0.437	0.168
KSk4 (four-row model)	25.5	0.496	0.160

2.2.3 Calculation of temperature pressure

The average temperature pressure is calculated by the formula:

$$\Delta t_{av} = \frac{\Delta t_g - \Delta t_s}{\ln\frac{\Delta t_g}{\Delta t_s}} \tag{17}$$

where Δt_g is a greater temperature difference between two media, Δt_s is a smaller temperature difference between two media.

We find the required heat transfer surface, m^2

$$F = \frac{Q}{K \cdot \Delta t_{av}} \tag{18}$$

where Δt_{av} is logarithmic temperature difference

Further we consider the cost of heaters such as KSK and its heat transfer area, respectively (Table 2).

Table 2. Heaters costs [18]

Name	Heat transfer area	Cost
Heater KSk 4-6	18	6800
Heater KSk 4-7	22.2	7689
Heater KSk 4-8	26.4	8462
Heater KSk 4-9	30.6	9187
Heater KSk 4-10	39	11081
Heater KSk 4-11	114.2	27454
Heater KSk 4-12	172.4	39736

Basing on Table 2 we can estimate the approximate cost of heaters depending on the heat exchange surface:

$$\text{C}h = 214.5 \cdot F + 2817 \quad (19)$$

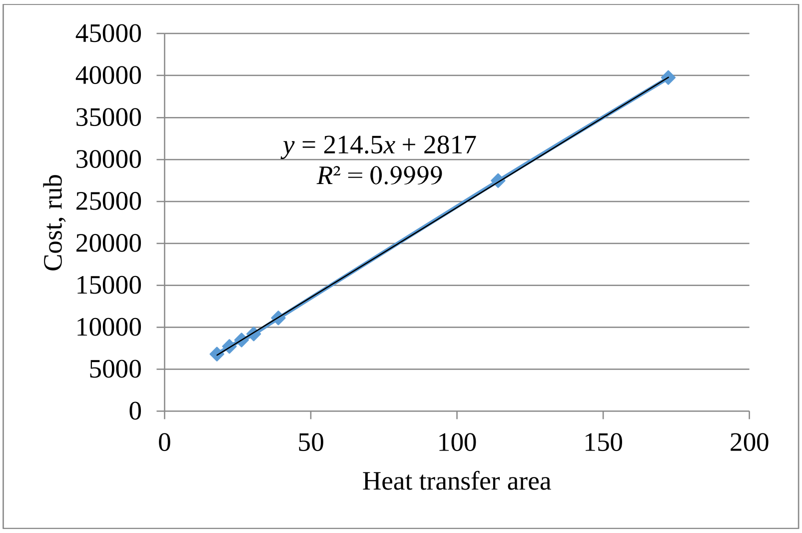

Fig. 1. Relation between cost and heat transfer area for KSk heaters

The cost of an air heating system can be defined as:

$$\text{C}_a = 1.2\text{C}h \quad (20)$$

2.3 Investments in the heat pump station

Capital investments of the enterprise comprise the cost of: construction and installation work in the construction of buildings and structures; purchase, installation and commissioning of machinery and equipment; design and survey work; training and retraining of personnel, etc [19, 11].

$$\text{КВ}_{\text{hps}} = (\text{C}_{\text{hp}} + \text{C}_{\text{мр}} + \text{C}_{\text{heat syst.}}) \quad (21)$$

where C_{hp} is cost of the NT 3000 heat pump, 7 440 615 rub, K_{inst} is cost of installing a heat supply system with an NT 3000 heat pump, 1500 ths.rub. Total investments in the heating system of the greenhouse $\text{C}_{heat\ syst.}$ will be:

$$\text{C}_{heat\ syst.} = \text{C}_{tr} + \text{C}_w + \text{C}_{aut} + \text{C}_{tank} \quad (22)$$

C_{aut} is cost of the system heat point automation

C_{tank} is cost of tank battery.

2.4 Savings due to the replacement of the boiler heat pump station

The cost of production is expenditures of an enterprise for production and sale of the products (works, services) expressed in cash.

We calculate the production expenses for heat generation at a heat pump setup. The production expenses are divided according to the objects of expenditure [20]:

$$\text{E} = \text{E}_{\text{el}} + \text{E}_{\text{sal}} + \text{E}_{\text{a}} + \text{E}_{\text{p}} + \text{E}_{\text{w}} + \text{E}_{\text{oth}} \quad (23)$$

where E_{el} is annual electricity charge;

E_{salary} is annual expenses for salary of the main industrial production personnel;

E_{a} is annual amortization expenses;

E_{rep} is annual expenses for repair the major production facilities;

E_{w} is annual expenses for purchasing auxiliary materials for production (for example, water);

E_{oth} is other annual expenses.

Calculation of each compound:

$$E_c = C_{to} \cdot B_o^{year} \quad (24)$$

where C_{to} is unit price of electricity, rub/kW;

B_o^{year} is annual demand in electricity, kW.

$$E_c = E_{hpu} \cdot n \cdot C \quad (25)$$

where E_{hpu} is heat pump compressor drive demand for electricity, $kW \cdot h$;

C is electricity price per $kW \cdot h$.

Expenses for salary are:

$$E_{salary} = \Phi_{salary}(1 + P_{main})H \quad (26)$$

where Φ_{salary} is payroll (without premiums paid from profits);

P_{main} is coefficient taking into account social contributions (0.3);

H is average number of personnel (without administrative and managerial personnel).

$$E_{salary} = 152000(1 + 0.3) \cdot 1 = 197\ 600 \text{ rub}$$

The amortization component of production expenses is determined by the amortization rates N_{am} for each type of fixed assets $\overline{\Phi}_{main}$:

$$E_a = \overline{\Phi}_{main} \cdot N_{am} \quad (27)$$

Annual expenses for repair the major production facilities E_{rep} are determined by the following way:

$$E_{rep} = 0.3 \cdot E_a \quad (28)$$

$$E_{rep} = 0.3 \cdot 3\ 573\ 276.7 = 1\ 071\ 983 \text{ rub}.$$

where 0.3 is the standard of deductions to the repair fund for the i-type of production equipment.

Expenses for auxiliary materials and water E_w are calculated as follows

$$E_w = \sum C_{aux}^i \cdot M_{aux}^i \quad (29)$$

where C_{aux}^i is price per unit of auxiliary material of i-th type;

M_{aux}^i is annual need for the i-th volume support material.

For a heat pump, only an oil change is necessary. We use X-30 oil, which costs 47.4 rub per liter. A single pump requires 23 liters in a year.

$$E_w = 47.4 \cdot 1 \cdot 23 = 1090.2 \text{ rub}$$

Other expenses are calculated as a percentage of expenses:

$$E_{oth} = (E_c + E_{salary} + E_a + E_{rep} + E_w)K_{oth} \quad (30)$$

where K_{oth} is the other expenses factor.

The cost of heat energy production using heat pumps is:

$$C_{hps} = E/Q_{t.e.}^{hps}, \quad (31)$$

where $Q_{t.e.}^{hps}$ is thermal energy, produced by heat pump station in a year.

The savings will be:

$$S = \left(Sb_{\ 1MW \cdot h_{boil}} - Sb_{\ 1MW \cdot h_{hpu}}\right) Q_{\ MW \cdot h_{hpu}}(1 - H_{st}) + E_a \quad (32)$$

2.5 Determination of net present value (NPV)

NPV is the difference between the discounted amount of net cash receipts from investments and the amount of investments discounted at the same point in time [15].

Since investments in the development of the material and technical base in the energy sector are often carried out simultaneously, the NPV calculation is made according to the formula:

$$NPV = \sum_{t=1}^{T} R_t \cdot \alpha^t - K \quad (33)$$

where R_t is the amount of net cash receipts from investments;

α^t is the discount factor, calculated as:

$$\alpha^t = \frac{1-(1+q)^{-T}}{q} \quad (34)$$

К is size of one-time investment, q is the refinancing rate of the Central Bank of the Russian Federation (15%)

3 Results and discussions

The following parameters were obtained for a block typical greenhouse with an area of 1008 m^2 located in Tyumen as a result of thermal calculation:

The load of the heating system of the greenhouse is Q_{ot} = 593 W.

Annual heat consumption:

- For heating $Q_{gh}^{year} = 5\,560.93\,\text{GJ}$

- For heating hot water supply $Q_{\text{DHW}} = 152.57\,\text{GJ}$

- For heating irrigation water $Q_{\text{irrig}} = 1388.4\,\text{GJ}$

When using a heat supply system using heat pumps, it becomes possible to use heat energy obtained from solar radiation in the summer and transition period (815.637 GJ). When utilizing excess heat in a heat pump installation, it is possible to obtain a sufficient amount of thermal energy for the needs of hot water supply (63.536 GJ) and heating of irrigation water (581.98 GJ) in the summer and transition period.

Using these methods, we will compose a computer model for calculating net present value using the Excel software.

Using the method of orthogonal central compositional planning, we find a mathematical description of the dependence $NPV = f(t_{dir}, t_{ret}, t_{LPHS})$ as an equation [24]:

$$y = b_0 + b_1X_1 + b_2X_2 + \ldots + b_nX_n + b_{12}X_1X_2 + \ldots + b_{(n-1)n}X_{n-1}X_n + b_{11}X_1^2 + b_{22}X_2^2 + \ldots + b_{nn}X_n^2 \quad (35)$$

The regression equation will be:

$$y = 2\,464\,244.15 - 365612X_1 + 256129.8\,X_2 + 421931.3X_3 - 202672X_1X_2 - 89167{,}8X_1X_3 - 438241X_1^2 - 196182X_2^2 - 179518X_3^2$$

The average square error of the model is S = 0.03.

The goal function is found for coded factors; to go to the real factors, it is enough to make a substitution.

$$\mathrm{X}_i = \frac{\mathrm{x}_i - x_{io}}{\Delta x_i} \quad (36)$$

where xi , xi0 ,Δxi are values of the corresponding real factor.

$$\mathrm{X}_1 = \frac{\mathrm{x}_1 - 50}{20}$$
$$\mathrm{X}_2 = \frac{\mathrm{x}_2 - 22.5}{2.5}$$
$$\mathrm{X}_3 = \frac{\mathrm{x}_3 - 10}{5}$$

Then the function transforms to:

$$y = 2\,464\,244.15 - 365612\left(\frac{\mathrm{x}_1 - 50}{20}\right) + 256129.8\left(\frac{\mathrm{x}_2 - 22.5}{2.5}\right) + 421931.3\left(\frac{\mathrm{x}_3 - 10}{5}\right) - 202672\left(\frac{\mathrm{x}_1 - 50}{20}\right)\left(\frac{\mathrm{x}_2 - 22.5}{2.5}\right) - 89167.8\left(\frac{\mathrm{x}_1 - 50}{20}\right)\left(\frac{\mathrm{x}_3 - 10}{5}\right) - 438241\left(\frac{\mathrm{x}_1 - 50}{20}\right)^2 - 196182\left(\frac{\mathrm{x}_2 - 22.5}{2.5}\right)^2 - 179518\left(\frac{\mathrm{x}_3 - 10}{5}\right)^2$$

After some transformations we obtain:

$$y = -24\,524\,562.6 + 191398.8\,x_1 + 1717637\,x_2 + 272584.5\,x_3 - 4053.4\,x_1x_2 - 891.7\,x_1x_3 - 1095.6x_1^2 - 31389.1\,x_2^2 - 7180.7\,x_3^2$$

or

$$y = -24\,524\,562.6 + 191398.8 \cdot t_{dir} + 1717637 \cdot t_{ret} + 272584.5 \cdot t_{lphs} - 4053.4 \cdot t_{dir} \cdot t_{ret} - 891.7 \cdot t_{dir} \cdot t_{lphs} - 1095.6 \cdot {t_{dir}}^2 - 31389.1 \cdot {t_{ret}}^2 - 7180.7 \cdot {t_{lphs}}^2$$

3.1 Analysis of the obtained relationship

When the temperature of the low-potential heat source is 15 °C, and the temperature in the return pipeline is 20 °C, the optimum temperature in the supply pipeline will be 45 °C (Fig. 2).

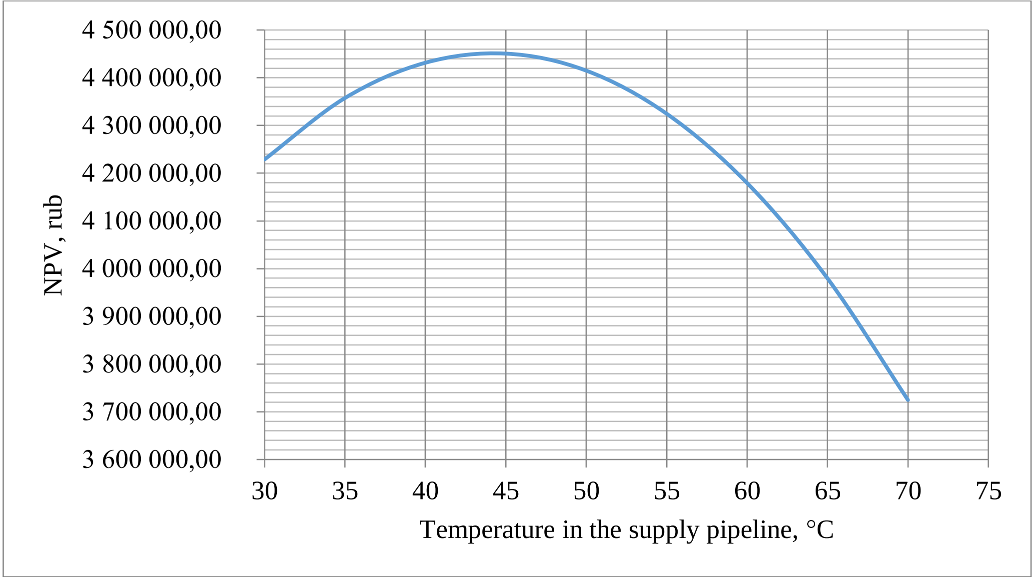

Fig. 2. Relation between NPV and temperature in the supply pipeline.

When the temperature in the supply pipe is 45 °C, and the temperature of the low-potential heat source is 15 °C, the optimum temperature in the return pipeline will be 25 °C (Fig. 3).

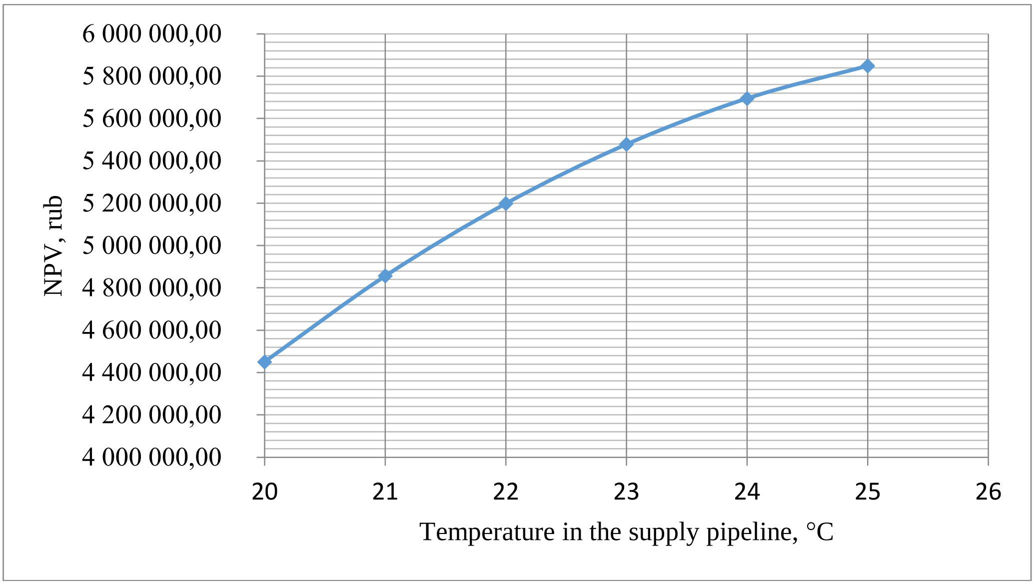

Fig. 3. Relation between NPV and temperature in the return pipeline.

All other things being equal, net present value grows in direct proportion to the temperature of the low-potential heat source (Fig. 4).

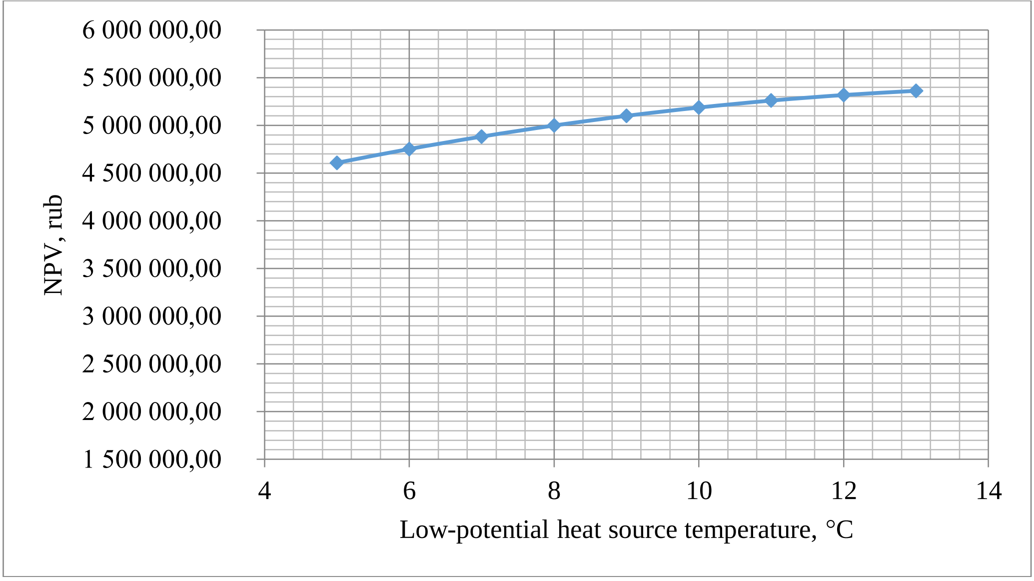

Fig. 4. Relation between NPV and temperature of the low-potential heat source.

4 Conclusions

This paper presents the investment in the ring system of microclimate formation using a heat pump, which amounted appeared to be 4 million 816 ths. rubles. At the same time, the savings received during a year of HPU operation when replacing the microclimate formation system of the greenhouse on the basis of the boiler house amounts to 1 million 207 ths. rub The obtained data from the conducted justification of the feasibility of investment in the replacement of a boiler-house with a heat-pump unit consisted of NPV = 2,742,916 rub; PI = 0.45.

At the same time, investments are considered feasible if NPV ≥ 0 and with DPP less than the useful life, which is 20 years for HPU.

The payback period of the ring heating system using a heat pump in the greenhouse of Tyumen will be DPP = 6.5 years.

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