Calculation and Determination of Energy Parameters of the Mini-CHP on the Basis of the Heat Pump

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Abstract In this paper, the calculation and determination of the parameters of a mini-CHP on the basis of a heat pump is carried out, using four different plant diagrams as the power supply for the heat pump. Thermodynamic calculation of the heat pump. Calculation of the efficiency of the heat pump. Analysis of structural schemes for generating electricity using micro-thermal power plants and based on heat pumps A comparative analysis of the effectiveness of various schemes with mini-CHP. An assessment of the capital costs of installation, operation and determination of the payback period of the mini-CHP on the basis of a heat pump with various plant diagrams is carried out and the most economically advantageous scheme is selected. The practical application of the studied structural schemes is evaluated.

1. Introduction

The proposed power plant can provide thermal energy settlement Priozerny, located in the Stavropol Territory, Shpakovsky district. A feature of this mini-CHP is that its autonomy is ensured through the use of four different schemes for providing a heat pump with electricity [1-9]:
- Gas piston installation on diesel fuel;
- Gas piston installation on liquefied natural gas (LNG);
- Wind power installation (wind turbine);
- Photoelectric converter (FEP).

2. Thermodynamic calculation of the basic system parameters

The purpose of thermodynamic calculation is to determine the efficiency indicators of the heat pump cycle. The section proposes a method for calculating heat pump cycles.

Initial data for calculation:
- heat load $Q_{th}$.................................................................1000 kWt;
- temperature of low potential coolant (brine) at the heat pump inlet $t_{p1}$..........................5 °C;
- temperature of low potential coolant (brine) after the heat pump $t_{p2}$..........................2 °C;
- temperature of low potential coolant (hot water) at the heat pump inlet $t_{w1}$..............45 °C;
- temperature of hot water after heat pump $t_{w2}$..........................................................55 °C;
- temperature of environment $t_{0}$..................................................................................1 °C;
- temperature drops at the outlet of heat exchangers: evaporator $\Delta t_e$, condenser $\Delta t_c$, subcooler $\Delta t_{sc}$....................................................................................5°C;
– temperature of steam superheat in the intermediate heat exchanger $\Delta t_{\text{he}}$………………..20 °C.

The refrigerant used is R152a freon, which is ozone-safe.

Temperature of evaporation of freon:

$$t_e = t_{e2} - \Delta t_e = 2 - 5 = -3^\circ C;$$

(1)

By evaporation temperature $t_e = -3^\circ C$ from the tables of thermodynamic properties of R152a refrigerant in the saturated state or p, h-diagram (Figure 1, 2) defines the parameters at point 1 - enthalpy on the right of the boundary curve $h''$ and the pressure $p$:

Figure 1. The cycle of vapor compression heat pump in the ph-diagram of the refrigerant R152a.
Figure 2. Heat pump cycle with intermediate heat exchanger and subcooler in ph-diagram of the refrigerant R152a.

\[ h_1 = 502.73 \text{ KJ/kg}; \]  
\[ p_c = 0.24 \text{ MPa}; \]  
\[ (2) \]

point 1 is marked on the ph-diagram.

The condensation temperature of freon is determined as follows:

\[ t_c = t_{w2} - \Delta t_c = 55 + 5 = 60 \degree \text{C}; \]  
\[ (4) \]

1. By temperature of condensation \( t_c \) parameters at point 3 are determined from the tables of thermodynamic properties or from the ph-diagram — the enthalpy on the left boundary curve \( h' \) and the pressure \( p \):

\[ H_3 = 304.14 \text{ kJ/kg}; \]  
\[ p_c = 1.51 \text{ MPa}; \]  
\[ (5) \]

point 3 is marked on the ph-diagram.

2. On the ph-diagram, at the intersection of the constant entropy line \( S_1 \) passing through point 1 and the isobar line \( p_c \), passing through point 3, point 2a is determined, then the enthalpy at this point is determined by the diagram:

\[ H_{2a} = 565.56 \text{ kJ/kg}; \]  
\[ (7) \]

3. The adiabatic efficiency of the compressor \( \eta_a \) is determined as follows:

\[ \eta_a = 0.98 \times \frac{273 + t_a}{273 + t_c} = 0.98 \times \frac{273 - 1}{273 + 60} = 0.8; \]  
\[ (8) \]

The enthalpy of freon after compression with allowance for losses is determined as follows:

\[ h_2 = h_1 + \frac{h_{2a} - h}{\eta_a} = 502.73 + \frac{565.56 - 502.73}{0.8} = 581.3 \text{ kJ/kg}; \]  
\[ (9) \]

According to the value of enthalpy \( h_2 = 581.3 \text{ kJ/kg} \) and pressure \( p_c = 1.51 \text{ MPa} \) point 2 is marked on the diagram. Temperature at this point:

\[ t_2 = 90 \degree \text{C}; \]  
\[ (10) \]
4. According to the enthalpy \( h_3 = h_4 = 304.14 \) kJ/kg and pressure \( p_e = 0.24 \) MPa, point 4 is marked on the diagram.

5. Specific heat loads in the nodes of the heat pump:

\[
q_e = h_1 - h_4 = 502.73 - 304.14 = 198.59 \text{ kJ/kg} \quad (11)
\]

\[
q_c = h_2 - h_3 = 581.3 - 304.14 = 277.16 \text{ kJ/kg} \quad (12)
\]

\[
l_{\text{com}} = h_2 - h_1 = 581.3 - 502.73 = 78.57 \text{ kJ/kg} \quad (13)
\]

The correctness of the calculation is determined by checking the heat balance:

\[
198.59 + 78.57 = 277.16 \text{ kJ/kg} \quad (14)
\]

The heat load of the heat pump is determined as follows:

\[
q_{hl} = q_e = 277.16 \text{ kJ/kg} \quad (15)
\]

The energy consumed by the electric motor \( W \) is determined by the formula:

\[
W = \frac{l_{\text{com}}}{\eta_{\text{el.m}} \cdot \eta_{el}} = \frac{78.57}{0.95 \cdot 0.8} = 103.4 \text{ kJ/kg} \quad (16)
\]

6. Energy efficiency indicators of the heat pump:

- heat conversion factor:

\[
\mu = \frac{q_{hl}}{l_{\text{com}}} = \frac{277.16}{78.57} = 3.53 \quad (17)
\]

- electric power conversion coefficient:

\[
\mu_{el} = \eta_{\text{el.m}} \cdot \eta_{el} \cdot \mu = 0.95 \cdot 0.8 \cdot 3.53 = 2.68 \quad (18)
\]

- specific primary energy consumption:

\[
EC = \frac{1}{\eta_{\text{el.m}} \cdot \eta_{el} \cdot \eta_{\text{prm}} \cdot \mu} = \frac{1}{0.95 \cdot 0.8 \cdot 0.4 \cdot 0.95 \cdot 3.53} = 0.98 \quad (19)
\]

Since \( EC < 1 \), from the energy point of view, heating with the use of a heat pump is more profitable than when burning fossil fuel used for electricity generation.

7. The degree of pressure increase in the compressor is determined by the expression:

\[
\pi_k^* = \frac{p_c}{p_e} = \frac{1.51}{0.24} = 6.29 \quad (20)
\]

8. Produced exergy calculation circuit:

- logarithmic average temperature of the cold coolant

\[
T_{\text{mid,p}} = \frac{t_{pl} - t_{p2}}{\ln t_{pl} + 273} = \frac{5 - 2}{\ln 5 + 273} = 276.5 K \quad (21)
\]

The results of the calculated options are shown in table 1.

**Table 1.** “Indicators of energy efficiency of the calculated options”.

| Scheme № | 1        | 2        |
|----------|----------|----------|
| Specific heat load of the heat pump \( q_{hl} \), kJ/kg  | 277.16   | 318.25   |
| Specific energy consumed by an electric motor \( W \), kJ/kg | 103.4    | 111.84   |
| The degree of pressure increase in the compressor \( \pi_k^* \) | 3.53     | 6.29     |
| Heat conversion coefficient \( \mu \) | 3.53     | 3.74     |
| electric power conversion coefficient \( \mu_{el} \) | 2.68     | 2.84     |
| specific primary energy consumption \( EC \) | 0.98     | 0.93     |
| Exergetic efficiency \( \eta_{el} \) | 0.411    | 0.444    |

For further calculations, choose the scheme № 2.
The mass flow rate of the refrigerant $G_{\text{ref}}$ determined by the formula:

$$G_{\text{ref}} = \frac{Q_{\text{ref}}}{q_{\text{ref}}} = \frac{1000}{318.25} \approx 3.14 \, \text{kg/s};$$

(22)

Full load nodes heat pump is determined:

– in the evaporator:

$$Q_e = q_e \cdot G_{\text{ref}} = 233.22 \cdot 3.14 = 732.31 \, \text{kWt};$$

(23)

– in the condenser:

$$Q_{\text{cond}} = q_{\text{cond}} \cdot G_{\text{ref}} = 304.11 \cdot 3.14 = 954.91 \, \text{kWt};$$

(24)

– in the subcooler:

$$Q_{\text{subc}} = q_{\text{subc}} \cdot G_{\text{ref}} = 14.14 \cdot 3.14 = 44.4 \, \text{kWt};$$

(25)

– in the intermediate heat exchanger:

$$Q_{\text{ihe}} = q_{\text{ihe}} \cdot G_{\text{ref}} = 20.49 \cdot 3.14 = 64.34 \, \text{kWt};$$

(26)

9. Proposed installations for solving the problem of autonomy and their schemes[1-9].

3. GPI on diesel fuel

To ensure the autonomous operation of the mini-CHP one of the installations was chosen as a GPI on diesel fuel, this circuit arrangement is shown in Figure 3.

4. Gas piston installation on liquefied natural gas (LNG)

To ensure the autonomous operation of the mini-CHP one of the installations was chosen as a natural gas GPI, the scheme of this unit is shown in Figure 4.
Figure 4. Scheme of mini CHP on the basis of a heat pump with the provision of compressor autonomy by a gas piston installation on liquefied natural gas (LNG).

1 - evaporator, 2 - circulation pump, 3 - throttle, 4 - compressor, 5 - circulation pump, 6 - intake device located in the non-freezing part of the reservoir, 7 - evaporator, 8 - electric generator, 9 - gas piston installations (GPI) operating on liquefied natural gas (LNG), 10 - subcooler, 11 - intermediate heat exchanger, 12 - electric generator, 13 - expansion turbine, 14 - throttle, 15 - LNG cylinder.

5. Wind power installation (wind turbine)

To ensure the autonomous operation of the mini-CHP one of the installations was chosen wind turbine with a horizontal axis of rotation, the scheme of this installation is shown in Figure 5.

Figure 5. Scheme of mini CHP on the basis of a heat pump with the provision of autonomy of the compressor by a wind power installation.

1 - evaporator, 2 - circulation pump, 3 - choke, 4 - compressor, 5 - circulation pump, 6 - intake device located in the non-freezing part of the reservoir, 7 - evaporator, 8 - electric generator, 9 - inverter, 10 - controller, 11 - battery, 12 - wind power installation, 13 - subcooler, 14 - intermediate heat exchanger.

6. Photoelectric converter (FEP)
To ensure the autonomous operation of the mini-CHP one of the installations was chosen solar power plant based on a photoelectric converter, the scheme of this installation is shown in Figure 6.

![Figure 6. Scheme of mini CHP on the basis of a heat pump with the provision of compressor autonomy by a solar power plant based on photoelectric converters.](image)

1 - evaporator, 2 - circulation pump, 3 - choke, 4 - compressor, 5 - circulation pump, 6 - water intake device located in the non-freezing part of the reservoir, 7 - evaporator, 8 - electric generator, 9 - inverter, 10 - controller, 11 - battery, 12 - solar power station, 13 - subcooler, 14 - intermediate heat exchanger.

7. CONCLUSION

Thus, it is proposed to use mini-CHP on the basis of a heat pump, used as a heat supply system in the village of Priozerny, located in the Stavropol Territory, Shpakovsky district. Four systems are considered as a system for providing a heat pump with electric power: a liquefied natural gas combined-cycle plant, a diesel-fired combined-cycle plant, a wind power plant, a solar power station based on photoelectric converters.

For the heat pump in the Coolpack program, Carnot cycles were constructed, the cycle parameters were calculated for the vapor compression heat pump and for the heat pump with an intermediate heat exchanger and a subcooler. Refrigerant R152a was selected for this installation. Based on the obtained results, the optimal cycle was chosen - a heat pump with an intermediate heat exchanger and a subcooler with optimal values of the heat pump specific heat \( q_{th} = 318.25 \text{kJ/kg} \) and heat conversion coefficient \( \mu = 3.74 \).

The same was carried out calculation of the cost and payback period of these installations.

It is impossible to pay back the mini-CHP on the basis of the heat pump in combination with the GPI on diesel fuel, due to the high cost of diesel fuel and the further rise in prices for it.

The recoupment of the mini-CHP on the basis of the heat pump in combination with the GPI on liquefied natural gas will be 5 years.

The recoupment of the mini-CHP on the basis of a heat pump in combination with a wind power installation will be 27 years.

The recoupment of the mini-CHP on the basis of a heat pump in combination with a solar power station on the basis of solar cells will be 25 years.

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