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The method of assessing the effectiveness of air-water heat pumps for heating individual buildings

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Abstract. This paper provides a justification for the assessment of the effectiveness of the use of air-water heat pumps in the heating systems of individual residential buildings in conjunction with the water boiler. The criterion for the cost-effectiveness of the heating system with a combined heat source is the relative cost of equipment and operation of the system, given to the duration of the heating period. Cost components are presented in the form of a system of equations reflecting the dependence of the price parameters of heating system equipment on thermal characteristics. The proposed method of assessing the benefits of renewable energy is applicable to different climatic areas.

1. Introduction

In the practice of applying heat pumps in the heat-consuming systems of buildings, there is a lot of experience [1-6]. Having a large range of models and sizes of these industrial products allows you to choose the most suitable device for a particular object. However, it should be noted that heat pumps have been most prevalent in areas with moderately temperate "heat" climates, and in colder areas the use of heat pumps is stimulated by economic measures [7,8]. This is due to a decrease in the amount of heat extracted from the environment when its temperature is lowered, which affects the profitability of the system [9]. This is especially true for objects using air-water heat pumps. But on the other hand, these "heat generators" are the most environmentally friendly, easy to operate and install, do not require highly skilled and expensive maintenance, which makes them the most attractive for use in individual residential buildings.

The peculiarity of heating systems with heat pumps is the divergence in the production and need of thermal energy with a decrease in the temperature of the outside air. This leads to the need to use either a heat pump with notoriously high thermal power, sufficient to compensate for the heat residues of the building in the calculated conditions and excess in the rest of the period, or to apply a less powerful pump in conjunction with the traditional heat generator, connected to work only during the peak period of heat consumption.

Both solutions are associated with an increase in the cost of the system and may seem unjustified compared to systems with a traditional heat generator (carbon boilers on hydrocarbon or electric fuel) that can change performance in proportion to the needs of the object. But it should be borne in mind that the possibility of using a renewable energy source contributes to the savings of fossil resources is in itself useful and self-sufficient (without regard to economic feasibility), and the profitability of this method in heating systems can be increased by the appropriate design solution, based on taking into account as many factors as possible affecting technical and operational performance.

2. Materials and methods

This paper presents a method of evaluating options for building heating systems with air-water pumps in changing heat and heat-producing environments. The technique is based on the use of mathematical models of technical devices and statistical models of outdoor air parameters in different climatic areas of the country.

3. Results

The criterion of the cost-effectiveness of the heating system with a combined heat source (heat pump and boiler) will accept relative costs $\overline{C}_{co}$ for the equipment and operation of the heating period:

$$\overline{C}_{co} = \frac{C_{KT} \cdot k_{KT} \cdot K_{M.KT} + C_{TH} \cdot k_{TH} \cdot K_{M.TH} + C_{эл.KT} + C_{эл.TH}}{C_{KTo} \cdot k_{KT} \cdot K_{M.KT} + C_{эл.KT.o}} \quad (1)$$

where is C_{KT} and C_{TH} - cost of boiler and heat pump, ruble respectively. rub;

k_{KT} and k_{TH} - self-sufficiency ratio, respectively, boiler and heat pump, year^{-1};

$C_{эл.KT}$ and $C_{эл.TH}$ - the cost of operating the boiler and heat pump in the heating period, rub./year;

C_{KTo} - the cost of the boiler at the estimated thermal power of the heating system Q_{KTo}, rub.;

$C_{эл.KT.o}$ - the cost of operating the boiler with capacity Q_{KTo} during the heating period, rub./year.

$K_{M.KT}$ and $K_{M.TH}$ - corrective coefficients that take into account the cost of installing the boiler and heat pump respectively, rub.

The cost of thermal equipment usually depends on its power and can be represented by the following equations determining statistical distribution by different brands, models and manufacturers:

- for heat pumps with minimum prices [10]:

$$C_{TH} = Q_{TH.0} \cdot \exp(3{,}463 - 0{,}0478 \cdot Q_{TH.0} + 0{,}00051 \cdot Q_{TH.0}^2) * 10^3 \quad (2)$$

where is $Q_{TH.0}$ - thermal nominal power of the heat pump, kW:

- for water-heating electric boilers (model ZETA) [11,12]:

- with nominal power $N_{KT.0}$ up to 15 kW:

$$C_{KT} = N_{KT.0} \cdot 1947 \cdot (N_{KT.0} - 1{,}8)^{-0{,}3} \quad (3)$$

- with nominal power $N_{KT.0}$ 18 kW. up to 45 kW.:

$$C_{KT} = N_{KT.0} \cdot 1860 \cdot (N_{KT.0} - 15)^{-0{,}263} \quad (4)$$

Operating costs will be expressed through the cost of heating the heat in the heating system in the respective devices.

In a water heater with an electric heater:

$$C_{эл.KT} = c_{эл} \cdot W_{KT} = c_{эл} \cdot \sum_i (Q_{KTi} \cdot \tau_{KTi}) \quad (5)$$

where is $c_{эл}$ - electricity tariff, rub./W* hour;

W_{KT} - amount of electricity spent on the production of the necessary heat during the boiler's operation τ_{KT}, W*hour;

Q_{KTi} - boiler power, in operation period τ_{KTi} (hour), W.

Energy source heat performance at the time τ_{KTi} determined by the required power of the heating system $Q_{co.t}$, which in turn depends on the temperature of the outdoor air for this period:

$$Q_{KTi} = Q_{co.t} \cdot \eta_{KT}^{-1} = Q_{co} \frac{t_{в} - t_{H.i}}{t_{в} - t_{H.o}} \cdot \eta_{KT}^{-1} \quad (6)$$

where is η_{KT} - heat generator useful factor;

$t_{в}$, $t_{H.o}$ and $t_{H.i}$ - air temperatures are respectively calculated indoor, outdoor for heating and outdoor in the period τ_{KTi}, °C;

Q_{co} - estimated heating system capacity, W.

Accordingly, the formula (4) will take the form:

$$C_{эл.KT} = c_{эл} \cdot \eta_{KT}^{-1} \cdot \sum_i (Q_{co} \cdot \frac{t_{в} - t_{H.i}}{t_{в} - t_{H.o}} \cdot \tau_{KTi}) = c_{эл} \cdot \eta_{KT}^{-1} \cdot Q_{co} \cdot \sum_i k_{t\tau.i} \quad (7)$$

where is $k_{t\tau.i} = \frac{t_{в} - t_{H.i}}{t_{в} - t_{H.o}} \cdot \tau_{KTi}$ - coefficient, taking into account the standing period $\tau_{H.i}$ (hour) outdoor air temperature $t_{H.i}$.

For this task $t_{H.i=1}$ corresponds to the beginning of the heating period - +10°C, and the distribution of the duration of the standing temperature of the outer air in the annual period for the characteristic geographical points is cited in the [13-15].

Operating costs when using a heat pump are determined through electrical power to operate it N_{TH} and running time τ_{TH}:

$$C_{эл.TH} = c_{эл} \cdot W_{TH} = c_{эл} \cdot \sum_i (N_{THi} \cdot \tau_{THi}) \quad (8)$$

where is $N_{TH.i}$ - the power of the heat pump, at the current temperature of the heat-containing environment, W.

For the temperature of the coolant in the heating system $t_w = 55°C$ the power spent is determined from the expression [10]:

$$N_{TH.i} = N_{TH.0} \cdot (0{,}899 + 0{,}0125 \cdot t_{нi}) \quad (9)$$

where is N_{TH0} - installation power of the heat pump, W, proportional to the nominal heat power of the pump $Q_{TH.0}$ [10]:

$$N_{TH.0} = 0{,}0277 + 0{,}257 \cdot Q_{TH.0} - 0{,}00015 \cdot Q_{TH.0}^2 \quad (10)$$

Since the heat pump power used to produce heat depends on the temperature of the air, the amount $\sum_i (N_{THi} \cdot \tau_{THi})$ (9) can be replaced with:

$$N_{TH.0} \cdot \sum_i (\overline{N}_{THi} \cdot \tau_{THi}) = N_{TH.0} \cdot \sum_{i=10°C}^{t} \frac{N_{THi}}{N_{TH.0}} \cdot \tau_{THi} = N_{TH.0} \cdot f(t_{H.i}) \quad (11)$$

The amount of heat transferred by the heat pump to the heating system during the period T, determined through the transformation factor k_{Qt} and the energy spent on the pump W_{TH}:

$$W_{in} = k_{Qt} \cdot W_{T.TH} = \sum_i k_{Qt.i} \cdot (Q_{THi} \cdot \tau_{THi}) \quad (12)$$

where is $k_{Qt.i}$ - the conversion rate of the heat pump at the temperature of the environment at the time of the period T.

For nominal heat pumps $Q_{TH.0}$ (kW), and with the temperature of the heated environment $t_w = 55°C$ factor $k_{Qt.i}$ decide [10]:

$$k_{Qt.i} = \frac{Q_{tt}}{Q_{TH.0}} = \exp(0{,}0333 \cdot t_{н.i} - 0{,}49) \tag{13}$$

Required nominal pump thermal power $Q_{TH.0}$ to cover the thermal needs of the heating system and determine the cost of the device, accordingly, will be determined from the expression:

$$Q_{TH.0} = Q_{co.t} \frac{Q_{co.t}}{k_{Qt.i}} = Q_{co} \cdot \frac{t_в - t_{H1}}{t_в - t_{H.o}} \cdot \frac{1}{\exp(0{,}0333 \cdot t_{H1} - 0{,}49)} \tag{14}$$

where is

$Q_{co.t}$ - maximum required heating system capacity, compensated by heat pump, V;

t_{H1} - the temperature of the outside air, which determines the thermal power of the heat pump, $°C$

The choice of the size of the equipment and the period of its operation in the heating system depends on the preferences of the owner, but in general, two options can be identified (figure 1):

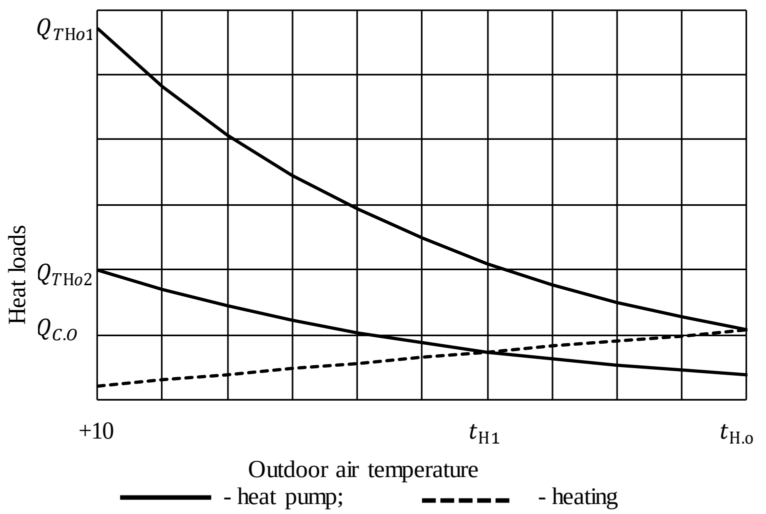

Figure 1. Scheme to change the thermal power of the heating system and heat pumps from the temperature of the outside air.

- the heat capacity of the pump fully provides the required power of the heating system $Q_{TH.to} = Q_{co}$ at any given time:

$$Q_{TH.0} = \frac{Q_{co}}{\exp(0{,}0333 \cdot t_{н.о} - 0{,}49)} \tag{15}$$

- the need for thermal energy of the heating system is provided by the heat pump to the temperature of the outdoor air, corresponding to the equality of thermal power of the heating system and the power generated by the heat pump (bivalent temperature), and then the current heat load of the system is covered only by the boiler:

$$Q_{TH.0} = \frac{Q_{co}}{\exp(0{,}0333 \cdot t_{H.1} - 0{,}49)} \cdot \frac{t_в - t_{H.1}}{t_в - t_{H.o}} \tag{16}$$

At the same time, the value t_{H1} appointed from the conditions of minimizing the cost of the system (1).

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