Assessing the energy efficiency of air-to-water heat pumps

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Abstract. This paper considers the model of assessing the energy efficiency of energy generation by air-to-water heat pumps in the changing temperatures of heat-containing and heat-perceived environments. The results of the assessment of the heat transformation rate for different climatic areas are presented.

1. Introduction

The presence of huge reserves of low potential thermal energy in the environment contributes to the development of methods of its use in heat-consuming systems of buildings (heating, hot water) [1-3]. The most promising and already quite common technique of implementing this "philosophy" is to use devices that extract heat from environments with the conversion of capacity to the required level [4-6] – heat pumps.

The extraction of heat from the environment usually occurs in conditions of changing energy potential. Even in relatively stable environments - soil, reservoirs - the temperature does not remain constant, and in the most accessible resource - the outdoor air this change occurs continuously and with large (up to several tens of degrees) amplitudes. As the analysis of the thermodynamic cycle of the heat pump works, the efficiency of its operation depends significantly on the stability of the thermal potential of the heat-containing environment [7]. It is therefore useful to assess the extent to which energy is transformed in a changing capacity.
2. Materials and methods
This paper considers a model for assessing the energy efficiency of heat energy extraction by air-to-water heat pumps in changing heat-containing and heat-perceived environments. The methodology is based on the use of statistical models of outdoor air parameters in different climatic areas of the country.

3. Results
The most affordable and environmentally friendly way to generate thermal energy is the air-to-water heat pump system, in which heat is extracted from the outside air, transferred to the heat-carrier heating system and returned to the atmosphere in the form of transmission heat flows through the external fencing and exhaust ventilation systems of buildings. The energy efficiency of heat pumps is estimated by the heat transformation factor - COP [8]:

$$COP = \frac{\text{W}_{\text{in}}}{\text{A}}$$

where is $\text{W}_{\text{in}}$ - heat energy transferred by the pump to the heat-consuming system, W*hour;

$\text{A}$ - energy spent on the heat pump, W*hour;

The main operational feature of the system in question is the dependence of the heat performance of the pump on the temperature of the outside air. And since the heating system is operated precisely in the conditions of variable temperatures, for the objective performance of the heat pump the transformation factor will be imagined as a weighted average in the temperature of the outside air and the duration of its standing in the period in question:

$$COP_{T} = \frac{\sum_{n}^{n_{k}} \frac{Q_{\text{in},t}}{T_{\text{in},n-m,k}} \cdot \tau_{t}}{\sum_{n}^{n_{k}} \frac{Q_{\text{in},t}}{T_{\text{in},n-m,k}}},$$

where is $COP_{T}$ - the transformation factor weighted average in the temperature of the outside air and the duration of its standing in the period in question;

$Q_{\text{in},t}$ - thermal power generated by the pump at the current temperature of the outside air, W;

$Q_{o.t}$ - the electrical power of the heat pump at the current temperature of the outside air, W;

$\tau_{t}$ - the duration of the period of standing temperature of the outdoor air, hour;
$T_{m-k}$ - the duration of the period for which is determined is hour.

$COP_i$ - the current value of the transformation factor that corresponds to the conditions of heat extraction and transmission.

$t_{u.1}$ и $t_{u,2}$ - outdoor air temperatures corresponding to the beginning and end of the determination period $COP_T$, °C.

Current Transformation Rate $COP_i$ it is difficult to determine with sufficient accuracy from the analysis of the heat pump's thermodynamic cycle, as the real cycle depends on many factors that cannot be taken into account [8].

Therefore, data of natural tests of heat pumps of type conducted at the manufacturer are used to solve the problem. [9] and presented in figure 1. It is fair to assume that the change in the characteristics of pumps of other brands has the same tendency as those shown in Picture 1. According to the

![Picture 1. Dependence of the current transformation factor on temperature conditions](image)

Analysis of the available results, the current efficiency of the heat pump depends not only on the temperature of the heat-containing environment $t_H$,
but also from the temperature of the heat-perviating contour \( t_w \) and the estimated power of the device \( Q_o \).

The presented graphic dependence with an accuracy of up to 2% is approximated by the following model:

\[
COP_t = \exp(2.8746 + 0.00157Q_o - 0.064t_w - 0.0417t_H + 0.00007Q_o \cdot t_w - 0.000153Q_o \cdot t_H - 0.00022t_w \cdot t_H + 0.0000135Q_o^2 + 0.00004t_H^2 + 0.000067t_H) \quad (3)
\]

**Picture 2.** The duration of the temperature of the outdoor air for the "cold" a) and "moderate-cold" b) climate.

**Picture 3.** The duration of the external air temperature for the "moderate" (a) and "moderate-warm" b) climate.

The duration of periods of standing of outdoor air temperatures \( \tau_c \) is cited in [10] for the characteristic points of climatic zones. Picture 2-3 provides the
distribution of temperature standing periods for geographic points of "cold," "moderately cold," "moderate" and "moderately warm" climatic zones in the working ranges of heating and heat pump temperature systems (from q 10 degrees Celsius to -20 degrees Celsius).

As can be seen from the graphs, the nature of the distribution of temperature periods is almost incalding to any generalization even for the same zone. Therefore, the definition of the weighted average energy conversion rate by heat pumps was conducted by (2) taking into account (3) for each of these points.

**Picture 4.** Change in the weighted average heat transformation rate during different heat pump periods

Settlement results $COP_T$ made for intervals of external temperatures starting with $t_{nH}=10^\circ C$ Until the appropriate pump temperature is running - $t_{HK}$, Picture 4.
4. Debate

These calculations show a steady trend of reducing the energy efficiency of heat pumps when working in conditions of reduced outdoor temperature potential. Despite the different periods of the duration of standing of lowered and negative temperatures, the value $COP_T$ roughly the same in any interval of the possible pump period of operation for almost all climatic zones, except for the point in the "moderate-warm" but humid zone (Novorossiysk). In general, the efficiency of pumping heat is reduced from a range of outdoor air temperatures (10 degrees Celsius - 5 degrees Celsius) to (10 degrees Celsius - -20 degrees Celsius) by (18-14) %., which is significantly less than the variation of the transformation factor itself $COP_T$ (50-60)%.

The absolute value is mainly determined not by the temperature range of the heat-containing environment, but by the level of thermal energy of the locomotive-taking environment - $t_w$ and the power of the device $Q_o$. At the same time for powerful pumps $Q_o \geq 30$ Kw ratio $COP_T$ retains a value of about 3, even at low outdoor temperatures, which allows us to talk about their effectiveness for relatively cold regions. Of course, for less powerful systems (up to 10 kW) the efficiency of heat conversion under these conditions is much lower - at the level (2.5-1.7), but it should be borne in mind that in such areas the use of low-power pumps is not relevant because of the high heat need of systems heating even in individual homes of small heated volume.

Interestingly, in the presented model $COP_T$, its values intersect at about one point corresponding to the period. This indicates a certain semblance of climatic conditions and an uncritical difference in the energy efficiency of heat pumps when used in most regions.

Naturally, the most stable value $COP_T$ corresponds to a warm climate with a relatively short heating season and with small temperature amplitudes (Novorossiysk, $T_{+10-(20)} = 3392h$). Energy efficiency $COP_T$ remains within 95% of the maximum value during any operational period, and the weighted average transformation rate is between 82% and 92% compared to the maximum (with $t_H = +10^\circ C$). At the same time, it should be borne in mind that the distribution of periods of standing of outdoor air temperatures can have a significant impact on the efficiency of the pump. For example, the nature of the change $COP_T$ for a point related to the "moderately warm" climate, but with a longer heating season (Minsk, $T_{+10-(20)} = 5229h$) has the same tendency and about the same values as in colder regions.
5. Conclusion

This analysis shows that it is not correct to assess the effectiveness of heat pumps by the passport value of the heat transformation factor. A more reliable estimate can only be obtained using the weighted average of its value focusing on the possible duration of the pump's operation period and the distribution of air temperatures during this time.

Another conclusion from the results of the calculations is the presence of a similarity of change for different climatic zones. This feature can be taken into account when selecting a heat pump and assigning its operating mode.

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