Simulation investigation of a heat pump, operating on a low-temperature source of heat and a constant condensation pressure

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Abstract. The simulation investigation was carried out at the “Vapor Compression Heat Pump” stand, which allows simulating the annual cycle of operation of the heat pump. Values and further calculations were determined by the operating characteristics of the cycle. Calculations were made according to generally accepted dependencies. As a result of simulating the annual cycle of the heat pump operation, the operational and energy characteristics of the heat pump were determined under the specified conditions: maintaining the specified condensing pressure \( p_c = 1.31 \) MPa and the changing temperature of the low-potential heat source – water \( t_{\text{w,4}} \), which varied from from \(-0.3^\circ\text{C}\) to \(+10.1^\circ\text{C}\). Based on the obtained data, it was estimated the change in the heat pump coefficient of performance (COP) as a function of the low-grade heat source temperature, as well as the application potential of renewable energy sources.

1. Introduction

The source of heat for heating, ventilation and air conditioning systems is usually fossil fuel (gas, coal, peat, shale, oil), which is burned at power plants (GRES, TPP) to produce electricity and heat. The result is a deterioration of the environmental situation, both in the production area and in the combustion area. According to studies, life support systems consume about 50% of the total energy consumption in buildings [1]. These facts are the basis for the development of renewable energy sources.

Soil, rock, water and air can be used as a source of low-grade heat for the heat pump. These sources of energy are considered renewable.

Life-support systems that use groundwater or water bodies as a source of low-potential heat are advantageous in terms of energy efficiency [2].

The temperature of the source of low-potential heat and its thermal power are important parameters affecting the energy efficiency and productivity of the heat pump [3]. A higher boiling point, which corresponds to the temperature of the source of low-grade heat, has a positive effect on the heating coefficient \( \mu \) (hereinafter referred to as the international term – coefficient of performance or COP), provided that the condensation temperature is kept constant [4]. The thermal power of the low-potential heat source affects the amount of heat output and the power consumption of the heat pump compressor.
drive. The amount of energy extracted from the source of low-grade heat affects its efficiency and payback period [5, 6].

In recent decades, the world has seen a trend of increasing the use of heat pumps, both in developed countries such as the United States, Japan, some countries of the European Union, and in developing countries. The people's Republic of China is a prime example of countries that pay attention to the alternative energy.

Recently, the People's Republic of China (PRC) has experienced a high level of urbanization, resulting in increased demand for thermal energy for heating, ventilation and air conditioning. 22% of all energy consumed in China falls on the operation of buildings, of which 60% is spent on life support systems. The coal-fired boilers for heating are gradually prohibited. Based on the above circumstances, heat pumps are an obvious alternative, and also have a high potential for development. The average cost of a heat pump installing is 50 – 65 us dollars per 1m² of the building area [7].

Over the past few years, China has paid attention to energy saving and greenhouse gas emissions. In this regard, a number of laws and regulations of the government were adopted:

- The Renewable Energy Law of the People’s Republic of China, 2005;
- The Energy Conservation Law of the People’s Republic of China, 2007;
- Energy Conservation Regulations of Civil Buildings, 2008;
- The Action Plan for China’s Energy Strategy (2014–2020), 2014;
- The Thirteenth Five-Year Plan for Development and Utilization of Geothermal Energy, 2017.

According to the national statistics of the PRC, by the end of 2016, more than 22,000 heat pumps with a serviced area of more than 487 million m² were installed.

It is necessary to note that over the past 10 years, the average annual sales of heat pumps in Italy were about 1300000 units (as of 2018). The heat pump market was stimulated by the introduction of a special tariff in 2014, that was available only to private consumers using the heat pump as the main heating system.

The review shows that in the Russian Federation (RF) it is necessary to pay more attention to this topic in connection with its active development in the countries close to the borders of the Russian Federation, and not only to them.

2. Results and discussion

Stand "Vapor compression heat pump" allows you to simulate the annual cycle of operation of the heat pump both in cooling mode and in heating mode, which makes it possible to obtain operating characteristics close to the actual.

The schematic diagram of the stand of the vapor compression heat pump is shown in figure 1 and includes the following main elements: a spiral compressor, a plate condenser, an evaporator, a source of low-grade heat – an isolated tank with cold water, a heat storage device – an isolated tank with hot water, a fan coil unit, an automatic control Board, shut-off and connecting valves, a set of control and measuring devices. The working substance circulating in the circuit is R134a. The source of low-grade heat – insulated tank with cold water is equipped with electric heaters installed electric power of 6 kW and filled with 15% ethylene glycol solution – these measures allow you to maintain the desired temperature of the source of low-grade heat from negative to positive values of the liquid temperature. Heat storage is an insulated tank with hot water is filled with prepared tap water, purified from insoluble substances, it does not contain specific impurities. The cycle of the experimental stand in the h – lgp diagram with the main nodal points is shown in figure 2.

Registration of values was made at the steady-state operation mode: at constant value of \( p_{c} \), and also at constant value of temperature \( t_{s} \). It should be noted that the operating mode was determined by the temperature value of the low-potential heat source \( t_{s} \).

The aim of the study is to obtain and accumulate experimental data on the operation of the vapor compression heat pump cycle, as well as the values of the heating coefficient (transformation coefficient or conversion coefficient) of the steam compression heat pump in the conditions of maintaining a
constant condensation pressure and changing temperature values of the low-potential heat source, simulating the annual course of the temperature of the natural source of low-potential heat.

Figure 1. Schematic diagram of experimental stand.

Figure 2. The cycle of the experimental stand in $h - lg p$ diagram.

Based on the values obtained as a result of the physical modeling the parameters of the cycle at the nodal points were determined, and the necessary calculations were made to estimate the performance of the heat pump: the values of the heat transferred from the heat pump to the consumer $Q$ and the values of the conversion coefficient of the heat pump $COP$ were calculated.

The heat transferred from the heat pump to the consumer by means of a fan coil unit is determined by the following dependence:

$$Q = \frac{G \cdot c_a \cdot (t_{a2} - t_{a1})}{3600},$$

(1)

where $G$ – mass air flow through the fan coil unit, kg/h;

$c_a$ – the heat capacity of air, J/(kg·K);

$t_{a1}$ – the temperature of the air at the inlet of the fan coil unit, °C;

$t_{a2}$ – the air temperature at the outlet from the fan coil unit, °C.

The conversion factor of the actual heat pump cycle depends only on the heat $Q$ and the electrical energy expended on the compressor drive $W$: 
\[ COP = \frac{Q}{W}. \]  

It should be noted that the conversion factor is the most important parameter in assessing the efficiency of the heat pump.

As a result of the experimental study data were obtained on the basis of which the performance data of the heat pump were built. The choice of a low-potential heat source temperature was based on the accumulated long-term climate data in different regions of Russia.

Figure 3 shows the dependence of the temperature change of the working substance in the first circulation circuit \( t_1, t_2, t_3, t_4, t_5 \) on the temperature of the source of low-potential heat \( t_s \). Analyzing the presented figure, it can be noted that the increase in the temperature of the source of low-potential heat \( t_s \) leads to a reduction in the temperature difference between \( t_2 \) and \( t_5 \), which positively affects the performance of the heat pump – this leads to an increase in the value of the heating coefficient. Temperature \( t_3, t_4 \) remain virtually unchanged, which confirms the maintenance of the given values of the condensation pressure during all the physics experiment.

![Graph of the controlled temperatures of the working substance depending on the temperature of the low-grade heat source.](image)

Figure 3. Graph of the controlled temperatures of the working substance depending on the temperature of the low-grade heat source \( t_s \).

From figure 4 one can notice that with increasing value of temperature of low-grade heat source \( t_s \) the controlled values of the temperature values at the inlet to the \( t_{w2} \) capacitor are linearly reduced. The controlled values of the temperature values at the inlet \( d \) of the condenser \( t_{w1} \) and the temperature at the outlet of the air heater \( t_{w3} \) increase in proportion to the increase in the temperature of the source of low-grade heat \( t_s \). The values of the above parameters when the temperature of the source of low-potential heat \( t_s \) is 5.0°C and 6.0°C are out of the General series (linear approximations \( t_{w1}, t_{w2}, t_{w3} \)), this is due to the influence of external factors on the system.

The data presented in figure 5 show that as the temperature of the low-potential heat source \( t_s \) increases, the amount of heat transferred from the heat pump to the consumer increases. Linear approximation of the calculated data reflects the absence of significant deviations.

Analyzing the data presented in figure 6, we can make the following conclusion: an increase in the temperature of the source of low-potential heat \( t_s \) leads to an increase in the value of the heating coefficient (conversion factor). The difference between the calculated values and the values of the linear approximation does not exceed 3%, which suggests a high accuracy of the values and calculations. There is a direct correlation between the values of the transmitted heat \( Q \) and the value of the conversion coefficient \( COP \).
Figure 4. Graph of the controlled parameters of the working fluid on the warm side of the heat pump depending on the temperature of the low-grade heat source $t_s$.

Figure 5. Characteristic of the dependence of heat transmitted to the consumer from the temperature of the source of low-potential heat $t_s$.

Figure 6. The characteristic of the heating efficiency (COP) dependence from the temperature of the low-grade heat source $t_s$. 
3. Conclusion
As a result of the study, the values of the conversion coefficient of the Vapor compression heat pump in the conditions of maintaining a constant condensation pressure \( p_k = 1.31 \) MPa and when the temperature of the low-potential heat source changes in the range from \( 0.3^\circ \)C to \( 10.1^\circ \)C, simulating the annual temperature of the natural source of low-potential heat.

The European Parliament adopted the "Directive on the use of renewable energy sources" in 2008, according to which the use of heat pumps with a conversion factor below the value of 2.875 is prohibited.

Taking into account the requirement of the Directive for European countries, the use of a heat pump on the working substance \( R_{134a} \) and condensation pressure \( p_k = 1.31 \) MPa, possibly at a source of low-grade heat above \( 7^\circ \)C.

After analyzing the values of sea water temperatures in different regions of the Russian Federation, it can be concluded that the use of a heat pump at the declared values is possible only in the coastal zone of the Black sea (Tuapse and Sochi) [8]. In the conditions of energy shortage in the southern regions of Russia as well as in order to reduce operating costs in the cold period of the year for heating in a mild winter in the design of new facilities and buildings, it is necessary to take into account the results of this study.

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