Heat pumps as alternative energy sources: characteristics, state and prospects for use

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Abstract: Currently, heating and hot water supply of urban facilities is provided, as a rule, by centralized heating systems. The source of thermal energy in such systems are city combined heat and power stations (CHPs) – which combine generation of electricity and heat – or district boilers. The benefits of centralized heat supply are widely recognized. However, their use also has drawbacks and limitations. The construction of extended heating mains to remote objects, as well as to objects in areas with low building density, is associated with significant capital investments and large heat losses along the mains. Their total operating expenses are significant. Serious problems also arise in the reconstruction of existing facilities and the construction of new ones in populated urban areas with dense buildings. The current tariffs for thermal energy, combined with the cost of connecting to the urban heating networks, make it increasingly necessary to think about alternative methods of heating. In addition, a large amount of fuel is burned at CHPs and boiler houses, which adversely affects the environment. A modern rural house is mainly heated from autonomous boilers, private heat generators, or stove heating. Solid fuel is traditionally used as energy in the stoves. The stove usually has a firebox (where fuel is burned), channels through which flue gases are transported, and a chimney that removes flue gases to the atmosphere.

1. Introduction

At present, Russia – as well as the whole world – is facing two interconnected problems: saving fuel and energy resources, and reducing environmental pollution. In the conditions of depletion of organic fuel reserves and a sharp increase in the cost of developing new deposits, it is becoming increasingly irrational to burn coal, gas and oil products in millions of low-power boiler houses and individual furnace units, causing a large amount of harmful emissions into the atmosphere and significant environmental degradation situation in cities and the world [1]. When stocks of traditional energy sources, such as oil, gas and coal, inexorably decrease, their cost is high enough, and their use leads to the formation of the greenhouse effect on the planet, an increasing number of countries in their energy policy, turn their eyes to alternative energy sources.

2. Problem statement

To solve the problem of limited fossil fuels, researchers around the world are working to create and put into operation alternative sources of energy.

Alternative energy sources are environmentally friendly renewable resources which conversion yields electrical and thermal energy used for human needs. Such sources primarily include the energy
of wind and sun, the waters of rivers and seas, geothermal energy, as well as biofuels, derived from the biological mass of animal and vegetable origin.

In addition to traditional types of alternative energy, Recycle (a project on an environmentally friendly lifestyle) chose the most interesting and environmentally friendly energy sources of the future [2]. Among them:

1) Energy from the turnstiles. Several research centers in the world had the idea to use the flow of people through the turnstiles as an innovative energy generator. The Japanese company East Japan Railway Company decided to equip each turnstile at the railway stations with generators. The installation operates at a train station in Shibuya district of Tokyo: piezoelectric elements are embedded in the floor under the turnstiles, which generate electricity from pressure and vibration, which they receive when people step on them. Similar is being introduced in China and Holland.

2) Energy from road humps. The concept of power generation with the help of the so-called road humps began to be implemented first in Great Britain, then in Bahrain. The invention is a road ramp generator consisting of two metal plates, slightly rising above the road. Under the plates, an electric generator is laid that generates current whenever a car passes the ramp.

3) Energy from a soccer ball. The principle of the accumulation of energy by the Soccket ball is fairly simple: the kinetic energy generated from hitting the ball is transferred to a tiny pendulum-like mechanism that drives the generator. The generator produces electricity that accumulates in the battery. The stored energy can be used to power any small electrical appliance, for example, a desk lamp with an LED.

4) Energy of volcanoes. One of the main developments in the development of volcanic energy belongs to American researchers from the pioneer companies of AltaRock Energy and Davenport Newberry Holdings. The test subject was a sleeping volcano in Oregon. Salt water is pumped deep into rocks the temperature of which, due to the decay of the radioactive elements present in the crust of the planet and the hottest mantle of the Earth, is very high. When heated, the water is converted into steam, which is supplied to a turbine that generates electricity.

5) Energy from human heat. The principle of thermoelectric generators operating on temperature difference has been known for a long time. But only a few years ago, technology began to allow the heat of the human body to be used as an energy source. A group of researchers from the Korea Advanced Institute of Science and Technology (KAIST) has developed a generator built into a flexible glass plate. Such a gadget will allow fitness bracelets to be recharged from the heat of the human hand, for example, during jogging when the body is very hot and contrasts with the temperature of the environment.

6) The energy of walking on paving slabs. Each of the busiest streets in the cities undergoes up to 50,000 steps a day. The idea of using pedestrian flow for the useful transformation of steps into energy was implemented in a product developed by Laurence Kemball-Cook, director of a British company Pavegen Systems Ltd. The engineer created paving slabs that generate electricity from the kinetic energy of walking pedestrians.

7) Energy from a bicycle. To recharge a player, phone or tablet, it is not necessary to have an outlet nearby. Sometimes it is enough just to work the pedals. For example, Cycle Atom, an American company, released a device that allows charging an external battery while cycling and subsequently recharging mobile devices.

8) Energy from wastewater. One of the pioneers of the idea was Professor Bruce Logan of the University of Pennsylvania. The general concept is very difficult for a non-specialist to understand and is built on two pillars: the use of bacterial fuel cells and the installation of so-called reverse electrodialysis. Bacteria oxidize organic matter in wastewater and produce electrons in this process, creating an electrical current.

However, at the present stage of development of science and production forces we consider the main type of alternative energy is to use low-grade heat of the earth’s natural resources (air, water and soil) to generate thermal energy using heat pumps (TN).

3. The principle of operation and types of heat pumps
The topic of using heat pumps is becoming increasingly important not only because of the increase in the cost of energy, but also as climate conditions change. Today, this method of heating, as well as cooling buildings in the summer, is even considered as one of the methods to combat global climate change on our planet [3].

Heat pumps are energy efficient structures that use renewable energy of the earth’s natural resources – heat from the soil, water, and air (Fig. 1).

By regulating pressure by the expansion valve, a such coolant flow into the evaporator is set which provides a definite calculated boiling temperature; on boiling, the coolant takes the heat provided by the collector from environment. Gas formed from the coolant is pumped into the compressor where it is compressed and, being heated, ejected into the condenser The condenser is the heat-rejecting element of a heat pump. Heat is rejected into water in the heating circuit with gas cooling down and turning back into liquid. Coolant is decompressed in the expansion valve and returns into the evaporator. The working cycle begins all over.

![Figure 1. Heat pump operation principle](image)

The device consists of:
- external contour with a heat carrier;
- internal circuit with a coolant;
- evaporator;
- compressor;
- capacitor.

The working principle is as follows. Non-freezing liquid moves through the external contour of the heating system and absorbs the heat of the environment. In the pump, this liquid gives off about 5 degrees to the refrigerant and continues to circulate. The refrigerant boils (at minus 10 °C) and turns into gas; the compressor compresses the gas, which increases the temperature. Once in the heat exchanger, this gas gives off heat to the internal heating circuit, cools itself, turning back into liquid and returning to the evaporator.

Like a refrigeration unit, a heat pump consumes a certain amount of energy to realize the thermodynamic cycle (compressor's drive).

Depending on the type of a heat pump, the method of their installation differs. For example, for an air-water pump, drilling of wells and earthworks will not be required.

The system also uses freon. The external contour of the heat pump can absorb energy from different environments: earth, water, air. Labor costs for its creation depend on the type of pump and its configuration. It is most difficult to arrange a ground-water pump in which the outer contour is horizontally located in the ground, since this requires large-scale earthworks. If there is a reservoir near the house, it makes sense to make a water-water heat pump. In this case, the outer contour is simply lowered into the pond.

There are different classifications of heat pumps.
1. According to the operational functions of heat pumps, we conditionally distinguish four main categories:

- Heat pumps used only for heating, i.e. ensuring a comfortable temperature in the room, as well as heating sanitary water.
- Heat pumps used for both heating and air conditioning throughout the year. The most common are reversible air-air machines. Heat pumps use hydraulic circuits to distribute heat and cold, and they can provide both operating modes at the same time.
- Integrated systems based on heat pumps that provide heating of premises, cooling, hot sanitary water and, sometimes, disposal of exhaust air. At the same time, the water can be heated either by superheat removal supplied from the gas compressor, or by a combination of superheat removal and using the regenerated heat of the condenser. Using only the selection of heat overheating is advisable when only space heating is required.
- Heat pumps designed exclusively for heating sanitary water. Most often, they use ambient air as a heat source, but they can equally use exhaust air.

Heat pumps vary depending on the source of heat extraction:
- geothermal: the unit uses heat from the soil, underground or surface groundwater. Information the costs of this unit and installation works of geothermal heat pumps for heating is fairly large; however, the solution is advantageous in terms of operating costs. This is due to the fact that the temperature of the earth at a depth is constant even in the winter period and is quite high, which means that the electricity costs will be lower;
- water: a device with the collector arranged in a reservoir below the depth of frost as rings or a zig-zag. The lowest-cost option. The drawback are the requirements for the volume of water and depth for a particular region;
- air heat pump for heating uses air as the heat source. Air heat pumps are not effective everywhere, as they depend on wind energy. They are mounted in a windy spot;
- using secondary heat: for them, the sources of heat are sewage and other water resources.

4. Characteristics of heat pump operation

A heat pump is characterized by the following parameters: thermal power \( Q_{\text{CON}} \) (thermal energy released during condensation of the vapor of the working substance in the condenser per unit time); cooling capacity \( Q_{\text{EVAP}} \) (thermal energy transferred to the working substance when it evaporates in the evaporator per unit time); power \( P_{\text{COM}} \) spent on pumping the working substance, and the coefficient of energy transformation \( \mu_{\text{HPU}} \).

The energy efficiency of a heat pump unit (HPU) is estimated by the transformation coefficient, which is the ratio between the received thermal power in the condenser per unit time and the power consumption \( P_{\text{COM}} \) by the compressor's drive:

\[
\mu_{\text{HPU}} = \frac{Q_{\text{CON}}}{P_{\text{COM}}}
\]

The transformation coefficient is greater than one, and it is the higher, the smaller the amount of additional energy expended in the compressor. Usually it equals 2...4, i.e. per 1 kWh of energy expended on the drive, 2...4 kWh can be obtained by using a low-grade energy source.

The higher the \( \mu_{\text{HPU}} \), the more efficient the heat pump is. The transformation coefficient depends on:

- temperature difference between a low-grade heat source (LPHS) and a high-potential heat source (HPHS); the higher it is, the lower the coefficient of performance (COP),
- thermodynamic properties of the refrigerant,
- features of the thermodynamic cycle,
- technical perfection of the heat pump design.

Depending on these factors, the COP ranges from 2.5 to 5.
The efficiency of heat pumps is usually characterized by the value of the dimensionless energy transformation ratio (Ktr), determined for an ideal Carnot cycle by the following equation:

\[ K_{tr} = \frac{T_{rej}}{T_{rej} - T_{src}} = \frac{T_{cond}}{T_{cond} - T_{evap}} \]  

(2)

where \( T_{rej} \) is the temperature potential of the heat rejected to a heating or heat supply system, K; \( T_{src} \) is the temperature potential of a heat source, K; \( T_{cond} \) the condensation temperature of the working fluid; \( T_{evap} \) the evaporation temperature of the working fluid.

The transformation coefficient of a heat pump, or heat-pump heat supply system \( K_{tr} \) is the ratio between the useful heat rejected into the consumer’s heating system and the energy spent on the system operation. It is equal to the amount of useful heat obtained at the temperatures \( T_{rej} \) and \( T_{src} \), per unit of energy spent on the drive of the heat pump or heat supply system.

5. State of heat pump application abroad

The production of heat pumps in each country is primarily focused on meeting the needs of its domestic market. Air-air reversible heat pump installations for heating and summer air conditioning are the most common in the USA, Japan and some other countries, while in Europe water-water and water-air pumps prevail. In Sweden and other Scandinavian countries, the availability of cheap electricity and the widespread use of centralized heating systems have led to the development of large heat pump installations. In the Netherlands, Denmark and other countries of this region, the most accessible type of fuel is gas, and therefore, gas-driven and absorber-driven heat pumps are rapidly developing [4].

Millions of heat pump installations are being exploited in the United States and more than half of them in the housing and utilities sector. The most common are reversible air-air heat pump installations with electric drive for year-round air conditioning in rooms. More than 50 companies produce heat installations, 30% of newly built houses, such as cottages, are equipped with heat pump installations.

The systems of heat supply of residential and public buildings from heat sources of low and high levels such as soil-water are rapidly developing. Highly efficient technologies and technical means of selection of the heat of the soil have been developed. There is an effective system of fines (for CO2 emissions from fuel combustion) and incentives for using low-grade heat sources for heat supply.

In Sweden, since the beginning of the 80s, the development of heat pump installations has been very intensive. This country is characterized by the use of large installations with a thermal power of more than 30 MW. The source of low-grade heat is mainly purified wastewater, sea water and wastewater from industrial enterprises. Among these heat pump installations, the largest are located in the cities of Malmö (40 MW), Uppsala (39 MW) and Örebro (42 MW).

The most powerful (320 MW) Stockholm installation using the water of the Baltic Sea as low-grade heat source. This unit, located on barges attached to the shore, cools the sea water in winter from 4 to 2 °C. The cost of heat from this installation is 20% lower than the cost of heat from boilers. The amount of heat generated by heat pump installations in Sweden is already about 50%.

In Germany, there are hundreds of thousands of heat pump installations that are used in water- and air-based heating and air conditioning systems. Electric heat pumps are predominant. In addition, they use hundreds of high-power units driven by diesel and gas engines. Sources of heat are air (external and exhaust), soil, water, etc. [4].

In Switzerland, the first heat pump installations were built back in the 30s. Nowadays, tens of thousands of heat pump installations are in operation, mostly of a small thermal capacity. Large plants have been built for operation in systems of centralized heat supply. The largest one is in Lausanne with a thermal capacity of 7 MW with an electric drive [5].

6. State of heat pump application in Russia.

The experience in the implementation of heat pumps in our country is still modest, but there are conditions for their wider application. Nevertheless, in Russia the process of applying heat units has
already begun. Of course, the total capacity of the installed equipment is immeasurably small compared to the leading countries, but many public buildings in Perm, Kaliningrad, Tuapse, Samara, Penza, Moscow and Leningrad regions are already heated by this energy-saving technology.

In Russia, the development and implementation of heat pumps is carried out by the Siberian Branch of the Russian Academy of Sciences (Institute of Thermal Physics), Irkutskenergo OJSC. Heat pumps are manufactured in Novosibirsk, Moscow, and Nizhny Novgorod [5].

But, unfortunately, in most regions of the country, the works in this direction have practically stalled. For instance, in the territory of North Ossetia-Alania, no thermal stations operate. Considering the importance of using alternative types of fuel by the example of heat pumps, the staff and students of the North-Caucasian Mining and Metallurgical Institute have initiated a project on application of alternative types of energy using a soil-water heat pump for single-storey buildings in rural areas of the country [5].

The project proposed the use of a geothermal heat pump. The parameters of the primary circuit of the heat pump unit were calculated, as well as the total length of the collector pipes, the total area of the site under it and the calculations of technical and economic indicators. The results showed that the annual volume of generated heat energy – as a result of the implementation of proposed idea – was 669.6 Gcal/year with a capital investment in the construction of the installation of 1,792.81 thousand rubles. Prevented environmental and economic damage in this case amounts to 1,171.67 thousand rubles, and the profit from the sale of products is 867.27 thousand rubles. As a result, the payback period for these calculations is only 2.1 years.

7. Conclusions
The accumulated long-term experience of practical operation of heat pump heating systems abroad and in Russia, feasibility studies and design studies of their implementation in real small and large construction sites located both in dense urban areas and in rural areas, indicate wide possibilities of effective application of heat pump systems and ensure noticeable economic, energy saving and environmental effects due to their utilization. Additional potential for improving the efficiency of heat pump use also lies in the possibility of their implementation not only for heating and hot water supply, but also for air conditioning, including monitoring and managing indoor air humidity and in a number of technological processes. This is done using reversible heat pumps that allow changing the direction of the heat flow.

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