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Heat pumps and their applications

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Abstract: Recently, there has been a significant interest in heat pumps (HP) both in our country and abroad. The areas of their application have also expanded. This is primarily due to rising energy prices and environmental issues. Therefore, research on increasing the energy efficiency of heat pumps remains a relevant topic.
This paper examines the design and working principle of heat pumps. Additionally, it analyzes the different types of heat pumps and ways to improve their energy efficiency.

Keywords: Heat pumps (HP), World Energy Committee (WEC), higher-temperature body.

Introduction: According to forecasts by the World Energy Committee (WEC), by 2020, 75% of heating supply (both municipal and industrial) in developed countries will be provided by heat pumps. Heat pumps have been successfully used in households and industries in Europe and the United States for more than 25 years [1,2].

A heat pump is essentially a refrigeration machine that transfers heat from a lower-temperature body to a higher-temperature body, thereby increasing its temperature. Heat pumps serve as alternative energy sources, allowing the production of affordable heat without harming the environment. Their unique feature is the ability to convert low-potential heat from the environment—such as the ground, water, or air—into high-potential thermal energy for consumers. In many countries, this eco-friendly technology has only recently become widely adopted.

Just like in refrigeration machines (RMs), heat pumps transfer heat from a low-temperature medium to a higher-temperature medium.

It is also worth noting that heat pump technology has a long history, dating back to the 1950s. This technology has been well-developed by foreign specialists and is widely applied in construction projects across Europe, the U.S., and Japan. The majority of these projects involve comprehensive energy supply systems that include ventilation, heating, hot water supply, and heat recovery. Undoubtedly, such projects are much more efficient than conventional heating methods. However, they are also actively supported and subsidized by the government.

Uzbekistan's Potential for Heat Pumps

Uzbekistan has great potential for utilizing solar energy. One of the key measures for its utilization is converting it into low-potential thermal energy, particularly for hot water supply and heating needs. However, due to technical and economic limitations, autonomous solar heating systems have not yet gained widespread use in the country. The main reason is the inability to receive stable heat from solar systems throughout the year. The high dependence on fossil fuels in our energy supply is becoming a problem due to limited reserves of oil and gas [8].

Many scientific and popular science studies have been dedicated to heat pump design and operation principles [3,4,5,12].

A heat pump is essentially a refrigeration machine that transfers heat from a lower-temperature medium to a higher-temperature medium, increasing the temperature of the latter. Heat pumps serve as alternative energy sources, allowing the production of affordable heat without harming the environment.

The working principle of a heat pump is based on the fact that any object with a temperature above absolute zero contains thermal energy. The amount of energy stored is directly proportional to the mass and specific heat capacity of the substance.

For example, seas, oceans, the atmosphere, and underground water have enormous thermal energy reserves due to their large mass. Therefore, a portion of this vast energy resource can be extracted using heat pumps for heating buildings and other thermal processes without negatively impacting the global environmental balance.

Compression of Refrigerant by the Compressor

At the next stage, the refrigerant in its gaseous state enters the compressor. Here, the compressor compresses the refrigerant (Freon), which causes a sharp increase in pressure and, consequently, an increase in temperature. A similar process occurs in a household refrigerator compressor. The only significant difference between a refrigerator compressor and a heat pump compressor is that the heat pump compressor has significantly higher capacity [9,10].

Heat Transfer to the Heating System (Condensation)

After compression in the compressor, the high-temperature refrigerant enters the condenser. In this case, the condenser is also a heat exchanger, where during condensation, heat is transferred from the refrigerant to the heating system's working medium (e.g., water in an underfloor heating system or radiator heating system) (see Fig. 1).

In the condenser, the refrigerant transitions from a gas phase back to a liquid phase. This process is accompanied by the release of heat, which is used for the home heating system and domestic hot water supply (DHW).

Reduction of Refrigerant Pressure (Expansion)

Now, the liquid refrigerant needs to be prepared to repeat the working cycle. To achieve this, the refrigerant passes through a narrow opening in the thermostatic expansion valve (TXV).

After being pushed through the narrow expansion valve opening, the refrigerant expands, causing its temperature and pressure to drop. This process is similar to spraying an aerosol from a can. After spraying, the can becomes cold for a short time. This occurs because of the sudden pressure drop as the aerosol is released, leading to a corresponding drop in temperature.

At this stage, the refrigerant is again under conditions where it can boil and evaporate, which is necessary for absorbing heat from the heat carrier.

Everyday Heat Pump Applications

In everyday life, people interact with heat pumps without realizing it—for example, in a household refrigerator.

A refrigerator extracts thermal energy from inside the cooling chamber (from food and air) and transfers it to the surrounding air through a hot panel, usually located on the back of the refrigerator. Essentially, it heats the room in which it is placed.

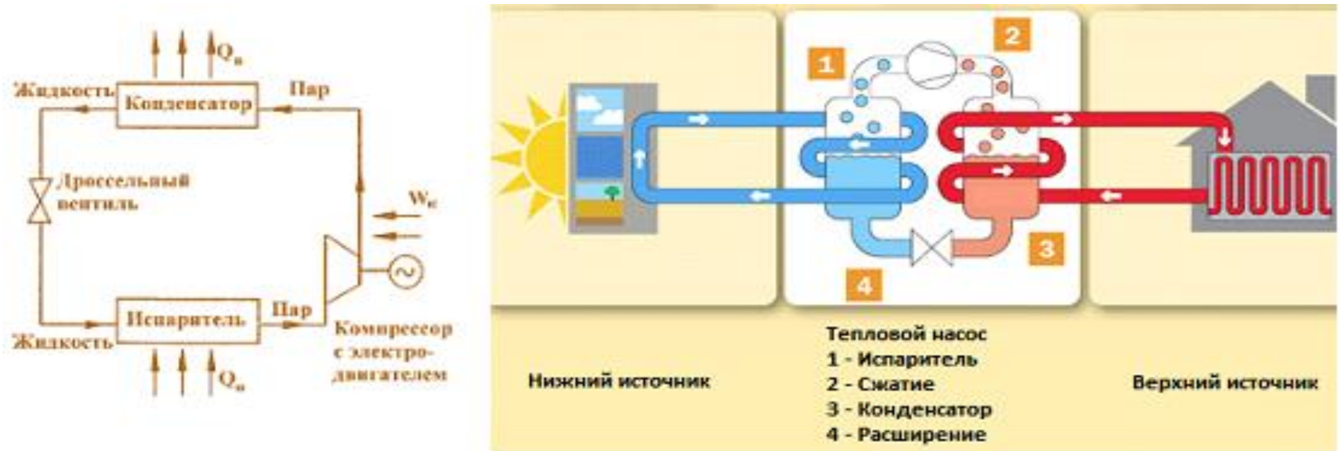

Figure 1. Structure and Operating Principle of a Heat Pump

All thermal machines (such as internal combustion engines, refrigerators, steam engines, etc.) operate cyclically. The term "cycle" ("cyclic process") refers to the continuous change in the state of a system (working fluid), which eventually returns to its initial state, from which these changes began.

Graphically, a cyclic process (cycle) is represented as a closed loop. In thermodynamics, cycles consist of a strictly defined sequence of some of the simplest thermodynamic processes (isoprocesses), through which the working fluid returns to its original state [10].

In 1824, engineer S. Carnot first used the thermodynamic cycle to describe and analyze the operation of an ideal heat engine. Essentially, the Carnot cycle efficiency defines the theoretical limit for the maximum efficiency of a thermal machine within a given temperature range.

This cycle remains a fundamental benchmark for comparing and evaluating heat pump efficiency, as a heat pump can be considered a reversed heat engine.

In direct cycles (also known as power cycles or engine cycles), useful work is produced. In reverse cycles (also called refrigeration cycles), energy must be supplied for the process to occur.

The Second Law of Thermodynamics dictates the direction of spontaneous thermodynamic processes, stating that heat cannot spontaneously transfer from a colder body to a warmer body.

"A Heat Pump is a Refrigerator in Reverse"

In articles popularizing heat pumps, one often encounters the phrase:

"A heat pump is just a refrigerator working in reverse."

It is important to understand that both refrigerators and heat pumps operate on the same thermodynamic cycle— the reversed cycle.

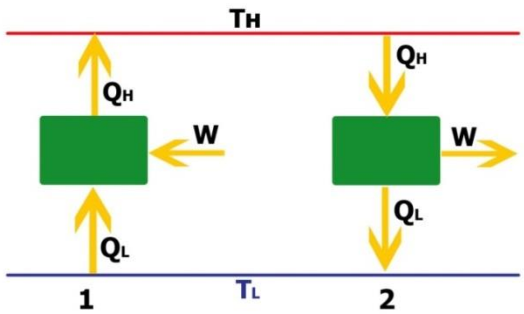

Figure 2. Thermodynamic Diagram of a Heat Pump (1) and a Heat Engine (2)

In the first case, the goal is to create a lower temperature inside the refrigerator compartment. By expending additional energy, the heat from inside the refrigerator is removed into the surrounding environment.

In the second case, the goal is to create a higher temperature inside a building. By expending additional energy, heat from the surrounding environment is transferred into the building, effectively cooling the environment.

A heat engine (Figure 2) absorbs heat (QH) from a high-temperature source and releases it (QL) at a lower temperature (TL) while performing useful work (A).

A heat pump, on the other hand, requires an input of work (A) to extract heat (QL) at a low temperature (TL) and transfer it to a higher temperature (TH).

It can be shown that if both of these machines are reversible (i.e., the thermodynamic processes do not involve heat or work losses), there exists a fundamental efficiency limit for each system.

In both cases, this efficiency limit is defined by the ratio QH/A [10].

Basic Working Principle of the Most Common Vapor-Compression Heat Pump System (Figure 3):

1. In the external heat exchanger (evaporator), thermal energy from the outdoor environment or another available heat source is transferred to the working fluid of the heat pump (typically a refrigerant such as Freon), which circulates through the internal circuit.
2. The refrigerant absorbs heat, evaporates, and moves toward the compressor. The compressor compresses the refrigerant, causing its temperature to rise significantly.

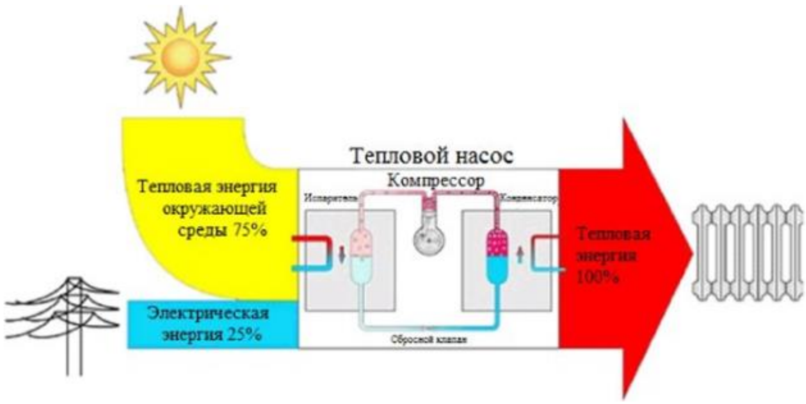

Figure 3. Schematic Diagram of a Heat Pump

3. The compressed refrigerant then passes through the internal heat exchanger (condenser), where it condenses and releases heat into the consumer system. This can be used for:

o Direct air heating

o Heating of a liquid heat carrier for the building's heating system or industrial processes

o Hot water production for consumers

4. The refrigerant then moves through the expansion valve, which reduces the pressure and lowers the temperature of the refrigerant.

As the high-pressure refrigerant flows through a capillary or expansion valve into the evaporator, a sudden pressure drop occurs, leading to evaporation. This absorbs heat from the evaporator walls, which in turn draws heat from the ground or water loop, constantly cooling the evaporator.

The compressor then draws in the refrigerant from the evaporator, compresses it, causing a sharp temperature increase, and pushes it into the condenser.

Inside the condenser, the compressed and heated refrigerant releases its stored heat (approximately 85-125°C) to the heating circuit and returns to a liquid state. This cycle continuously repeats.

Understanding the Working Principle of a Heat Pump

To grasp how a heat pump functions, it is essential to understand key thermodynamic concepts, including:

- Low-potential heat
- Carnot cycle
- Heat energy transfer
- Refrigerant (Freon)
- Compressor operation, etc.

Heat Pump Efficiency and the "Efficiency Paradox"

When discussing the energy efficiency of a heat pump, it is important to note that, like a refrigeration machine, it has extremely high efficiency. This can sometimes appear counterintuitive or even paradoxical.

The COP (Coefficient of Performance) of a heat pump is often greater than 1, sometimes reaching values of up to 5. This means that the device produces more heat energy than the electrical energy it consumes, which is a key advantage of heat pump technology.

Although this may seem unusual, it is not a violation of energy conservation laws. The phenomenon is easily explained using the well-known Carnot efficiency formula for maximum theoretical efficiency of a heat engine [10,11].

Heat Pump Performance Coefficient Formula

In technical thermodynamics, the efficiency of heat pumps is measured using a special parameter called the Heating Efficiency Coefficient (ε_отоп), which is calculated using the following formula:

$$\varepsilon_{отоп} = \frac{Q_1}{A} \leq \frac{1}{1 - T_2 / T_1} \quad (1)$$

Thus, when using a heat pump, the heated space receives more energy than it would through direct heating.

As stated above, according to formula (1), when the temperature difference between the environment and the heated space is small, the latter receives significantly more heat than is released during fuel combustion. This may seem paradoxical. However, in reality, there is no paradox in heat pumps and dynamic heating, which becomes clear when considering the concept of internal energy quality, associated with the chaotic thermal motion of molecules.

CONCLUSION

Based on the research conducted on heat pumps, the following conclusions can be drawn:

1. The structure and working principle of heat pumps were studied from a thermodynamic perspective, and their advantages over other thermal machines were demonstrated.

2. The use of heat pumps in air conditioning, space heating, and other applications significantly reduces electricity consumption (as well as fuel and other energy resources), making it energy-efficient and economically beneficial.

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