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THE HEAT PUMP AND ITS ENERGY EFFICIENCY

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Abstract:
Refrigerators and heat pumps occupy a special place among heat engines. Heat pumps are used for air conditioning, space heating and other purposes. The operation of a refrigerating machine and a heat pump is based on the same thermodynamic laws, and it is advisable to consider them from a single point of view. In the last decade, interest in heat pumps has grown significantly and their applications have expanded. Therefore, research and ways to improve the energy efficiency of heat pumps is relevant. This paper analyzes the energy efficiency of heat pumps and shows the advantage of dynamic space heating in comparison with the traditional method.

Keywords: Energy efficiency, heat pump, conversion factor, Carnot cycle, refrigerating machine, heat engine efficiency, quality of internal energy, dynamic heating.

I. INTRODUCTION

In the last decade, there has been a significant interest in heat pumps (HP) in the CIS countries. This is primarily due to the rise in energy prices and environmental problems. Foreign experience also contributes to this [1]. According to forecasts of the World Energy Committee (WOREC), by 2020 75% of heat supply (communal and industrial) in developed countries will be carried out using heat pumps [2].

Heat pumps have been successfully used in everyday life and industry in Europe and the USA for over 25 years. Their feature is the transformation of the so-called low potential heat of the environment: earth, water, air. In many countries, this ecological technology has spread relatively recently.

A lot of scientific and popular scientific works are devoted to the device and the principle of operation of heat pumps [3, 4, 5, 13].

A heat pump is a kind of refrigeration machine, with which you can transfer heat from a less heated body to a more heated one, increasing the temperature of the latter. Heat pumps are alternative energy sources that provide cheap heat without damaging the environment.

II. LITERATURE REVIEW

The principle of operation of a heat pump is based on the fact that anybody with a temperature above absolute zero has a reserve of thermal energy. This reserve is directly proportional to the mass and specific heat of the substance. For example, seas, oceans, earth's atmosphere, underground waters have a huge mass, so we can conclude that their enormous reserves of thermal energy can be partially used with the use of a heat pump for heating houses and other heat engineering processes without harming the global ecological situation.

If we are talking about the energy efficiency of a heat pump, then as a refrigeration machine it is characterized by a very high efficiency, which is sometimes perceived and interpreted as a paradoxical phenomenon.

The efficiency of the heat pump is more than 1, sometimes it reaches 5, if we consider the heat pump as a "black box", then in fact, and the device consumes less energy than it produces heat, which is fundamentally important. In reality, there are no fundamental difficulties in this matter, and a simple quantitative explanation of the emerging paradox can be given [5, 9]. The availability of the material is ensured by the fact that it is based on the use of the well-known S. Carnot's formula for the maximum value of the efficiency of a heat engine.

III. ANALYSIS

The operation of a heat engine, a refrigerating machine, and a heat pump is based on the same thermodynamic laws, and it is advisable to consider them from a unified standpoint.

A schematic diagram of a heat engine is shown in Fig. 1a. In a heat engine, a certain amount of heat Q_1 is transferred to the working fluid from a heater - a reservoir with a constant temperature T_1.

As a result of the processes occurring with the working fluid, some of this heat turns into work A, and the rest of the heat is transferred to the refrigerator - a reservoir with a lower temperature T_2.

The coefficient of performance (COP) of the heat engine η is the ratio of the work performed per cycle A to the amount of heat Q_1 received from the heater.

$$\eta = \frac{A}{Q_1} = \frac{Q_1 - Q_2}{Q_1} \quad (1)$$

If the heat engine works reversibly, i.e. according to the Carnot cycle, then, in accordance with the second law of thermodynamics, its COP depends only on the temperatures of the heater and refrigerator:

$$\eta = \frac{A}{Q_1} = \frac{T_1 - T_2}{T_1} \quad (2)$$

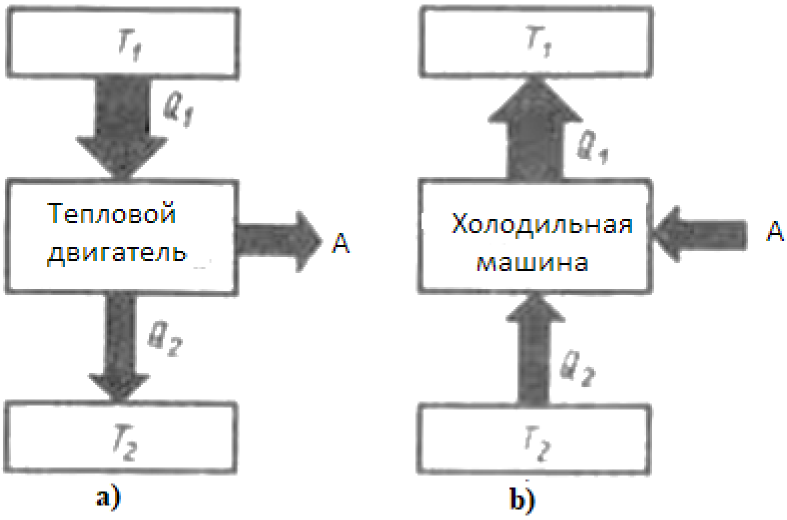

Fig. 1. Schematic diagram of a heat and refrigeration machine

In the refrigerating machine, all processes occur in the opposite direction (Fig. 1b.). Due to mechanical work, a certain amount of heat Q_1 is taken away from the reservoir with a lower temperature T_2. In this case, the amount of heat Q_1 equal to the sum of A + Q_2 is transferred to the reservoir with a higher temperature T_1. If the refrigerating machine works reversibly, that is, it can be used as a heat engine, and then relation (2) is also valid for it.

The actual COP of a heat engine with the given temperatures of the heater and refrigerator cannot exceed COP of an ideal heat engine, i.e.

$$\eta = 1 - \frac{Q_2}{Q_1} \le 1 - \frac{T_2}{T_1} \quad (3)$$

If we analyze the above formulas, then when calculating the work A obtained from the heat engine as the difference in the amount of heat Q_1 and Q_2; $A = Q_1 - Q_2$ only the law of conservation of energy is used for thermal processes. The first law of thermodynamics does not impose any restrictions on the amount of heat Q_2 (for example, the complete conversion of the energy received by the working fluid from the heater into mechanical work, i.e. Q_1 = A, Q_2 = 0 does not contradict the I law of thermodynamics). The inevitability of transfer of a certain amount of heat Q_2 to the refrigerator is due to the II law of thermodynamics, the content of which is reflected in formula (3). From (3) follows a relation called the Clausius inequality:

$$\frac{Q_1}{T_1} - \frac{Q_2}{T_2} \le 0 \quad (4)$$

The equal sign in (4) corresponds to reversible processes. Thus, from (4) it follows that the work $A = Q_1 - Q_2$ that can be obtained using a heat engine is related to the amounts of heat Q_1 and Q_2 and temperatures T_1 and T_2 by the following relationships:

$$A \le Q_1\left(1 - \frac{T_2}{T_1}\right), \quad A \le Q_2\left(\frac{T_2}{T_1} - 1\right). \quad (5)$$

The COP of a heat engine determined by (1) is not the only possible thermodynamic characteristic of a heat engine. The introduction of this very characteristic is due to historical reasons. If at the dawn of the use of heat engines, engineers were more interested in the heat given to the refrigerator (into the environment) than that received from the heater, then, for example, the ratio of A to Q_2 could serve as a characteristic of a heat engine with the same success.

In a refrigerating machine, a schematic diagram of which is shown in Fig. 2, all processes occur in the opposite direction to that corresponding to the engine. Due to the performance of mechanical work A, a certain amount of heat Q_2 is taken away from the reservoir with a lower temperature T_2. In this case, the amount of heat Q_1 equal to the sum of A + Q_2 is transferred to the reservoir with a higher temperature T_1 (the role of which is usually played by the environment). For a refrigerating machine cycle, the inequality sign in relations (4) and (5) should be replaced by the opposite one, since Q_1 now means the amount of heat removed from the working fluid, Q_2 supplied to it, and A - work on the working fluid [5 ,9].

To characterize the operation of the refrigerating machine, the most interesting is the amount of heat Q_2 taken from the cooled tank.

It is found using the second of relations (5). Taking into account the above remark about the inequality sign, we get:

$$Q_2 \leq A \frac{1}{T_1 / T_2 - 1} \tag{6}$$

where the equal sign corresponds to a reversible process.

The graph of Q_2 versus ambient temperature (for a reversible process) is shown in Fig. 2, a. It can be seen from the figures that at T_1 »T_2 the amount of heat $Q_2 \to 0$, but at a small temperature difference $T_1 \to T_2$ can be very large, since the amount of heat Q_2 taken away from the cooled bodies can significantly exceed the work A, which in real refrigerating machines commits a compressor driven by an electric motor.

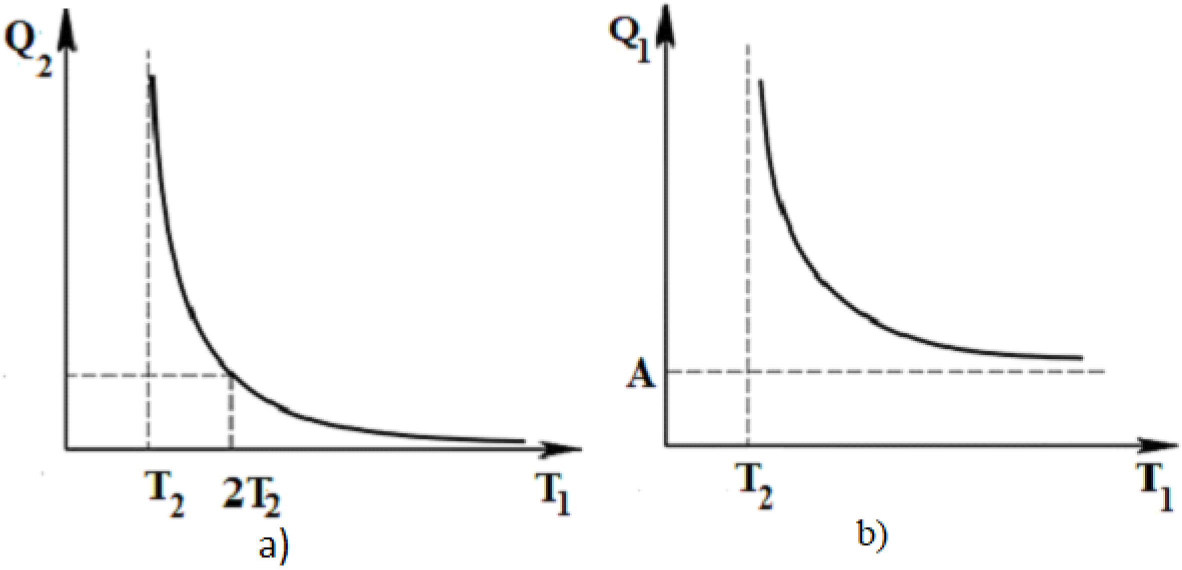

Fig. 2. Curve of Q_2 and Q_1 versus temperature.

In technical thermodynamics, the so-called refrigeration coefficient ε is used to characterize a refrigeration machine, defined as the ratio of the amount of heat Q_2 taken from the cooled bodies to the work of external forces A:

$$\varepsilon = \frac{Q_2}{A} \leq \frac{1}{T_1 / T_2 - 1} \tag{7}$$

In contrast to the efficiency of a heat engine (1), the coefficient of performance ε can take on values greater than unity. In real industrial and domestic heating installations ε = 3 or more. As can be seen from (7), the refrigerating coefficient is the greater, the less the difference between the temperature of the environment and the cooled bodies.

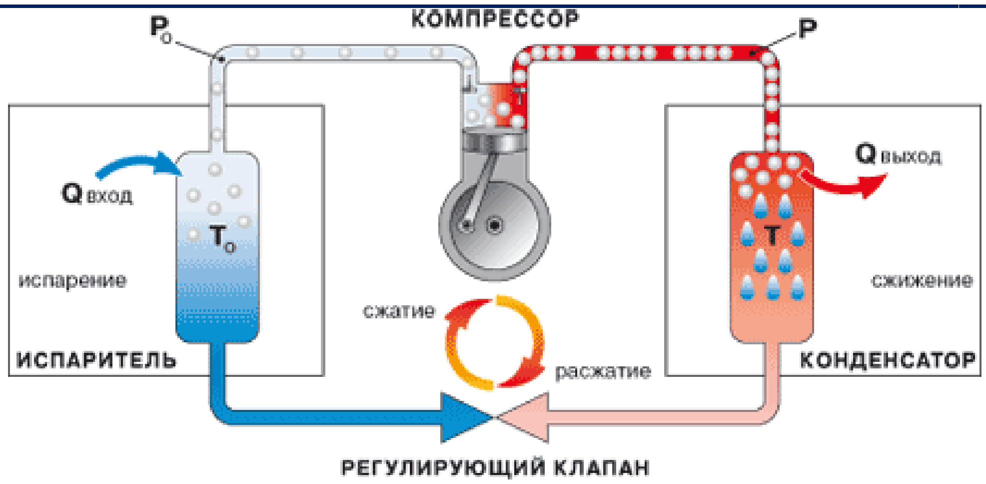

Fig. 3. Heat pump devices.

IV. DISCUSSION

Let us now consider the operation of a heat pump, i.e. a refrigerating machine, which serves to heat the room, due to the heat taken away from the cold reservoir (environment). The schematic diagram of the heat pump is identical to that of the chiller (see Fig. 3.). Unlike a refrigerating machine, for a heat pump, it is not Q_2 that is important, but Q_1 - the amount of heat received by the heated bodies. From formulas (5) we obtain:

$$Q_1 \leq A\left(\frac{1}{1-T_2/T_2}\right) \qquad (8)$$

The graph of this dependence for a reversible process is shown in Fig.2.b. at $T_1 \gg T_2$ we have $Q_1 \rightarrow A$; with a small temperature difference $T_1 - T_2$, the amount of heat transferred to the heated bodies can significantly exceed the work A (for example, obtained from electricity) is directly converted into internal energy for the heated room.

In technical thermodynamics, to characterize the efficiency of heat pumps, the so-called heating coefficient ε_{otop} is introduced, calculated by the formula:

$$\varepsilon_{omon} = \frac{Q_1}{A} \leq \frac{1}{1-T_2/T_1} \qquad (9)$$

So, when using a heat pump, the heated room receives more than with direct heating.

Disassembled in the above problem, the principle of operation of the refrigeration machine allows us to understand the idea of dynamic heating, expressed by Thomson in 1852 [5,9]. This idea is as follows. The heat obtained during fuel combustion is not used for direct heating of the heated room, but is sent to the heat engine to obtain mechanical work Fig. 4.

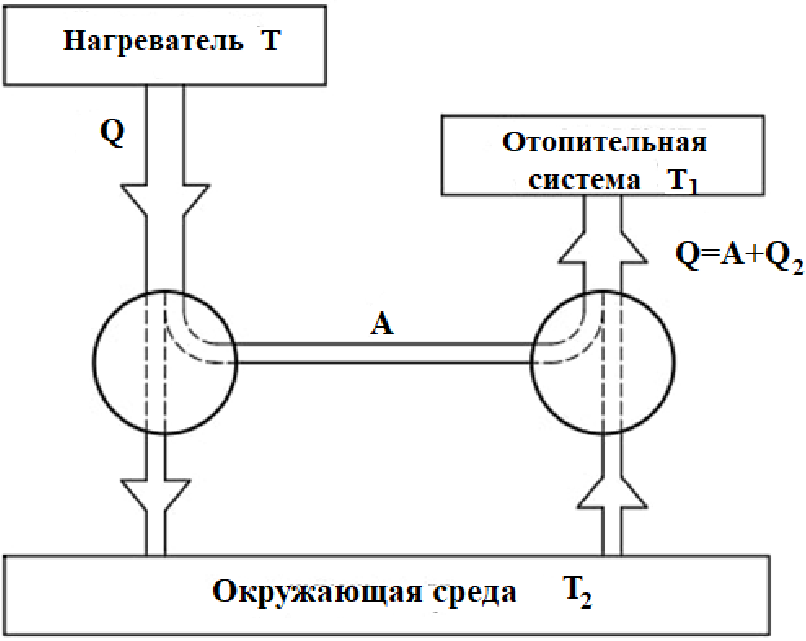

Fig. 4. Schematic diagram of dynamic heating

With the help of the work obtained, a refrigeration machine is activated, which takes heat from the environment and gives it to water in the heating system. As mentioned above, with a small temperature difference between the environment and the heated room, the latter receives noticeably more heat than it is released during fuel combustion. This may sound counterintuitive. In reality, there is no paradox in a heat pump and dynamic heating, which becomes completely clear if we use the concept of the quality of internal energy associated with the chaotic thermal motion of molecules.

The quality of internal energy is understood as its ability to transform into other types [8, 10, 15].

In this sense, the highest quality is characterized by energy in mechanical or electromagnetic forms (since it can be completely converted into internal energy at any temperature). As for the internal energy, its quality is the higher, the higher the temperature of the body in which it is stored.

Using the formula for the COP of a heat engine, we express the work A through the amount of heat Q received by the heater when burning fuel

$$\frac{A}{Q} = \frac{T - T_2}{T}$$

Whence $A = Q\frac{T_1 - T_2}{T_1}$ (10). The heat given to the refrigerator of the heat engine goes into the environment and is not used for heating.

Therefore, all the heat Q_1 received by the heating system in this case is due to the action of the refrigerating machine. Substituting expression (10) into formula (8) we find.

$$Q_1 = Q\frac{T_1}{T}\frac{T - T_2}{T_1 - T_2} = Q\frac{1 - T_2/T}{1 - T_2/T_2}$$

The scheme of operation of such a dynamic heating system is shown in Pic. 5.

To assess the energy efficiency of the processes of converting heat into work, it is convenient to use the concept of exergy. Exergy is called the maximum amount of work that can be obtained from a given amount of heat or substance if the parameters of this heat or substance are brought (through reversible processes) into equilibrium with the environment.

The concept of exergy E acts as a measure of value in thermodynamics. The exergy of mechanical or electrical energy is numerically equal to this energy, since it can be completely converted into work: E = L [8, 15].

Any naturally occurring irreversible process (for example, the transition of heat to a body with a lower temperature) leads to a "devaluation" of internal energy, to a decrease in its quality. In reversible processes, a decrease in the quality of energy does not occur, since all energy transformations can go in the opposite direction.

With a conventional heating method, all the heat released when fuel is burned in a furnace, when the coil is heated with an electric current etc., enters the room in the form of the same amount of heat, but since the temperature of the room is lower than in the oven, near the heated spiral, etc., a qualitative devaluation of internal energy occurs.

A heat pump or dynamic heating system eliminates direct irreversible heat transfer between bodies with different temperatures. When a heat pump or a dynamic heating system is operating, the quality of the internal energy transferred to the heated room from the environment is improved. With a small temperature difference, when the quality of this energy does not significantly increase, its quantity becomes larger, which explains the high efficiency of the pump and the dynamic heating system as a whole.

V. CONCLUSION

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

1. The use of heat pumps in the air conditioning system, space heating and other purposes significantly reduces the consumption of electricity (fuel and other energy resources), which is energetically beneficial.

2. The energy efficiency of heat pumps was analyzed from the point of view of thermodynamic positions and their advantages were shown in comparison with other heat machines. It is shown that the smaller the difference between the temperatures of the low-grade heat source and the coolant in the heating system, the higher the energy efficiency of heat pumps.

3. The ideas of dynamic heating, expressed by Thomson, are considered, and the advantages of this phenomenon are given. When a heat pump or a dynamic heating system is operating, the quality of the internal energy transferred to the heated room from the environment is improved.

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