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Theoretical Foundations Of Heat Pump 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.

1. INTRODUCTION

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. 1. In a heat engine, a certain amount of heat Q1 is transferred to the working fluid from a heater - a reservoir with a constant temperature T1. As a result of the processes occurring with the working fluid, some of this heat is converted into work A, and the rest of the heat is transferred to the refrigerator - a reservoir with a lower temperature T2.

2. MAIN PART

The coefficient of performance (efficiency) of the heat engine η is the ratio of the work performed per cycle A to the amount of heat Q1 received from the heater.

$$\eta = \frac{A}{Q_1} = \frac{Q_1 - Q_2}{Q_1} \tag{1}$$

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

$$\eta = \frac{A}{Q_1} = \frac{T_1 - T_2}{T_1} \tag{2}$$

In the refrigerating machine, all processes occur in the opposite direction (Fig. 2). Due to mechanical work, a certain amount of heat Q1 is taken away from the reservoir with a lower temperature T2. In this case, the amount of heat Q1 equal to the sum of A + Q2 is transferred to the reservoir with a higher temperature T1. If the refrigerating machine works reversibly, that is, it can be used as a heat engine, then relation (2) is also valid for it.

PROCEDURE OF RESEARCH.

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

$$\eta = 1 - \frac{Q_2}{Q_1} \leq 1 - \frac{T_2}{T_1} \tag{3}$$

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 Q1 and Q2; A = Q1-Q2 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 Q2 (for example, the complete conversion of the energy received by the working fluid from the heater into mechanical work, i.e. Q1 = A, Q2 = 0 does not contradict the I law of thermodynamics). The inevitability of transfer of a certain amount of heat Q2 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:

$$\frac{Q_1}{T_1} - \frac{Q_2}{T_2} \leq 0 \qquad (4)$$

The equal sign in (4) corresponds to reversible processes. Thus, it follows from (4) that the work that can be obtained using a heat engine is related to the amounts of heat Q1 and Q2 and temperatures T1 and T2 by the following relationships:

$$A \leq Q_1(1 - \frac{T_2}{T_1}), \;\; A \leq Q_2(\frac{T_2}{T_1} - 1). \qquad (5)$$

The efficiency 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 Q2 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, all processes occur in the opposite direction to that corresponding to the engine. Due to the mechanical work A, a certain amount of heat Q2 is taken away from the tank with a lower temperature T2. In this case, the amount of heat Q1, equal to the sum of A + Q2, is transferred to a reservoir with a higher temperature T1 (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 Q1 now means the amount of heat removed from the working fluid, Q2 supplied to it, and A - work on the working fluid [5 ,9].

To characterize the operation of the refrigeration machine, the most interesting is the amount of heat Q2 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:

$$Q_2 \leq A\frac{1}{T_1 / T_2 - 1} \qquad (6)$$

Where the equal sign corresponds to a reversible process.

The graph of Q2 versus ambient temperature (for a reversible process) is shown in Fig. 3, a. It can be seen from the figures that at T1 »T2 the amount of heat Q2 → 0, but at a small temperature difference T1 → T2 can be very large, since the amount of heat Q2 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.

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 Q2 taken from the cooled bodies to the work of external forces A:

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

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 cooling coefficient is the greater, the less the difference between the temperature of the environment and the cooled bodies.

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 from the cold reservoir (environment). The schematic diagram of the heat pump is identical to that of the chiller. Unlike a refrigerating machine, for a heat pump, it is not Q2 that is important, but Q1 - the amount of heat received by the heated bodies. From formulas (5) we obtain:

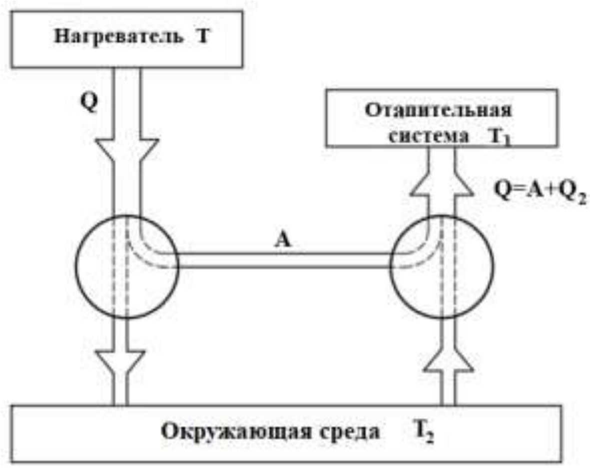
$$Q_1 \leq A(\frac{1}{1 - T_2 / T_2}) \qquad (8)$$

In technical thermodynamics, to characterize the efficiency of heat pumps, the so-called heating coefficient εotop 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.



With the help of the work obtained, the refrigeration machine is activated, which takes away 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 movement of molecules.

The quality of internal energy is understood as its ability to transform into other types [9,10]. 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 efficiency of a heat engine, we express the work A through the amount of heat Q received by the heater when burning fuel

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

From where

$$A = Q \frac{T_1 - T_2}{T_1} \qquad (10)$$

The heat given to the refrigerator of the heat engine goes into the environment and is not used for heating. Therefore, all the heat Q1 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.

3. 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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