Analysis of the influence of condensation temperature and compressor efficiency on heat pump system efficiency

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Abstract. In heat pump cycles, heat is supplied to the working fluid from a certain group of low-temperature bodies and transferred to a group of high-temperature bodies, i.e. the heat source is at a lower temperature and the heat sink at a higher temperature. Using the method of circular processes, in synergy with the possibility of mutual conversion of thermal and mechanical interactions, the process of heat transfer from a lower temperature level to a higher temperature level is enabled. Mechanical work, which, as compensation, should be given by the environment to the system (working substance), is a difference between heat removed and heat supplied. The efficiency of the heat pump mostly depends on the temperature interval at which the process takes place, however, the efficiency of the heat pump is also affected by the thermodynamic parameters of its parts: compressor, condenser, throttle valve, and evaporator. In this paper, the influence of condensing temperature and compressor efficiency on the efficiency of the system as a whole is examined. The calculation was performed for two working substances, R123 and R134a, using the EES software package (Engineering Equation Solver) which is used for numerical modeling of thermodynamic systems, process optimization, and making process diagrams.

1. Introduction

Recently, there is a growing awareness of the dangers of increased global warming and environmental pollution as a result of the use of energy, which is mainly obtained from fossil fuels. Precisely for these reasons, as well as the accelerated growth of fossil fuel prices predicted by their disappearance in the future, the world is increasingly turning to the use of renewable energy sources.

Heat pumps are known in systems for saving and using renewable energy sources. Their recent development has yielded significant results. In the past, the ratios of invested electricity and obtained heat energy using a heat pump were 1:2, while today these ratios have been brought up to 1:6, all thanks to significant investments in the development of this energy system. Heat pumps are environmentally friendly devices, which is why there is a tendency to research and improve them.

Thermal transformers work on the principle of the heat pump cycle, in which the heat source is at a lower and the heat sink at a higher temperature level. The beneficial effect (useful heat) of these devices can be the heat taken from the cycle to the heat sink or the heat brought into the cycle from the heat
source depending on whether they are used for heating or cooling. A heat pump is a device whose basic function is heating with heat that is removed from the cycle. According to the energy balance, the amount of heat dissipated to the heat sink, at a higher temperature level, is the sum of the added mechanical work from the environment and the heat brought from the heat source at a lower temperature level. [1] [2]

The efficiency of a heat pump is expressed by the Coefficient of Performance (COP):

$$COP = \frac{Q_{\text{cond}}}{W_{\text{comp}}}$$

$Q_{\text{cond}}$ – the part of the heat that is transferred from the working substance to the heat sink (beneficial effect),

$W_{\text{comp}}$ – the work required to drive the compressor.

Changes in the state of the working substance in the heat pump cycle according to Figure 1:
1) evaporation: $5 \rightarrow 1$,
2) compression: $1 \rightarrow 2$,
3) cooling of steam to condensation temperature: $2 \rightarrow 3$,
3) condensation: $3 \rightarrow 4$,
4) expansion: $4 \rightarrow 5$

![Figure 1](image_url)

**Figure 1.** Representation of a real heat pump cycle in a T- s diagram [3].

$T_{gr}$ – heat sink temperature, $T_{ok}$ – heat source temperature, $T_p$ – subcooling temperature, $T_k, T_i$ – condensation temperature, evaporation temperature, $T_{pr}$ – superheated steam temperature.

The working substance in the heat exchanger (evaporator) takes energy from the heat source, during which it passes from the liquid to the vapor phase. To be able to transfer heat to the consumer (in heating mode), it is necessary to increase the pressure and temperature of the working substance, which is achieved by compression using a compressor. At a higher temperature than the sink temperature, the working substance can transfer heat to the sink in the exchanger (condenser) where it returns to the liquid phase (condenses). To return its pressure to the pressure of evaporation, the refrigerant is led from the condenser to the expansion valve, where its pressure is reduced, thus closing the cycle and repeating the procedure.
Figure 2. The principle of operation of the heat pump.

It is obvious that heat pumps transfer heat energy from a body of lower to a body of higher temperature, so there is a question does this contradict the second law of thermodynamics which says that heat spontaneously passes from a warmer to a cooler body. The answer is no, heat pumps do not contradict the second law of thermodynamics due to the nature of heat pump processes and the energy consumption in the compressor. By compression, in addition to pressure, the working substance also increases the temperature, which must be higher than the temperature of the heated medium, thus enabling the spontaneous transfer of heat from a warmer to a cooler body (the second law of thermodynamics is satisfied when exchanging heat in a condenser). By expansion, the working substance temperature is decreased below the temperature of the heat source, so that the evaporator also enables the spontaneous transfer of heat from a warmer body (source) to a cooler body (working substance). We can say that heat pumps transfer heat from a cooler to a warmer body at a macro-level, but at a micro-level, they still transfer heat from a warmer to a cooler body, all under the second law of thermodynamics.

Inside the heat pump, as a heat transformer, we have a flow of working fluid which is a mediator in the process of heat exchange between two heat tanks (heat source and heat sink) which are at different temperatures. Thermophysical properties of the working substance significantly affect the thermodynamic efficiency of the heat pump itself, due to different behavior during heat transfer, flow resistance, differences in viscosity, different boiling points, and condensation, etc.

Depending on the chemical composition, working substances can be divided into:
- pure hydrocarbons (R290 – CH₃CH₂CH₃; R600a – C₄H₁₀),
- halogenated hydrocarbons (R134a – C₂H₂F₄, R123 – C₂HF₃Cl₂; R142b – CH₃CClF₂),
- azeotropic mixtures,
- zeotropic mixtures (R404a – C₂H₂F₃, R407a, R407c) and
- inorganic substances (R744, R764).

Despite many theoretical assumptions that indicated a significant improvement in thermodynamic efficiency using zeotropic mixtures, experiments did not confirm this. The reason for this is the poorer heat transfer in exchangers when using these working materials. Changes in the composition of the two-phase flow of the working substance in the evaporator and condenser lead to deviations to the one-component working fluids. Weaker heat transfer is caused by an increase in the content of a weaker volatile component with heated surfaces, less suitable physical properties (conductivity and viscosity), and difficult bubble evaporation.

By choosing the working fluid and changing the condensing temperature, we directly influence some of the parameters (fluid density, heat capacity, dynamic viscosity, etc.), on which the heat transfer coefficient and friction resistances in the system depend, which ultimately determines the heat efficiency of the pump.
In the following, a comparison of two working fluids, R134a (HFC) and R123 (HCFC) will be made, in terms of their impact on the efficiency of the heat pump system.

2. Review of previous research
Energy, exergy and characteristics of heat pumps with different refrigerants have been analyzed in numerous scientific publications, of which we will mention only a few.

A comparison of the energy and exergy efficiency of a cascade cooling system using R170-R161 and R41-R404A as refrigerant pairs was analyzed in the paper by Roy and Mandal. The calculation code for this analysis was developed in the power system software that uses the basic equations of energy and exergy of the cascade cooling system. The influence of evaporator temperature on basic parameters, such as COP, compressor power and total exergy loss, was analyzed. Analysis of the results shows that for each evaporation temperature, an optimal point exists where the system shows maximum performance. Efficient reduction of compressor operation and total exergy loss is observed in systems using R170-R161 than in systems with R41-R404A. This ultimately results in a higher optimal COP as well as exergetic efficiency for the system with R170 - R161 compared to the system R41 - R404A. [5]

Saeidi, V. and Mafi, M. use Engineering Equation Solver (EES) in their work, examining the behavior of the thermodynamic system when using working tools R152a, R600 and R717 and comparing with the behavior results of conventional refrigerants R22 and R134a for geothermal heat pumps with horizontal and vertical heat exchangers. Fluids, R152a, R600 and R717, were introduced as replacement refrigerants to replace synthetic agents in the above-mentioned geothermal heat pump systems, increasing by 2.97 to 5.8% of the cooling coefficient, which means a reduction in the operating costs of the system relative to conventional working fluids. [6]

The influence of different cooling fluids on the efficiency of a geothermal heat pump was analyzed in the work of Dashtebayaz and Maddah. The analysis was performed for five HFC refrigerants R125, R134A, R404A, R407C and R507A used in the geothermal heat pump. Critical parameters, such as performance coefficient (COP), exergetic efficiency and exergy destruction for different components were calculated. The results show that in the geothermal heat pump cycle, R134A and R125 refrigerants have the highest and lowest COP as well as exergetic efficiency. For the mentioned refrigerants, the destruction of exergy by the compressor, as the primary equipment for energy consumption, is achieved between 26.7 and 27.3% concerning the entire system. [7]

3. Description of the research
In this paper, it was interesting to perform a thermodynamic analysis to see the effects of the abovementioned substances on the overall operation of the heat pump system. For this analysis, the EES (Engineering Equation Solver) program was used, specifically to examine the influence of condensation temperature on the efficiency of the heat pump system, i.e. to determine the amount of energy losses in individual components concerning changes in the temperature of condensation. A simulation calculation was performed for two working fluids R123 and R134a to conclude which working fluid is better, i.e. which requires lower mass flow with the highest heat and energy transfer. Also, heat pumps use compressors with different degrees of efficiency, so the impact of the same on the overall efficiency of the cycle, and its impact on energy loss is analyzed. The evaluation of the quality of operation of the heat pump is shown by the heating factor.

The calculation was performed for heating a building with a volume of 11 x 10 x 3 m, assuming the supply of 75 W/m³ of heat flow to maintain a room temperature of 20°C, at an outdoor temperature of –5°C. The compressor sucks in dry saturated steam at a temperature of –10°C and compresses it isentropically to the condensing pressure, assuming the efficiency of the compressor from 0.7 to 1. In the condenser, the steam is completely condensed and the condensate is cooled by 5°C. Condensation temperatures vary in values: 30°C, 40°C, and 50°C.
3.1 Results analysis

Figures 3, 4, and 5 show diagrams for working substance R123. The analysis was also performed for working substances R123 and R134a and their mutual comparison at the condensing temperature $T_{\text{kond}} = 40^\circ\text{C}$ is shown in Figures 7, 8, and 9. [8]

**Figure 3.** Dependence of compressor power on the compressor efficiency and condensation temperature for the working substance R123.

Where is:

- $P_{1,2}$ – required compressor power,
- $\eta_{\text{komp}}$ – the degree of usefulness of the compressor,
- $T_{\text{kond}}$ – condensation temperature.

The previous figure shows a diagram for the working material R123, which shows the dependence of the compressor power on the condensing temperature and the efficiency of the compressor. As the condensing temperature increases, the required compressor power increases, and as the compressor efficiency increases, the required compressor power decreases.

**Figure 4.** Dependence of mass flow on the compressor efficiency and condensation temperature for the working substance R123.
Where is:
$q_m$ – required mass flow.

The figure shows a diagram for the working material R123 which shows the dependence of the mass flow ($q_m$) on the condensation temperature ($T_{kond}$) and the efficiency of the compressor ($\eta_{komp}$). As the condensing temperature increases, the required mass flow increases, and as the efficiency of the compressor decreases, the required mass flow decreases.

![Figure 5](image5.png)

**Figure 5.** Dependence of COP on the compressor efficiency and condensation temperature for the working substance R123.

Where is:
$COP$ – Coefficient of Performance.

The analysis was repeated for the working substance R134a.

![Figure 6](image6.png)

**Figure 6.** Dependence of compressor power on the compressor efficiency and condensation temperature for the working substance R134a.
The previous figure shows the diagram for the working substance R134a, which shows the dependence of the COP on the condensation temperature and the efficiency of the compressor. As the condensing temperature increases, the COP decreases, and as the compressor efficiency increases, the COP increases.

From the obtained results for the working substance R134a, it can be concluded that the increase of condensation temperature adversely affects the operation of the system because it increases the required mass flow of working material and the required compressor power and reduces the COP.
Figure 9. Comparison of the power curves for refrigerants R123 and R134a [5].

From the obtained, it can be concluded that for the working substance R134a for the given parameters the maximum power of the compressor is required, while for the working material R123 the minimum power of the compressor is required under the given process conditions.

Figure 10. Comparison of mass flow curves for refrigerants R123 and R134a [5].

From the obtained diagram it can be seen that for the working substance R123 the highest parameters of the required mass flow are required for the given parameters, while for the working material R134a.
Figure 11. Comparison of the COP curves for refrigerants R123 and R134a [5].

The previous figure shows that the heating coefficient is higher in the case of the use of the working substance R123.

4. Conclusion
The operation of the heat pump depends on the condensing temperature and the efficiency of the compressor, which was shown by the calculation and obtained graphs. With selected working fluids, it is seen that a large influence on the results of mass flow, compressor power, and COP has a change in condensation temperature and the efficiency of the compressor. The diagram of the dependence of the compressor power on the efficiency of the compressor and the temperature of condensation in both working materials shows how the power of the compressor increases with increasing condensing temperature and decreases with increasing the efficiency of the compressor. Also, based on the diagram of the dependence of mass flow on the condensing temperature and the compressor efficiency, it can be concluded that the required mass flow increases with increasing condensing temperature and decreases with decreasing compressor efficiency. The dependence of the COP on the efficiency of the compressor and the condensing temperature, shown in the diagram for given working materials shows that the value of the heating factor decreases with increasing condensing temperature and the value of the heating factor increases with increasing degree of compressor efficiency.

In the compressor power comparison diagram between the refrigerants, the working fluid R134a proved to be worse because it has higher irreversibility. In the mass flow comparison diagram for the given working fluids, the working fluid R123 proved to be worse, that is, the highest mass flow is required for the given conditions. In the COP comparison diagram, the working material R123 proved to be better since the COP is higher for the given conditions. As the condensation temperature increases, the losses in the system increase due to the larger temperature difference and the distance from the ideal Carnot process. Heat pumps should have a condenser that contains the refrigerant with the lowest possible condensing temperature for the device to be more efficient and consume less energy. In practice, it is difficult to achieve such low condensation temperatures with environmentally friendly working fluids, so today many types of research of working fluids are performed to find them with more optimal properties.

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