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WORKING SUBSTANCE INFLUENCE ANALYSIS ON IRREVERSIBILITY IN HEAT PUMP COMPONENTS

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Abstract: The heat pump is a device that raises thermal energy from a lower to a higher temperature level, while consuming energy. Thermodynamic analysis of the heat pump allows us to determine the interdependence of losses in particular parts of the device, as well as the impact of each local irreversibility on the efficiency of the device as a whole. The efficiency of a heat pump is influenced by the thermodynamic parameters of its individual parts: compressor, condenser, throttle valve and evaporator. In this paper, a comparison of different substances which are used as working fluids in heat pumps is analyzed, so as their influence on the irreversibility of heat pump components. The calculation was performed using the EES software package (Engineering Equation Solver) which is used for numerical modelling of thermodynamic systems, process optimization and creating process diagrams.
Keywords: heat pump, efficiency, working fluids, EES software package (Engineering Equation Solver)

INTRODUCTION

World trends in the rational use of renewable energy with the application of new and advanced technologies such as: wind farms, solar systems, heat pumps etc. aim to improve sustainable development and greater environmental protection. The latest works on the development of the heat pump has given significant results. In the past, the ratio of invested electricity and obtained heat energy, using a heat pump, was 1:2, while today these ratios have been brought to 1:6, all thanks to significant investments in the development of this energy resource.

Heat pumps work on the principle of processes in which the heat source is at a lower, and the heat sink at a higher temperature level. The beneficial effect of these devices is the heat taken from the cycle to the heat sink or the heat added 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 mechanical work added from the environment and the heat added from the heat source at a lower temperature level. [1] [2]

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

$$COP = \frac{Q_{cond}}{W_{comp}} \tag{1}$$

Q_{cond} – the amount of heat removed from the working substance to the heat sink (beneficial effect)

W_{comp} – work expended to drive the compressor

Changes in states of the working substance in the heat pump circular process according to Figure 1:

1. evaporation 5 – 1,
2. compression 1 – 2,
3. cooling 2 – 3,
4. condensation 3 – 4,
5. expansion 4 – 5

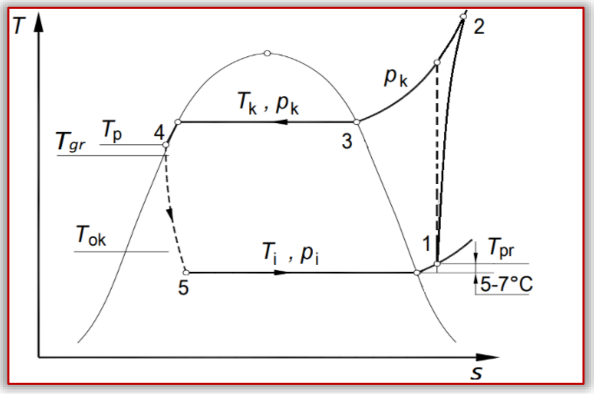

Figure 1. Representation of the real process of the heat pump in the T–s diagram [3]
T_{pr} – temperature of superheated steam before entering the compressor;
T_{gr} – temperature of the space being heated; T_p – subcooled condensate temperature;
T_{ok} – ambient temperature; T_k, p_k – temperature and pressure of condensation;
T_i, p_i – temperature and pressure of evaporation

Heat pumps are systems that transfer heat energy from a lower temperature level (water, earth, air) to a higher temperature level while performing the role of room heating. The heat pump system consists of a heat source circuit, a working substance circuit and a heat sink circuit as shown in Figure 2.

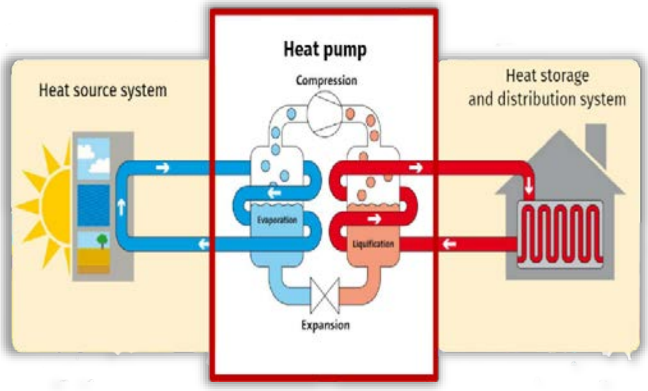

Figure 2. Operation principle of the heat pump

The working substance (working medium) in the heat exchanger (evaporator) takes energy from the heat source, during which it transforms from liquid to vapor. In order to be able to transfer heat to the consumer (in heating mode), we need to increase the pressure and temperature of the working substance, which is achieved by compression. Before entering the compressor, the steam is slightly overheated to temperature T_{pr} in order to avoid the possibility of the liquid phase entering the compressor and to prevent the occurrence of a water hammer.

At a temperature higher than the sink temperature, the working substance is able to transfer heat to the sink in the exchanger (condenser) where it returns to liquid phase (condenses). In order to bring the evaporating pressure back, the working fluid is led from the condenser to the expansion valve, where its pressure is reduced, thus closing the circular process and repeating the procedure.

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 in accordance with the second law of thermodynamics.

The real process differs significantly from the ideal, and this irreversibility of the real process can be shown by exergetic analysis.

The goal of exergy analysis is to determine which components of the cycle have the greatest irreversibility and to discover which components need to be improved, aiming towards an improvement to the whole system. The term of irreversibility of the system represents the loss of energy in the cycle, i.e. many unnecessary but inevitable losses due to friction, etc. in the operation of the system. The smaller the value of irreversibility, the closer the system is to the ideal cycle. [4]

The paper analyzes the behavior of the system with modifications of important parameters: dynamic viscosity η, thermal conductivity λ, density ρ, specific heat capacity c_p, velocity w, etc. Energy losses during the flow and the value of the heat transfer coefficient depend on a number of these parameters.

By choosing a refrigerant and changing the temperature of condensation, we influence the heat transfer coefficient and the flow losses, and thus the irreversibility or efficiency of the heat pump as a whole. [5]

GOAL

It is necessary to analyze the influence of different working substances that are used in heat pumps on the efficiency of the system, i.e. their influence on the magnitude of energy losses in individual components: compressor, condenser, expansion valve and evaporator. A simulation calculation was performed for five working fluids to conclude which working fluid is the most cost–effective, which requires the lowest mass flow with the highest heat/energy transfer.

The calculation was performed during the analysis of the heat pump heating system, a building with dimensions of 11 x 10 x 3 m, asuming adding 75 W/m^3 of heat flow to maintain a room temperature of 20°C, at an outdoor temperature of –5°C. The heat pump uses one of the five fluids as the working fluid (refrigerant) R134a, R123, R600a, R152a i R717. The compressor sucks in dry saturated steam at a temperature of –10°C and compresses it isentropically to the pressure of condensation, assuming the efficiency of the compressor from 0,7 to 1. In the condenser, steam is completely condensed and the condensate is subcooled by 5 °C. The calculation was performed for the temperature of condensation at 40 °C. [6].

EXAMINATION RESULTS AND EXERGY ANALYSIS

One of the indicators of the degree of imperfection of the real cycle is the difference between the maximum possible and the actual work in the cycle and is known as irreversibility.

$$Ir = T_0 \Delta S_{Ir} \quad (2)$$

This is often known as the Gouy–Stodola rule.

The rule can also be applied to individual (non–cyclic) processes that take place in individual parts of a complex plant (heat pump). Thus, the thermodynamic analysis is enriched with a new idea, which enables the evaluation of energy transformations. [7]

Irreversibility in the compressor:

$$Ir_{comp} = q_m \cdot T_{amb} \cdot (s_2 - s_1) \ [\mathrm{W}] \quad (3)$$

Irreversibility in the condenser:

$$Ir_{cond} = q_m \cdot T_{amb} \cdot (s_3 - s_2) + \frac{T_{amb} \cdot \phi_{23}}{T_{room}} \ [\mathrm{W}] \quad (4)$$

Irreversibility in the expansion valve:

$$Ir_{exp.valve} = q_m \cdot T_{amb} \cdot (s_4 - s_3) \ [\mathrm{W}] \quad (5)$$

Irreversibility in the evaporator:

$$Ir_{evp} = q_m \cdot T_{amb} \cdot (s_1 - s_4) - (\phi_{23} - P_{12}) \ [\mathrm{W}] \quad (6)$$

≡ q_m – mass flow of working substance
≡ T_{amb} – ambient temperature
≡ T_{room} – room temperature
≡ ϕ_{23} – heat flow for room heating
≡ P_{12} – compressor drive power
≡ s – entropy of numbered states

The overall results for the different working fluids are shown in the diagrams and calculated using EES (Engineering Equation Solver) software package. [8]

The following diagrams show a comparison of the change in irreversibility of the heat pump components: compressor, condenser, evaporator and expansion valve for five selected working substances and for the temperature of condensation T_{cond} = 40 °C. These diagrams help to select the most optimal working fluid for the heat pump system and the given task parameters, and also give information about quality of the working fluids.

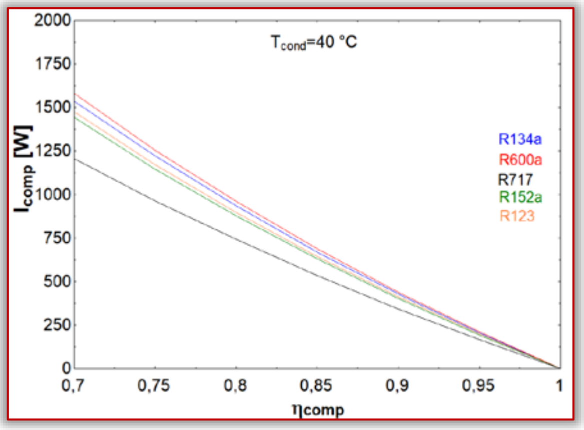

Figure 7. Comparison of compressor irreversibility lines for different working fluids
I_{comp} – irreversibility of the compressor; η_{comp} – compressor efficiency

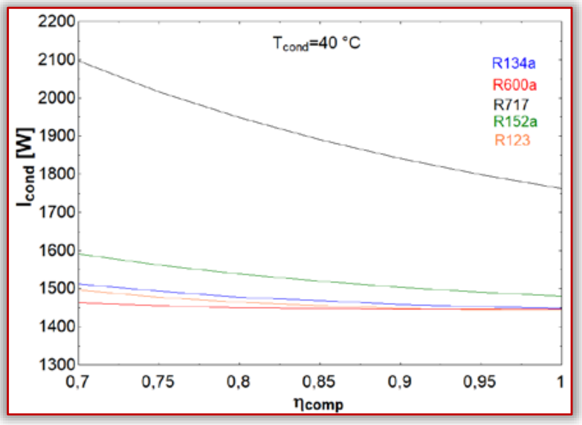

Figure 8. Comparison of condenser irreversibility lines for different working fluids
I_{cond} – irreversibility in the condenser; η_{comp} – compressor efficiency

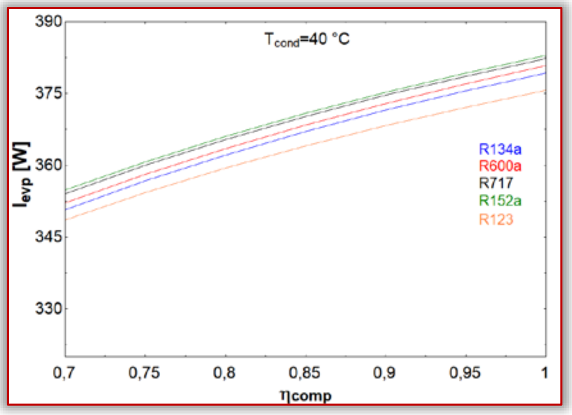

Figure 9. Comparison of evaporator irreversibility lines for different working fluids
I_{evp} – irreversibility in the evaporator; η_{comp} – compressor efficiency

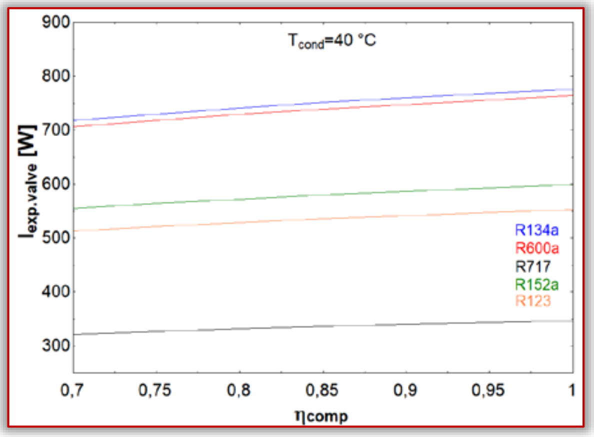

Figure 10. Comparison of expansion valve irreversibility lines for different working fluids
$I_{exp.valve}$ – irreversibility in the expansion valve; η_{comp} – compressor efficiency

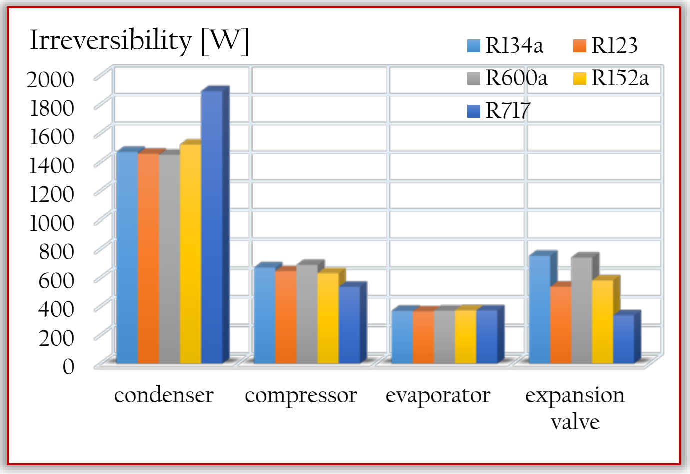

Figure 11. Comparison of the amount of irreversibility in heat pump components for different working fluids

CONCLUSIONS

The exergetic analysis of individual components of the heat pump has shown that most of the energy is lost in the condenser and that this energy loss increases with an increment of the temperature of condensation. From the diagram, it is easy to see that the irreversibilities in the condenser, compressor and expansion valve increase with the increment of the temperature of condesnsation, while the irreversibility in the evaporator decreases with the same increment. When it comes to the influence of compressor efficiency on the irreversibility in heat pump components, it has been shown that with the increment of compressor efficiency (which depends on the type and manufacturer) the irreversibility in condensers and compressors decreases, and the irreversibility in evaporators and expansion valves increases.

In the compressor irreversibility comparison diagram (Figure 7) for all five working fluids, R600a proved to be the worst, because the irreversibility or energy loss, was the highest, and working fluid R717 proved to be the best.

When it comes to the irreversibility in the condenser, the situation is different, the refrigerant R717 proved to be the worst, because the irreversibility is the greatest, whereas

R600a proved to be the best. In the evaporator, refrigerant R152a proved to be the worst because with use of that refrigerant, the irreversibility would be the greatest, while R123 proved to be the best. In the working fluid comparison diagram in terms of irreversibility in the expansion valve (Figure 10), refrigerant R134a proved to be the worst, and R717 proved to be the best.

Finally, the total irreversibility diagram (Figure 11) for the given parameters and selected working fluids shows that refrigerant R134a is the worst due to the highest value of the total irreversibility, and R123 the best. Due to different physical properties, densities and viscosities, the analyzed working substances have different effects on energy loss, so based on the given analyzes, in terms of irreversibility, the choice of a refrigerant has been facilitated.

The analysis was performed for a virtual building, whereas the data for the dimensions of the building, the temperature in the object, the outside temperature and the heat flux given by the heat pump are based on real values.

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