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About the evaluation of the coefficient of performance for a heat pump

Despre evaluarea coeficientului de performanță al unei pompe de căldură

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Abstract. *The present work represents a continuation of our research in the field of evaluating the thermal efficiency (coefficient of performance) of a heat pump, research started and published in 2019 [1]. In the previous work it was considered the refrigerating machine, this time we will refer exclusively to the mechanical vapor compression heat pump. The evaluation of the COP for a heat pump is absolutely mandatory in the calculation procedure of contribution of the renewable resources of energy, offered by the implementation of a heat pump in the thermal utility supply systems in buildings (space heating and/or hot water preparation).*

Key words: *heat pump, efficiency*

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1. Introduction

The efficiency of a heat pump is defined as the ratio between the thermal power delivered by the heat pump condenser and the mechanical power supplied by the heat pump compressor. Taking into account this definition and the theoretical graphical representations of the heat pump's operating cycle, the expressions of the two types of powers mentioned and finally the expression of the heat pump's performance coefficient were established, as will be presented below.

2. Description of the evaluation procedure

The thermodynamic cycle of the refrigerant in the pressure-specific enthalpy diagram (log)*p*-*h* [2] it is schematically shown in Fig. 1. The actual adiabatic compression process follows the line 1-2, the line 1-2' being the ideal situation in which the adiabatic compression process would take place at constant specific entropy.

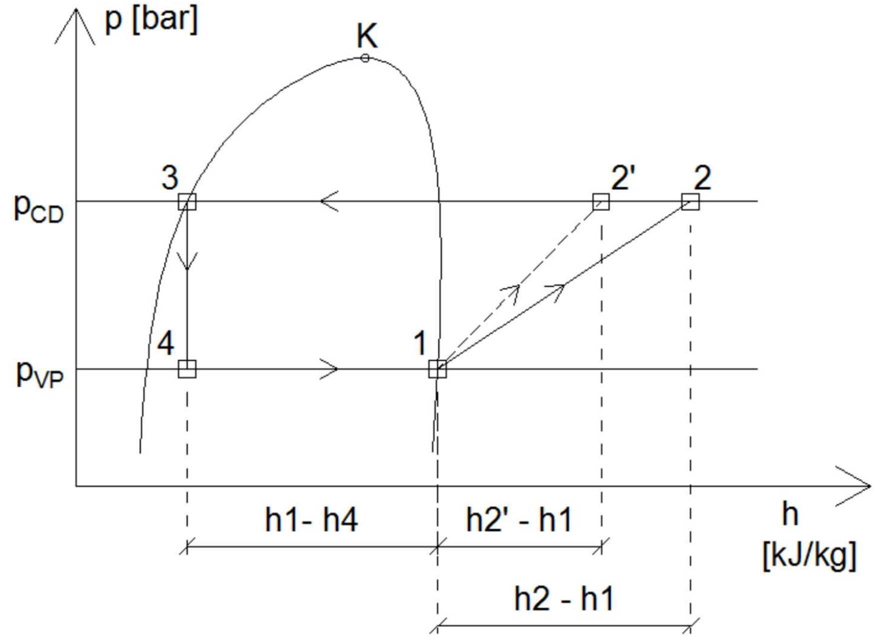

Fig. 1. The characteristic points in the log *p*-*h* diagram

The isentropic efficiency of the compressor [3] is defined as:

$$\eta_{iz} = \frac{h_{2'1}}{h_{21}} = \frac{h_{2'} - h_1}{h_2 - h_1} \tag{1}$$

The efficiency of the heat pump is defined as:

$$\begin{aligned} \varepsilon_{PC} &= \frac{h_{23}}{h_{21}} = \frac{h_{2'3} + h_{22'}}{h_{21}} = \frac{h_{2'3}}{h_{21}} + \frac{h_{22'}}{h_{21}} = \frac{h_{2'3}}{h_{2'1}} \cdot \frac{h_{2'1}}{h_{21}} + \frac{h_{21} - h_{2'1}}{h_{21}} = \\ &= \varepsilon_{PC}^{IZ} \cdot \eta_{iz} + 1 - \eta_{iz} = 1 + \eta_{iz} \cdot \left(\varepsilon_{PC}^{IZ} - 1\right) \end{aligned} \tag{2}$$

where;

$$\varepsilon_{PC}^{IZ} = \frac{h_{2'3}}{h_{2'1}} \tag{3}$$

The following notations were used:

$$\begin{aligned} &h_{23} = h_2 - h_3;\ h_{21} = h_2 - h_1;\ h_{2'3} = h_{2'} - h_3; \\ &h_{2'1} = h_{2'} - h_1;\ h_{22'} = h_2 - h_{2'}; \end{aligned} \tag{4}$$

As can be seen, apart from the efficiency of the heat pump, ε_{PC}, an isentropic efficiency of the heat pump, ε^{IZ}_{PC}, was defined. Relation (2) allows the determination of the energy efficiency of the heat pump, ε_{PC}, depending on the isentropic efficiency, ε^{IZ}_{PC}:

$$\varepsilon_{PC} = 1 + \eta_{iz} \cdot \left(\varepsilon_{PC}^{IZ} - 1 \right) \tag{5}$$

We define the overall coefficient of performance (COP) of the heat pump taking into account the efficiency of the electric motor, η_{el}, which feeds the pump compressor:

$$COP_{PC} = \eta_{el} \cdot \varepsilon_{PC} \tag{6}$$

The efficiency of the heat pump used as a refrigerator in the same temperature limits is:

$$\varepsilon_{MF} = \varepsilon_{PC} - 1 \tag{7}$$

In this case, the corresponding Energy Efficiency Ratio (EER) is:

$$EER_{MF} = \eta_{el} \cdot \varepsilon_{MF} \tag{8}$$

We obtain the final expressions for EER and COP:

$$\begin{gathered} EER = \eta_{el} \cdot \varepsilon_{MF} = \eta_{el} \cdot \eta_{iz} \cdot \left(\varepsilon_{PC}^{IZ} - 1 \right) \\ \text{and} \\ COP = \eta_{el} \cdot \varepsilon_{PC} = \eta_{el} \cdot \left[1 + \eta_{iz} \cdot \left(\varepsilon_{PC}^{IZ} - 1 \right) \right] \end{gathered} \tag{9}$$

As it turns out quite clearly, the central core of the energy efficiency of the heat pump is represented by the isentropic efficiency of the heat pump. To determine the isentropic efficiency of the heat pump, an analysis was undertaken between the energy efficiency and thermal parameters of 6 refrigerants (R410A, R134a, R407C, R507, R32, R152a) using the CoolPack and CoolTools software [2]. The range of temperatures investigated was between –15°C and 20°C for the cold environment and 35°C and 75°C for the warm environment.

The procedure for the use of the software was as follows:

- setting the refrigerant;
- setting the couple of temperatures of the cold and warm environments (θ_{VP} and θ_{CD});
- setting the compressor efficiency to the value 1;
- tracing the cycle and establishing the energy efficiency as a heat pump.

In addition, the energy efficiency of the cycle was also determined. In this way, 4 important parameters of the cycle could be determined, namely: vaporization and condensation temperatures of the refrigerant, Carnot energy efficiency and isentropic energy efficiency of the cycle.

Two types of correlations were made:

- the correlation between the isentropic energy efficiency, ε^{IZ}_{pc} and the Carnot energy efficiency, ε^{C}_{pc}
- the correlation between the isentropic energy efficiency, ε^{IZ}_{pc} and the difference between the condensation and vaporization temperatures of the heating agent, $\Delta t = t_{cd} - t_{vp}$.

We present below the 2 types of correlations obtained for each of the 4 refrigerants mentioned.

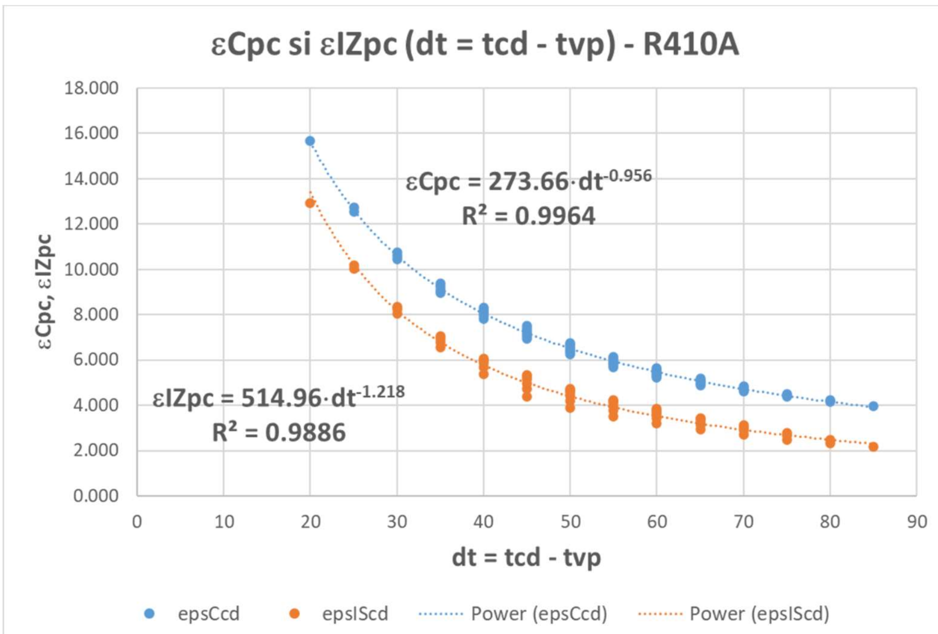

Fig. 2. The correlations for R410A

Figure 2 shows the correlations resulting from processing the data obtained using the CoolPack software, for the refrigerant R410A. We refer to the correlation between the Carnot energy efficiency of the heat pump, ε^{C}_{pc}, and the temperature difference dt, between the condensation temperature, t_{cd}, of the refrigerant and the vaporization temperature, t_{vp}. Figure 2 also shows the correlation obtained between the isentropic energy efficiency of the heat pump, ε^{IZ}_{pc}, and the temperature difference dt.

Figure 3 shows the same type of correlations, but related to the refrigerant R134a.

The mentioned temperature difference dt can be determined depending on the temperature difference between the warm environment, θ_{cd}, and the cold environment, θ_{vp}, due to the relationships:

$$
\begin{aligned}
& t_{cd} = \theta_{cd} + \Delta t;\ t_{vp} = \theta_{vp} - \Delta t \\
& dt = t_{cd} - t_{vp};\ d\theta = \theta_{cd} - \theta_{vp} \\
& dt = d\theta + 2 \cdot \Delta t
\end{aligned}
\tag{10}
$$

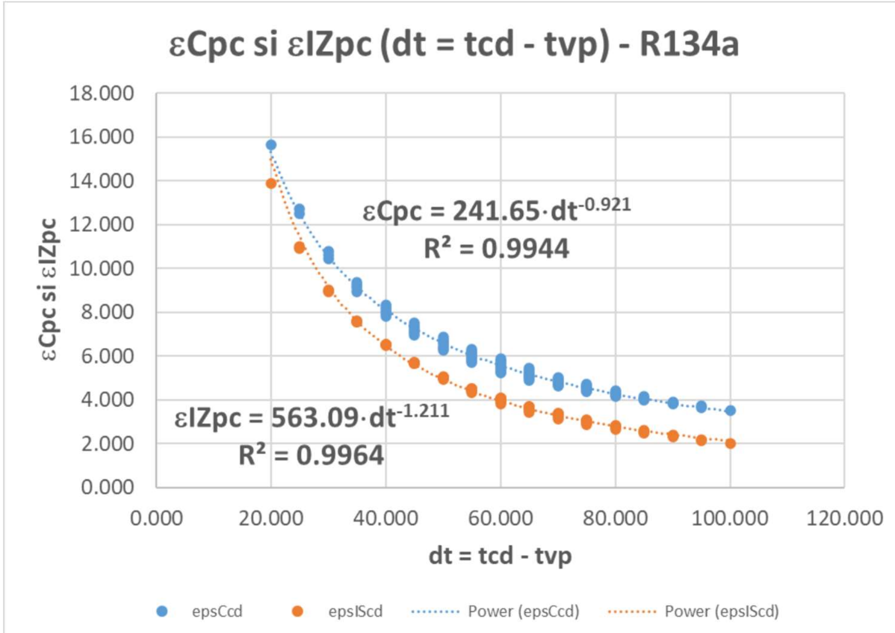

Fig. 3. The correlations for R134a

A second category of attempted correlations was made between isentropic energy efficiency and Carnot energy efficiency and the results were linear correlations, as one can see in figures 4 and 5.

Figure 4 shows, for the refrigerant R410A, the correlation between the isentropic energy efficiency of the heat pump, ε^{IZ}_{pc}, and the Carnot energy efficiency of the heat pump, ε^{C}_{pc}. Similar results are presented in Figure 5 for the refrigerant R134a.

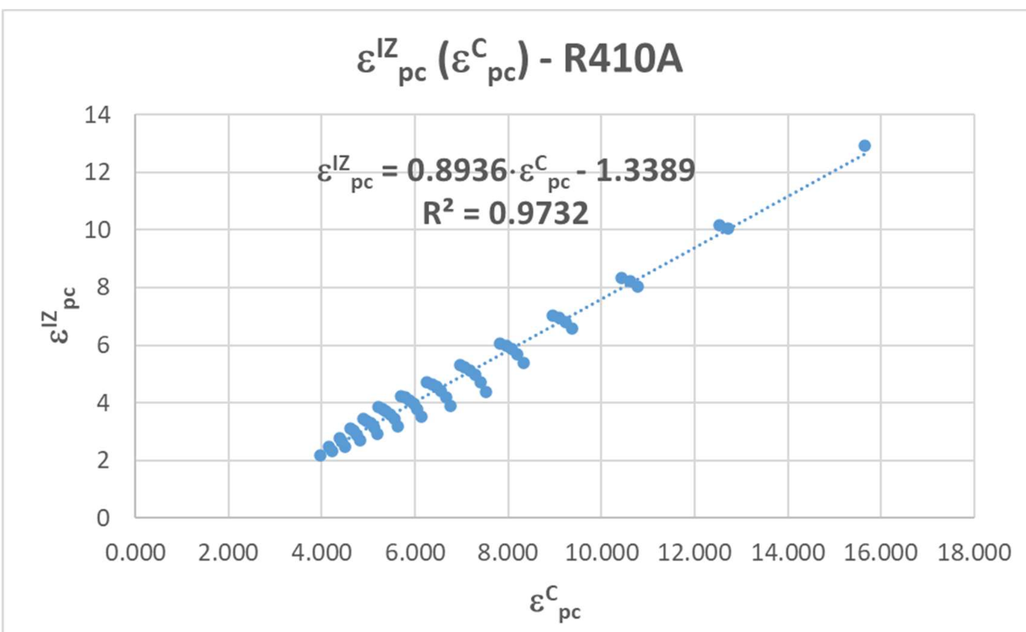

Fig. 4. The correlation between efficiencies for R410A

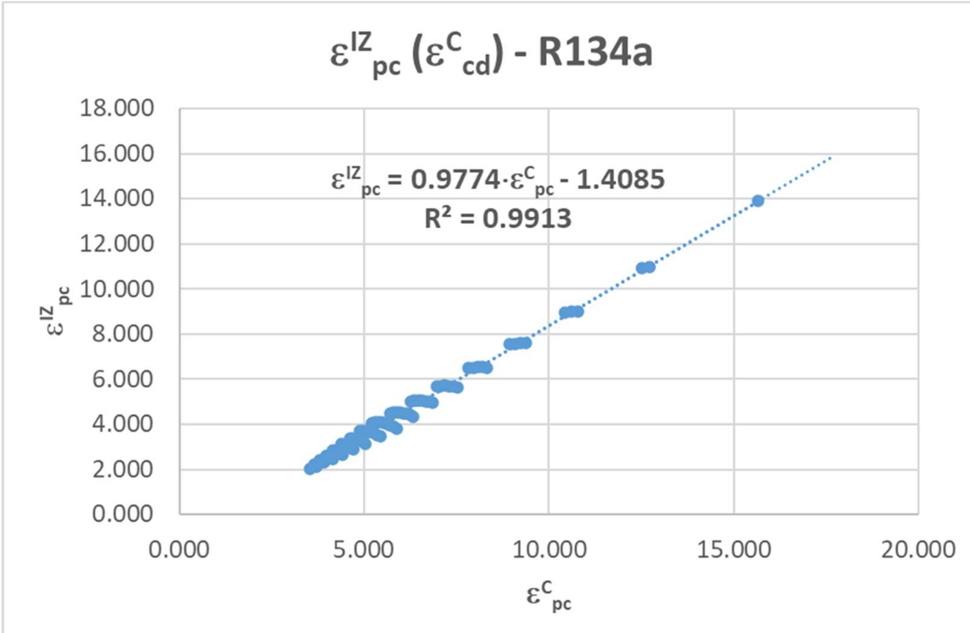

Fig. 5. The correlation between efficiencies for R134a

For the rest of the refrigerants analyzed, only the final results obtained are presented in Tables 1 and 2. As it was mentioned before and it results from relations (9), the central core is the isentropic energy efficiency of the heat pump, ε^{IZ}_{pc}, which makes the correlations shown in figures 2 and 3 preferable from an operative point of view.

For the 4 refrigerants the results are presented in Tables 1 and 2, containing the correlations regarding the isentropic energy efficiency of the heat pump.

Table 1

Correlation $\varepsilon^{IZ}_{pc} = \cdot f(dt)$ for various refrigerants

Refrigerant	Correlation
R410A	$\varepsilon^{IZ}_{pc} = 514.96 \cdot dt^{-1.218}$
R134a	$\varepsilon^{IZ}_{pc} = 563.09 \cdot dt^{-1.211}$
R407C	$\varepsilon^{IZ}_{pc} = 705.53 \cdot dt^{-1.284}$
R507	$\varepsilon^{IZ}_{pc} = 938.59 \cdot dt^{-1.385}$
R32	$\varepsilon^{IZ}_{pc} = 418.76 \cdot dt^{-1.145}$
R152a	$\varepsilon^{IZ}_{pc} = 378.87 \cdot dt^{-1.093}$

Table 2

Correlation ε^{IZ}_{pc} = ·f(ε^{C}_{pc}) for various refrigerants

Refrigerant	Correlation
R410A	$\varepsilon^{IZ}_{pc} = 0.8936 \cdot \varepsilon^{C}_{pc} - 1.3389$
R134a	$\varepsilon^{IZ}_{pc} = 0.9774 \cdot \varepsilon^{C}_{pc} - 1.4085$
R407C	$\varepsilon^{IZ}_{pc} = 0.9676 \cdot \varepsilon^{C}_{pc} - 1.6081$
R507	$\varepsilon^{IZ}_{pc} = 0.9454 \cdot \varepsilon^{C}_{pc} - 1.8408$
R32	$\varepsilon^{IZ}_{pc} = 0.9387 \cdot \varepsilon^{C}_{pc} - 1.3431$
R152a	$\varepsilon^{IZ}_{pc} = 0.9773 \cdot \varepsilon^{C}_{pc} - 1.0909$

Also of interest was the graphical representation as a whole of the 2 types of graphs that allow the visualization of the isentropic energy efficiency of the 4 refrigerants analyzed.

Figure 6 shows the graphs of the correlations between the isentropic energy efficiency, ε^{IZ}_{pc}, and the difference between the condensation and vaporization temperatures of the thermal agents. It is observed that for the 4 refrigerants analyzed, the group of corresponding curves is quite compact and it could be represented by the correlation corresponding to the refrigerant R407C (as a mean).

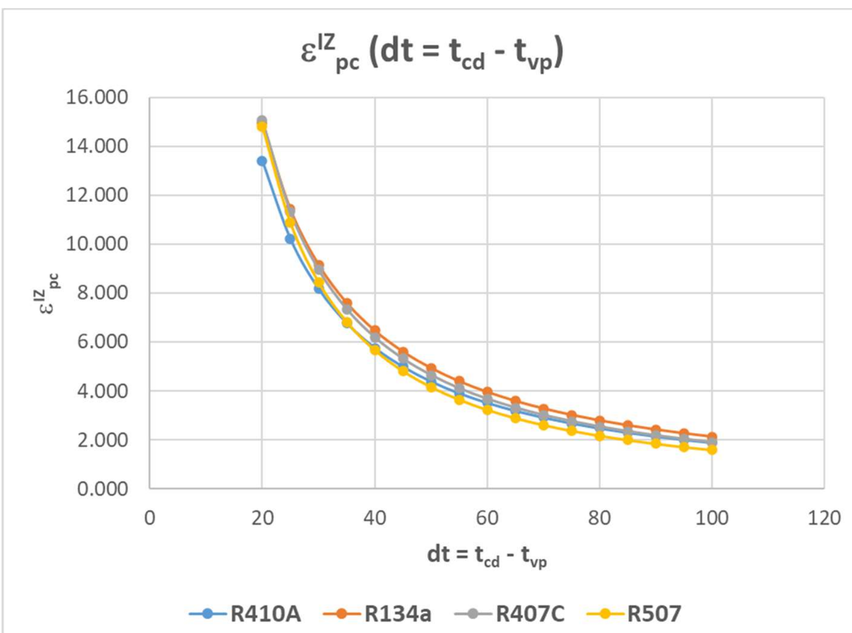

Fig. 6. The correlation ε^{IZ}_{pc} = ·f(dt) for various refrigerants

Figure 7 shows the graphs of the correlations between the isentropic energy efficiency, ε^{IZ}_{pc}, and the Carnot energy efficiency, ε^{C}_{pc}. It is observed that for the 4 refrigerants analyzed, the group of corresponding lines is quite compact and could possibly be also represented by the corresponding correlation of the R407C refrigerant.

If it will be proven for a larger number of refrigerants that the same correlation stands, it would be preferable to retain this correlation in the useful procedure of identification of the isentropic energy efficiency, ε^{IZ}_{pc}.

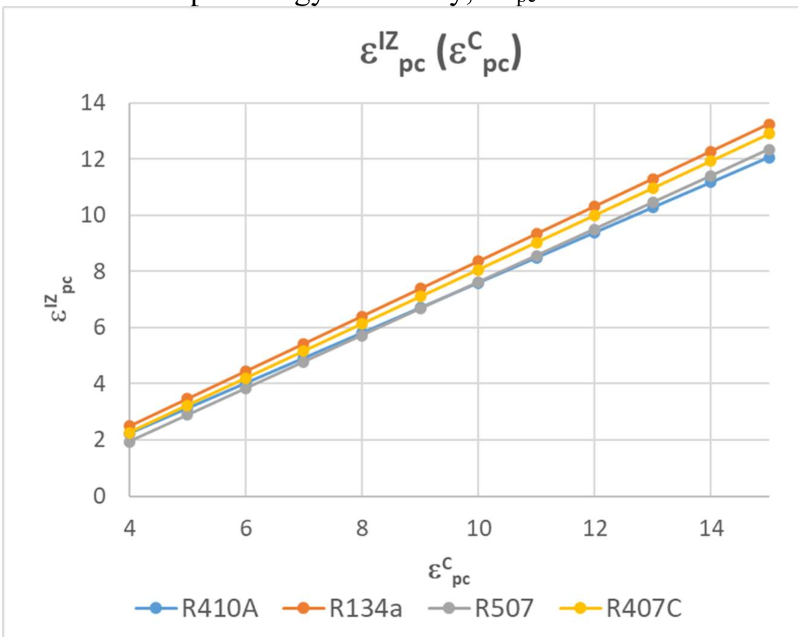

Fig. 6. The correlation $\varepsilon^{IZ}_{pc} = \cdot f(\varepsilon^{C}_{pc})$ for various refrigerants

Conclusions

As can be seen from the equation (9), that allow the evaluation of useful performance coefficients for heat pumps, they depend on the isentropic energy efficiency, ε^{IZ}_{pc}, on the isentropic efficiency of the compressor, η_{iz}, and on the efficiency of the electric motor which drives the heat pump compressor, η_{el}. The current work mainly refers to the isentropic energy efficiency of the heat pump, ε^{IZ}_{pc}, which can be determined by the correlations established and presented, depending on the temperatures of the ambient environments of the evaporator and the condenser of the heat pump.

The correlation based on the Carnot energy efficiency is simple and easy to use, being a linear correlation, but it requires the prior determination of the Carnot energy efficiency according to the temperatures of the ambient media, θ_{cd} and θ_{vp}.

The correlation between the isentropic energy efficiency and the temperatures of the ambient media, θ_{cd} and θ_{vp}, through relations (10) and those in lines 2, 3, 4 and 5 of table 1, allows the operational determination of the isentropic energy efficiency.

It is worth remembering the verification of the degree of uniqueness of the linear correlation between the isentropic energy efficiency and the Carnot energy efficiency of the heat pump.

Notations

t_{vp} – vaporization temperature of the refrigerant, °C;
t_{cd} – condensation temperature of the refrigerant, °C;
θ_{vp} – cold environment temperature, °C;
θ_{cd} – warm environment temperature, °C;
Δt – average temperature difference at the evaporator and at the condenser, °C;
h_1, h_2, h_3, h_4 – specific enthalpy for nodes 1, 2, 3 and 4 of the refrigeration cycle, kJ/kg;
$h_{2'}$ – specific enthalpy of node 2' of the refrigeration cycle, kJ/kg;
η_{iz} – isentropic efficiency of the compressor, -;
η_{el} – efficiency of the electric motor that drives the compressor, -;
ε_{pc} – energy efficiency of the machine as a heat pump, -;
ε_{mf} – energy efficiency of the machine as a refrigerator, -;
ε^{C}_{pc} – Carnot energy efficiency of the heat pump, -;
ε^{IZ}_{pc} – isentropic energy efficiency of the heat pump, -;
COP – coefficient of performance for the heat pump, -;
EER – energy efficiency ratio as a refrigerator; -.

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