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INFLUENCE OF COOLING AGENT TYPE ON THE DESIGN AND POWER DEMAND OF HEAT PUMPS

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Abstract

The paper presents the comparative exergetic analysis of different heat pump designs from an energy consumption point of view. Heat pumps are usually classified according to the environment from which they extract heat in order to help the consumer in choosing a heat pump type, based on the available heat sources. From the construction point of view, a wide variety of heat pumps have appeared as a result of the various heat sources to be considered, and the refrigerants used. Also, due to the desire to improve their operation, various constructive variants have been developed. Considering that all heat pumps use electricity to operate, their energy consumption for producing the same thermal effect should be a criterion for their choice, along with economic aspects.

Keywords*: heat pump, exergy analysis, power demand.*

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1. Introduction

A heat pump is a heat engine designed to extract heat from a lower temperature environment and transfer it to a higher temperature environment. It is used to manage thermal energy, whereby energy rejected in the cooling process and waste heat can be used for heating and hot water production, and ambient heat can be used likewise.

Heat pump technology is a relatively old technology, in fact the energy crisis of the 1970s gave a boost to research in this field.

Today, the EU and the UN have developed common goals for a sustainable future, and one of these goals is affordable and clean energy. In light of this directive, heat pump technology is experiencing a new renaissance, with more and more heat pumps being installed.

With heat pump heating playing a central role in the European Union's green energy transition, more and more companies are installing heat pumps, resulting in different companies adopting unique design solutions.

The aim of this paper is to highlight the different aspects of heat pump operation in terms of exergy efficiency and energy consumption.

2. Classification of heat pumps

Heat pumps are usually classified according to the environment from which they extract heat, helping the consumer to choose a particular type of heat pump based on the heat source available **[1–8]**.

According to most sources of information, the main types of heat pumps are:

- Geothermal heat pumps;
- Air-to-water heat pumps;
- Air-to-air heat pumps;
- Water-to-water heat pumps.

Consequently, they are classified according to the heat source, which is understandable since the target audience is the user.

However, heat pumps can also be classified according to the design of the system:

- Monovalent systems, which operate without auxiliary heating, are implemented by drilling geothermal boreholes, installing a flat plate collector, and are built to use thermal and other waste heat, groundwater heat.;
- Bivalent systems, which operate with auxiliary heating and are built using air, surface water heat.

From a structural point of view, a very wide range of heat pumps have been developed due to the different heat sources that have been considered for exploitation and the refrigerants used. In addition, the desire to improve their operation has also led to the emergence of different design variants.

The classification of heat pumps by process and type of operation [9–11] serves the purpose of this paper much better, and can be summarized as follows:

A. Heat pumps with vapour compression cycle:
  A.1. Compression heat pumps:
  – Rotary piston;
  – Rotary compressor;
  – Turbocompressor.
  A.2. Absorption heat pumps:
  – Indirectly heated;
  – Directly heated;
  – Adsorption heat pump;
  – Resorption heat pump;
  – Ejector heat pumps.
B. Gas Compression Heat Pumps:
  – Heat pumps using air as refrigerant;
  – Stirling cycle heat pumps;
  – Vortex tube heat pumps;
  – Vuilleumier cycle heat pumps.
C. Thermoelectric effect heat pumps.

Among the above-mentioned types of heat pumps, one type from each major class will be analyzed: vapour compression cycle, gas cycle and thermoelectric effect heat pumps.

3. Design and cycles of heat pumps

3.1. The vapour compression heat pumps

Vapour compression heat pumps are perhaps the most widely used type of heat pump. The first of these types uses R12 (ammonia) refrigerant and this refrigerant is still widely used in large refrigeration systems. The Freon family of compounds, the commercial name for halogenated hydrocarbons with excellent properties, is widely used in the refrigeration industry. Freon's chlorine content is highly ozone depleting and CFC refrigerants have been replaced by newer, less polluting refrigerants, hydrochlorofluorocarbons (HCFCs).

Water vapour is a type of refrigerant that is completely neutral from an environmental point of view, so, in the following, we will present vapour compression heat pumps using ammonia and water as refrigerants.

3.1.1. The vapour compression heat pump using ammonia refrigerant

Heat pumps suitable for exploiting low thermal energy sources are the vapour-compression, water-to-water system [10, 11] heat pumps. This type of heat pump (Figures 1 and 2) is suitable for extracting waste heat from water at temperatures below 40 °C and deliver domestic hot water at temperatures up to 50–80 °C.

A mathematical model of such a heat pump was developed in [12] so the thermal characteristics of the heat pump will be calculated based on that model.

3.1.2. Vapour compression heat pump using water as refrigerant

Figure 3 shows a vapour compression heat pump operating with water as refrigerant, while the cycle diagram is shown in Figure 4.

3.2. Gas compression heat pump

The basic design of a gas compression heat pump is similar to that of a vapour compression heat pump, as shown in Figure 5, while its cycle is shown in Figure 6.

From a thermodynamic point of view, the vapour compression heat pump (Figure 3) operates according to the Carnot cycle modified for practical applications.

In the expander, isentropic expansion is replaced by an isentropic process in the expansion valve, while in the compressor, isentropic compression occurs, resulting in a temperature Tc higher than the condensation temperature (Figure 4) [10, 11].

The theoretical cycle of a gas compression heat pump (Figure 3) is a Joule cycle [10, 11], in which expansion and compression are achieved by means of turbomachinery.

While the operation of the vapour compression heat pump has been described in several articles due to their widespread use, the gas compression heat pump is not used as often and therefore the literature on it is scarcer.

The basic characteristic of a gas compression heat pump is the compression ratio [10, 11]:

$$\beta_c = \frac{p_2}{p_1} \tag{1}$$

where p_2 is the outlet pressure, p_1 is the inlet pressure of the turbocompressor, in bar.

The characteristic parameter of heat pumps is the COP (coefficient of performance), which for gas compression heat pumps can be expressed by the following formula [10, 11]:

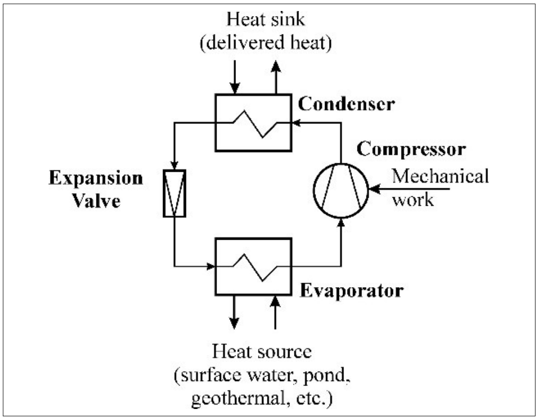


Fig. 1. *The vapour compression heat pump using ammonia refrigerant.*

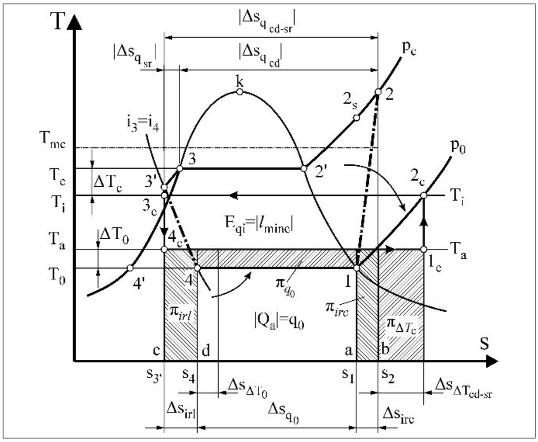


Fig. 2. *Cycle of the vapour compression heat pump using ammonia refrigerant.*

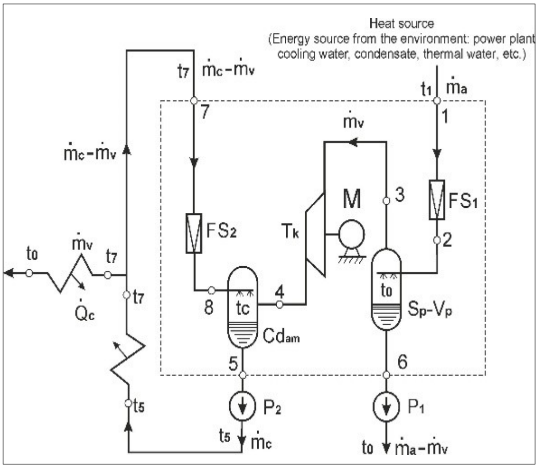


Fig. 3. *The vapour compression heat pump using water refrigerant.*

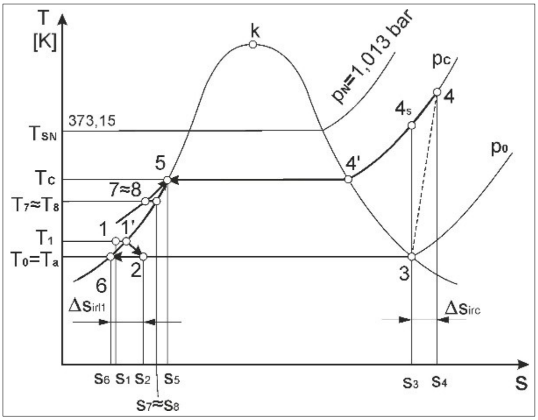


Fig. 4. *Cycle of the vapour compression heat pump using water refrigerant.*

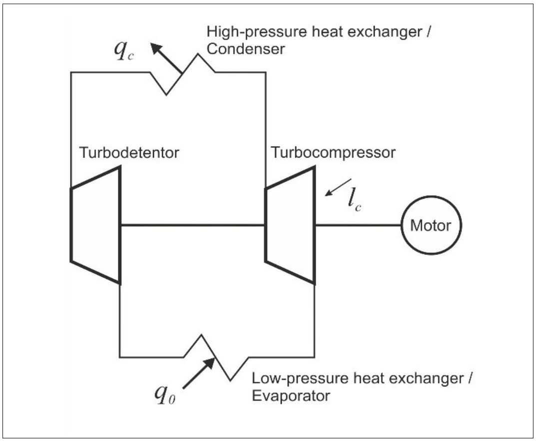


Fig. 5. *Gas compression heat pump.*

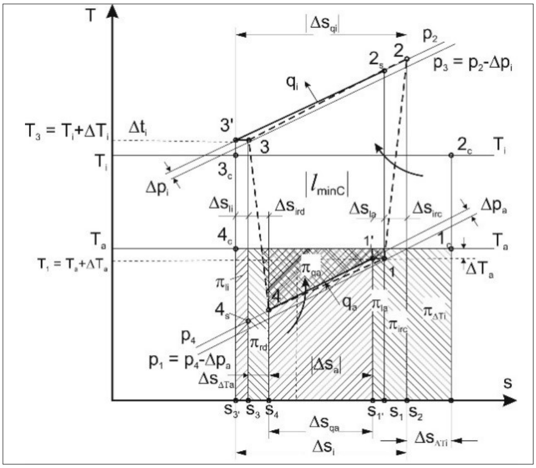


Fig. 6. *Cycle of the gas compression heat pump cycle.*

$$\mu_t = \frac{1}{1-\beta_c^{\frac{1-k}{k}}} \tag{2}$$

where k is the adiabatic coefficient.

Another parameter to compare heat pumps is the exergy efficiency, which can be calculated using the following equation **[10, 11]**:

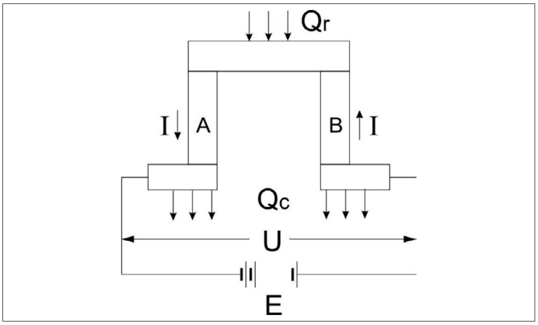
$$\eta_E = \frac{|l_{\min C}|}{|l|} \tag{3}$$

where l_{minC} is the specific minimum work of the ideal Carnot cycle in kJ·kg^{-1}, while l is the specific work of the actual cycle in kJ·kg^{-1}.

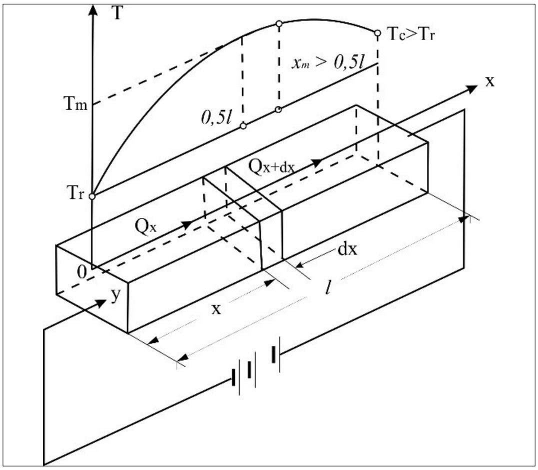
Based on the actual cycle of the gas compression heat pump (**Figure 6**) **[10, 11]** calculations can be performed to determine characteristic parameters that can be compared with the corresponding characteristics of the heat pumps analyzed.

3.3. Thermoelectric heat pump

Figure 7 shows a schematic of a thermoelectric heat pump while **Figure 8** presents a schematic of a thermoelectric element **[10, 11]**.



7. ábra. *Termoelektromos hőszivattyú*



8. ábra. *Termoelektromos elem*

These devices are based on the thermoelectric phenomenon, namely the Seebeck, Peltier and Thomson effects. The phenomenon in which a temperature difference between two different electrical conductors or semiconductors produces a voltage difference between the two materials is known as Seebeck.

When heat is applied to one of two conductors or semiconductors, the heated electrons flow towards the colder one.

The inverse of the Seebeck effect is called the Peltier effect; an electric current flowing through a junction between two materials releases or absorbs heat at the junction in unit time to compensate for the difference in chemical potential between the two materials.

The Thomson effect is the heat evolution or absorption when an electric current passes through a circuit of a single material with a temperature difference along its length.

This heat transfer relies on the common heat generation associated with the electrical resistance to currents in conductors. Note that the Thomson and Peltier effects refer to reversible processes. The Thomson effect is usually ignored in the design of thermoelectric systems.

The mathematical model of a thermoelectric heat pump is fundamentally different from the models of heat pumps presented above and will be described in more detail below.

For a thermoelectric heat pump, based on the schematic drawing of the thermoelectric element shown in **Figure 8** the heat flux through the cold point of the element can be calculated using the following equation **[10]**:

$$Q_r = \alpha \cdot I \cdot T_r - 0.5 \cdot R \cdot I^2 - \Lambda \cdot \Delta T, \text{ (W)} \tag{4}$$

where:

α is the total Seebeck coefficient V·K^{-1}-ben;
R is the total electrical resistance in Ω;
Λ is the total conductivity of the thermoelectric element in W·K^{-1}.

The equations to calculate these elements are:

$$\alpha = |\alpha_A| + |\alpha_B|, \quad \text{(V/K)} \tag{5}$$

where $\alpha_{A,B}$ – Seebeck coefficient of the A and B components of the thermoelectric element in V·K^{-1}.

$$R = \rho_A \cdot \frac{l_A}{A_A} + \rho_B \cdot \frac{l_B}{A_B}, \quad (\Omega) \tag{6}$$

where:

ρ_A, ρ_B – resistance of the thermoelectric element components A and B in Ω·m;

l_A, l_B – length of the thermoelectric element components A and B in m;
A_A, A_B – surface area of the thermoelectric element components A and B in m^2.

Finally:

$$\Lambda = \lambda_A \cdot \frac{A_A}{l_A} + \lambda_B \cdot \frac{A_B}{l_B}, \quad \text{(W/K)} \tag{7}$$

where λ_A, λ_B – thermal conductivity of the components of the thermoelectric element A and B in $W \cdot m^{-1} \cdot K^{-1}$.

To compute the thermal characteristics of the thermoelectric system, the heat exiting the hot spot of the thermoelectric element must be calculated, starting with the energy balance equation **[10]**:

$$Q_c = Q_r + P_i, W \tag{8}$$

where: P_i – electrical power required for operation, in W, Q_r – heat flux through the cold spot of the element, in W.

Maximum cooling efficiency of the system:

$$\varepsilon_{fmax} = \frac{Q_r}{P_i} \tag{9}$$

The maximum efficiency of a heat pump, also known as the coefficient of performance (COP):

$$\mu_{max} = \frac{Q_c}{P_i} \tag{10}$$

Exergetic efficiency of cooling:

$$\eta_{Ef} = \frac{m - \frac{T_c}{T_r}}{m + 1} \tag{11}$$

In which m is a parameter that can be calculated:

$$m = \sqrt{1 + Z \cdot \frac{T_c + T_r}{2}}, \tag{12}$$

where Z is the efficiency of the thermoelectric element, calculated by the following equation:

$$Z = \frac{\alpha^2}{\Phi_{min}}, \tag{13}$$

while the value Φ_{min} is given by equation:

$$\Phi_{min} = \left(\sqrt{\lambda_A \cdot \rho_A} + \sqrt{\lambda_B \cdot \rho_B}\right)^2. \tag{14}$$

The exergy efficiency of a thermoelectric heat pump can be calculated as follows:

$$\eta_{Et} = \frac{m - \frac{T_r}{T_c}}{m + 1} \tag{15}$$

4. Thermal characteristics of heat pumps

Heat pump heating is at the heart of the European Union's green energy transition, so it is mostly used in households for heating and hot water. Heat pumps that can be used to harness low heat energy sources are the vapour-compressed, water-to-water system **[10]**, **11]**. This type of heat pump is capable of harnessing waste heat from water at temperatures below 40°C to heat domestic hot water to 50-80°C.

The heat pumps described above use electricity to operate. The compressor (**Figure 1**), and the turbo compressor (**Figure 3** and **5**) are driven by an electric motor, while the thermoelectric heat pump as the name implies is driven by electricity directly and is therefore fundamentally different from other heat pumps.

As shown in **Figures 2**, **4.** and **6** the implementation of the heat pump's thermodynamic cycle (vapour compression, gas compression, etc.) and the type of refrigerant used strongly influences the design solutions employed. Heat pump designs are very diverse, and if multi-stage solutions were to be analyzed, the design solutions would be even more diverse and time-consuming to list.

The thermal characteristics of the heat pumps are calculated using the following initial data: the required heat input Q_i, to cover the demand of a household Q_i = 28 kW; T_i = 65 °C – domestic hot water temperature; T_a – ambient temperature (heat source). The heat source temperature is selected depending on the fact that the heat pump with water vapour cooling medium cannot be operated at a lower heat source temperature, i.e. T_a = 30, 35, 40 °C.

For the vapour compression heat pump, some more data are needed: ΔT_c = 5 °C – temperature difference for condenser heat transfer (heat transport); ΔT_0 = 5 °C – temperature difference for evaporator heat transfer; T_{sr} = 10 °C – temperature difference for sub-cooling; the refrigerant used is R717 (ammonia).

For the vapour compression heat pump using R717 (ammonia) refrigerant, the results are shown in **Table 1**, while the results for the heat pump using water refrigerant are shown in **Table 2**. Also, for the gas compression heat pump, the temperature difference for the condenser heat transfer (heat transfer) and the temperature difference for the evaporator heat transfer is set to $\Delta T_c = \Delta T_0$ = 5 °C.

The results obtained from the gas compression heat pump calculations are shown in **Table 3**.

The thermal characteristics of the thermoelectric heat pump were calculated considering the same heat source temperatures, temperature rises and the required 28 kW of heat dissipation.

In addition, the semiconductor materials used for the construction of the thermoelectric elements, in this case tellurium (A) and bismuth (B), must be selected.

The physical characteristics of the materials for bismuth are: diameter $d = 7$ mm, length $l = 3.2$ mm, Seebeck coefficient $\alpha = -0.21 \cdot 10^{-3}$ V·K^{-1}, electrical conductivity $\rho = 10^{-5}$ Ω·m; thermal conductivity $\lambda = 1.45$ W·m^{-1}·K^{-1}. And the physical characteristics of tellurium are: length $l = 3.2$ mm, Seebeck coefficient $\alpha = 0.23 \cdot 10^{-3}$, V·K^{-1}, electrical conductivity $\rho = 10^{-5}$ Ω·m; thermal conductivity $\lambda = 1.45$ W·m^{-1}·K^{-1}, while the dielectric strength is determined by calculations. For the thermoelectric heat pump, the results are plotted in **Table 4**.

Table 1. *Thermal characteristics of the vapour compression heat pump (R717 refrigerant)*

Thermal characteristic	Value		
Heat source temperature, T_a [°C]	30	35	35
Actual power, P_e [kW]	5.24	4.54	4.54
Specific internal energy absorbed as heat, q_0 [kJ·kg^{-1}]	996.29	999.80	999.80
Delivered specific heat, q_c [kJ·kg^{-1}]	1198.23	1170.64	1170.64
Ideal COP μ_C	9.66	11.27	11.27
Theoretical COP μ	5.93	6.85	6.85
Actual COP μ_e	5.34	6.17	6.17
Exergy efficiency, η_E [%]	61.41	60.79	60.79

Table 2. *Thermal characteristics of the vapour compression heat pump using water refrigerant*

Thermal characteristic	Value		
Heat source temperature , T_a [°C]	30	35	40
Minimum required power, P_{min} [kW]	3.02	2.84	2.65
Compressor power, P_c [kW]	4.86	4.86	4.86
Pump power , P_p [kW]	0.11	0.06	0.04
Total P_{tot} [kW]	7.99	7.76	7.55
Exergy loss due to the irreversibility of the compression process, π_{irc} [%]	15.82	15.82	15.82
Exergy loss in the throttle valve, π_{irl} [%]	3.97	7.83	11.60
Exergy loss due to irreversibility of heat transfer in the condenser, $\pi_{\Delta Tc}$ [%]	18.02	18.02	18.02
Maximum COP μ_{max}	9.26	9.87	10.56
Actual COP μ_e	5.07	5.13	5.15
Exergy efficiency η_E [%]	62.20	58.33	54.56

Table 3. *Thermal characteristics of the gas compression heat pump*

Thermal characteristic	Value		
Heat source temperature, T_a [°C]	30	35	40
Actual power, P_e [kW]	18.99	18.47	18.06
Specific work required to operate the actual cycle, l_e [kJ·kg^{-1}]	87.53	90.58	93.62
Specific heat absorbed in the evaporator, q_a [kJ·kg^{-1}]	44.99	50.01	55.04
The specific heat delivered by the condenser, q_i [kJ·kg-1]	129.02	136.97	144.91
Specific work of the ideal Carnot cycle, l_{minC} [kJ·kg-1]	13.36	12.16	10.72
Ideal COP μ_C	9.657	11.27	13.52
Theoretical COP μ	1.54	1.58	1.61
Actual COP μ_e	1.47	1.51	1.55
Exergy efficiency η_E [%]	15.90	13.98	11.93

Table 4. Thermal characteristics of the thermoelectrical heat pump

Thermal characteristic	Value		
Heat source temperature, T_a [°C]	30	35	40
Electrical power required for operation, P_e [kW]	13.61	11.96	10.22
Energy extracted as heat from a heat source, Q_r [kW]	14.39	16.04	17.78
Ideal COP μ_C	9.66	11.27	13.53
Actual COP μ_e	2.06	2.34	2.74
Exergy efficiency η_E [%]	21.30	20.80	20.20

5. Conclusions

Based on the data presented above, the following conclusions can be drawn.

In line with the values reported in the literature, the variation of the thermal characteristics of heat pumps with respect to the heat source temperature is as follows:

- the effective coefficient of performance, (COP) μ_e increases with increasing heat source temperature;
- the exergy efficiency η_E decreases with increasing heat source temperature;
- the electrical power required for operation, P_e decreases with increasing heat source temperature.

The exergy efficiency η_E decreases with increasing heat source temperature, by 1.1% for the thermoelectric heat pump, by 3.97% for the gas compression heat pump, by 7.64% for the water vapour refrigerant heat pump and by 2.16% for the vapour compression ammonia refrigerant heat pump.

In order to compare the different types of heat pumps in terms of electricity consumption, a suitable basis for comparison must be found.

A classical heating method is electric resistance heating, which is a good basis for comparison because electric resistance heating has a conversion efficiency of 100% in the sense that all the electrical energy input is converted into heat **[13, 14]**, and at the same time the exergy factor of electrical energy is 1 **[15]**. The exergy factor as defined in the literature **[15]**] is the ratio between exergy and energy, usually a number between 0 and 1.

Figure 9 shows the variation of the actual coefficient of performance (COP) μ_e as a function of heat source temperature. As can be seen, the effective coefficient of performance (COP) μ_e increases with increasing heat source temperature and from this point of view, the order of efficiency is as follows: the vapour-compressed ammonia refrigerant heat pump, the vapour-compressed water vapour refrigerant heat pump, the thermoelectric heat pump and, lastly, the gas-compressed heat pump. Since all electrical energy is converted into heat, the resistance power factor is set to 1, so all heat pumps perform better than resistance heating in this respect.

Figure 10 presents the variation of the exergy efficiency η_E as a function of the heat source temperature, where it can be seen that the efficiency decreases as the heat source temperature increases and, from this point of view, the order of efficiency is as follows: the vapour-compressed ammonia refrigerant heat pump, the vapour-compressed water vapour refrigerant heat pump , the thermoelectric heat pump and the gas-compressed heat pump in last place, from this point of view the resistance heating performs best since the electric current is essentially pure exergy.

Figure 11 shows the variation of electrical power required for operation, Pe as a function of heat

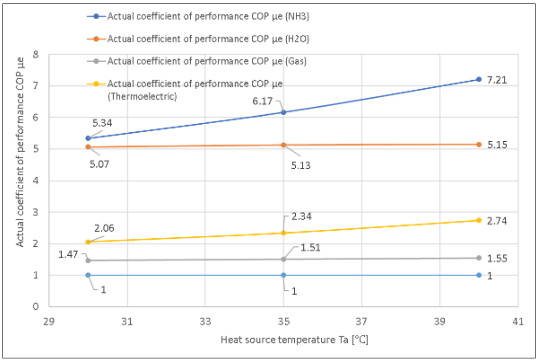


Fig. 9. *Actual coefficient of performance, COP*

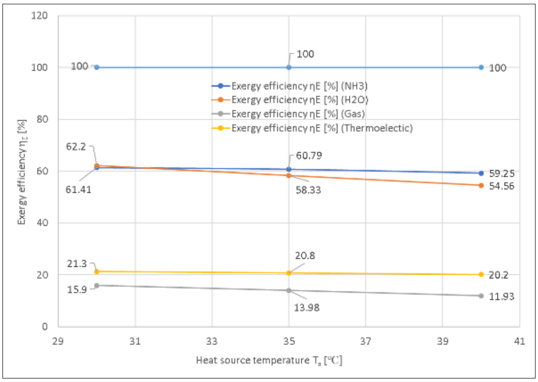


Fig. 10. *Exergy efficiency.*

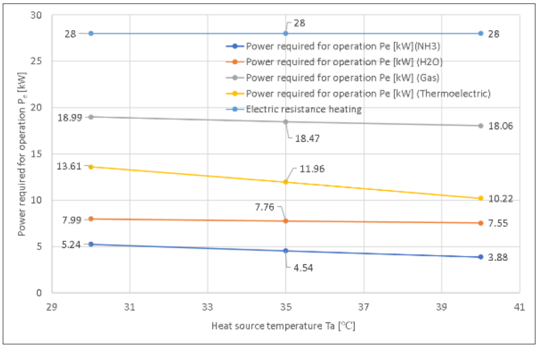


Fig. 11. *Power required for operation.*

source temperature, where it can be seen that the power decreases as the heat source temperature increases and, from this point of view, the order of efficiency is as follows: the vapour-compressed ammonia refrigerant heat pump, the vapour-compressed water vapour refrigerant heat pump, the thermoelectric heat pump and the gas-compressed heat pump in last place, from this point of view the resistance heating performs the worst because the exergy factor of the electric current is 1.

Summarizing, the choice of a heat pump for a particular application is more complex than one might think at first glance, and their classification by heat source can only be a starting point in choosing the right heat pump.

The performance required to operate should be an important criterion, as this will affect the operating costs in the long run, but other economic aspects, such as the initial investment, should not be neglected, as they all affect whether the investment will ever pay off.

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