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EXERGY ANALYSIS OF A VAPOUR COMPRESSION HEAT PUMP USING ENVIRONMENTALLY FRIENDLY REFRIGERANTS

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Abstract

The paper presents the comparative exergetic analysis of heat pumps using refrigerants with different ozone depletion potential and global warming potentials. Globally, the air conditioning of houses is seen as a major energy challenge as the economic development of countries, the majority situated in hot climates, will lead to a growing demand for chilling. Added to this is the increasingly widespread use of heat pumps in areas with a temperate climate to increase energy efficiency. As a result, the environmental impact of refrigerants from ozone depletion potential and global warming potential point of view cannot be overlooked. On the other hand, an environmental benefit of high energy efficiency is the reduction of greenhouse gas emissions from fossil fuel combustion for various purposes. The purpose of this approach is to highlight how the use of different types of refrigerants will impact the exergy efficiency of heat pumps.

Keywords*: heat pump, exergy efficiency, refrigerants, environmental impact.*

1. Introduction

Energy savings are a major concern in the modern world, as since the first energy crisis in 1973 mankind has basically suffered a chronic energy shortage, one that worsens once in a while, usually triggered by major political developments.

The energy crisis is aggravated by increasingly pressing environmental problems, which is why new, environmentally friendly energy production technologies are gaining more and more prevalence.

One such technology is the heat pump, which is a heat engine used to extract heat from a lower-temperature environment and deliver it to a higher-temperature environment, using a refrigeration cycle.

The purpose of its use is the management of thermal energy, during which ambient heat and waste heat can be used for heating and domestic hot water production.

Heat pumps use electricity to transfer heat from a cool space to a warm space but they can be used for cooling too. During the heating season, they move heat from the environment into your home and during the cooling season, heat pumps move heat from your house into the environment. Their efficiency results from the fact that they transfer heat instead of generating it.

Globally, the cooling of houses is considered a significant energy challenge, as the economic development of countries with mostly warm climates leads to an increase in the demand for air conditioners. Added to this is the increasingly widespread use of heat pumps in areas with a moderate climate in order to increase energy efficiency.

As a result, the environmental effects of refrigerants cannot be ignored.

On the other hand, the environmental advantage of high energy efficiency is the reduction of greenhouse gas emissions generated during the burning of fossil fuels for various purposes.

The purpose of this approach is to highlight how the use of different types of refrigerants will impact the exergy efficiency of heat pumps.

2. The vapour compression heat pump

Vapour compression heat pumps are perhaps the most widely used type of heat pumps. The first of these types worked with R-717 (ammonia) refrigerant, and this refrigerant is still common in large refrigeration systems today. Ammonia is a dangerous compound for both the environment and people as it is toxic and explosive. Later, propane (C_3H_8), methyl chloride (CH_3Cl), sulfur dioxide (SO_2), and several other compounds were used. The Freon family is the trade name for halogenated hydrocarbons, which are widely used in the refrigeration industry due to their excellent properties. Freons, or CFCs as they were also known, have been widely used due to their excellent stability and safe use: they are non-flammable and less toxic than other refrigerants. Unfortunately, one of their properties has become very dangerous: if freon reaches the upper atmosphere, its chlorine content destroys the ozone layer, which protects the earth's surface from the ultraviolet radiation of the Sun.

CFC refrigerants were replaced by newer and less polluting refrigerants, hydro-chlorofluorocarbons (HCFCs), such as R-22, which is used in most household refrigerators today, and HFCs (such as R-134a), which became popular in automobiles. Currently, researchers are developing more environmentally friendly refrigerants in order to replace these refrigerants as well, so more and more research is addressing this topic.

One such refrigerant, which is completely neutral from an environmental point of view and non-toxic, is water vapour (R-718). So, in the following, ammonia (R-717) and the more modern, environment-friendly refrigerant (R-134a) and heat pumps operating with water vapour (R-718) will be analysed in terms of energy efficiency and environmental point of view.

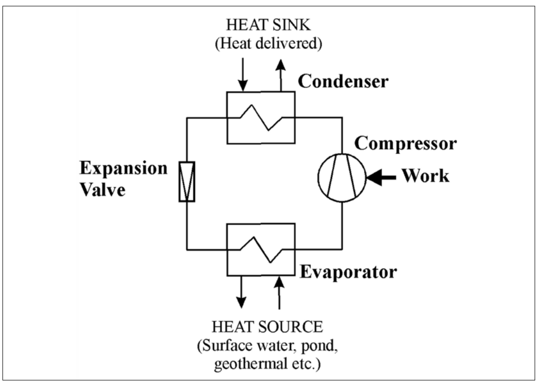

Fig. 1. *Schematics of vapour compression heat pump.*

2.1. The vapour compression heat pump

The water-to-water vapour compression heat pumps are suitable for transferring heat from a lower temperature source to a higher temperature sink **[1] [2]**. This makes them the first choice for low-temperature waste heat recovery systems.

This type of heat pump (**Figure 1**) is suitable for producing domestic hot water using waste heat from water below 40 °C and heating it up to 50-80 °C.

The mathematical model of such a heat pump was developed within the framework of the paper **[3]** so in the following the thermodynamic characteristics of the heat pump will be calculated based on that model.

Figure 2 shows the cycle of a vapour compression heat pump **[4]**. The development of the mathematical model of the vapour compression heat pump is based on this cycle.

2.2. Vapour compression heat pump using R-718 refrigerant

In **Figure 3** ea vapour compression heat pump using R-718 (water vapour) refrigerant is presented **[4]** followed by its cycle in T-s diagram (**Figure 4**).

Common elements can be recognized in both figures, such as the valves (throttle valves are marked FS1 and FS2 in **Figure 3** and the compressor, which is a turbo-compressor labelled with Tk in the case of the heat pump using R-718 refrigerant.

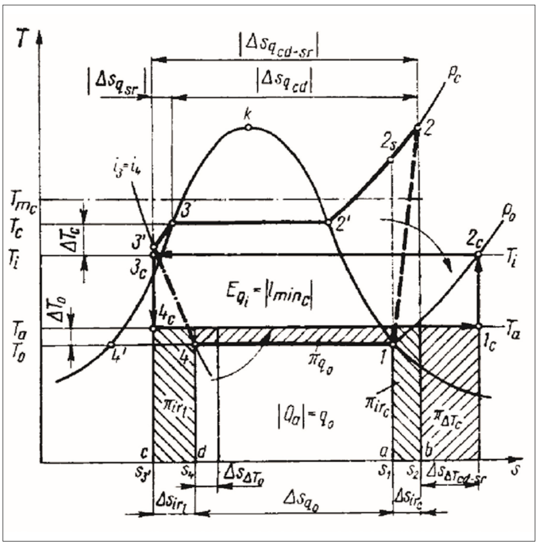

Fig. 2. *Vapour compression heat pump cycle T-s diagram.*

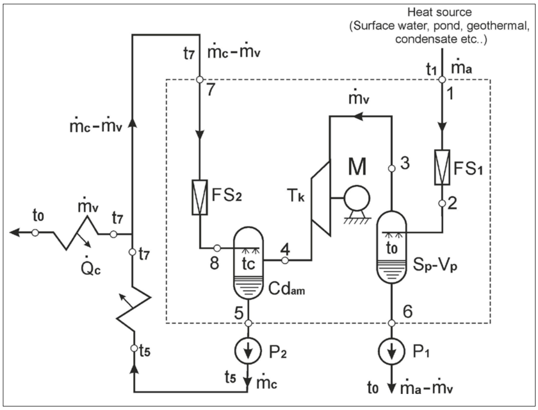

Fig. 3. *Schematics of vapour compression heat pump using water vapour (R-718) as refrigerant.*

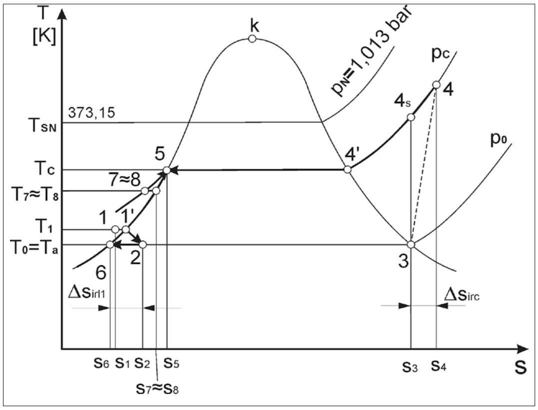

Fig. 4. *Vapour compression heat pump cycle T-s diagram for R-718 refrigerant.*

Due to the refrigerant used, the construction of the second heat pump is much more complicated, and as a result, a few common characteristics were selected for the purpose of comparison, namely: the power required for operation *Pe* [kW], the theoretical μ and actual μ_e coefficient of performance (COP), and the exergy efficiency *ηE*.

3. Efficiency of heat pumps

The mathematical model of the vapour compression heat pump was presented within the framework of paper [3] and based on this, the thermal characteristics of the heat pump assuming that it works with ammonium refrigerant (R-717) and R-134a refrigerant were calculated.

The mathematical model of the heat pump operating with water vapour refrigerant (R-718) can be found in literature [4–6] so in the following, the thermal characteristics of the heat pump based on those models were calculated.

The following assumptions were made in order to perform the calculus:

- *Q* – required heat delivery must be at least the amount of heat absorbed from the heat source *Q* = 30 kW (which is enough to meet the heating needs of a medium-sized household);
- T_i = 55 °C – temperature of delivered hot water;
- T_a – ambient temperature (heat source), which is set to 30, 35 and 40 °C respectively.

In addition, depending on the type of heat pump, we perform the calculations with the following data:

- for vapour compression heat pump:
  - ΔT_c = 10 °C – temperature excess required for heat transfer in condenser (heat delivery);
  - ΔT_0 = 5 °C – temperature drop required for the heat transfer of the evaporator;
  - T_{sr} = 5 °C – temperature drop needed for sub-cooling;
  - refrigerant used R-717 (ammonium) and R-134a;
  - η_{em} = 0,9 – compressor efficiency.
- for the water vapour compression heat pump calculations:
  - temperature of vapour-liquid separator $t_0 = t_a$ = 20, 25, and 30 °C, depending on heat source temperature
  - turbo-compressor internal efficiency η_i = 0,72,
  - mechanical efficiency η_{em} = 0,9.

In **Table 1** the thermal characteristics of the heat pump operating with ammonia (R-717) refrigerant, in **Table 2** the thermal characteristics of heat pump operating with R-134a refrigerant can be found, while **Table 3** presents the thermal characteristics of the heat pump operating with water vapour (R-718).

The data in the tables are presented in **Figures 5–10** in order to highlight the dependencies and to more easily compare the different characteristics of heat pumps operating with three types of refrigerants.

Figure 5 highlights that as the temperature rises, the amount of power required to operate the circuit decreases.

At the same time, it is clear that the heat pump operating with water vapour refrigerant requires less energy to operate the cycle.

The power required to operate the cycle is the largest in the case of the heat pump operating with R-134a refrigerant (**Figure 5**).

Table 1. *Thermal characteristics of a heat pump operating with R-717 refrigerant*

Temperature of heat source, T_a [°C]	30	35	40
Power supplied to the cycle, P_e [kW]	5,03	4,30	3,59
Exergy loss due to irreversibility of compression π_{irc} [%]	9,11	8,57	7,46
Exergy loss due to irreversibility of expansion π_{irl} [%]	5,55	4,90	4,22
Exergy loss due to irreversibility of heat transfer in evaporator π_{q0} [%]	9,43	11,12	13,45
Exergy loss due to irreversibility of heat transfer in condenser $\pi_{\Delta Tc}$ [%]	26,09	29,20	33,82
Theoretical coefficient of performance , COP μ	6,62	7,74	9,29
Actual coefficient of performance, COP μ_e	5,96	6,97	8,36
Exergy efficiency η_E	50,48	47,17	42,47

Table 2. *Thermal characteristics of a heat pump operating with R-134a refrigerant.*

Temperature of heat source, T_a [°C]	30	35	40
Power supplied to the cycle, P_e [kW]	5,54	4,52	3,75
Exergy loss due to irreversibility of compression π_{irc} [%]	12,15	9,21	7,61
Exergy loss due to irreversibility of expansion π_{irl} [%]	15,56	14,58	12,37
Exergy loss due to irreversibility of heat transfer in evaporator π_{q0} [%]	8,40	10,51	12,81
Exergy loss due to irreversibility of heat transfer in condenser $\pi_{\Delta Tc}$ [%]	16,96	21,87	25,35
Theoretical coefficient of performance , COP μ	6,01	7,37	8,89
Actual coefficient of performance, COP μ_e	5,41	6,64	8,01
Exergy efficiency η_E	46,91	43,82	41,86

Table 3. *Thermal characteristics of the heat pump operating with R-718 refrigerant.*

Temperature of heat source, T_a [°C]	30	35	40
Minimum power supplied to the cycle, P_{min} [kW]	2,1	1,64	1,44
Exergy loss due to irreversibility of compression π_{irc} [%]	16,47	17,86	19,34
Exergy loss due to irreversibility of expansion π_{irl} [%]	8,90	10,71	13,11
Exergy loss due to irreversibility of heat transfer in evaporator $\pi_{\Delta Tc}$ [%]	29,91	30,30	31,67
Theoretical coefficient of performance, COP μ	6,37	7,51	9,1
Actual coefficient of performance, COP μ_e	5,62	6,60	7,95
Exergy efficiency, ηE	44,63	41,13	35,87

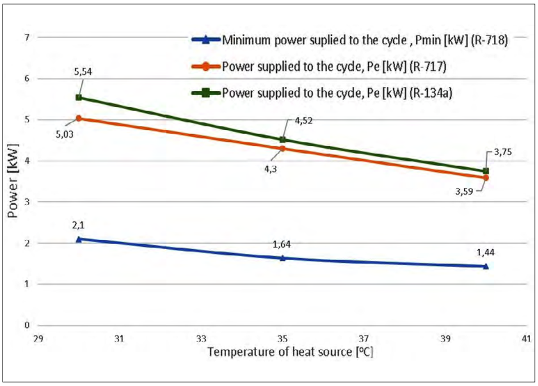

Fig. 5. *Power supplied to the cycle.*

Figure 6 shows that there is the same dependence between the temperature of the heat source and the exergy efficiency as in the case of the supplied power, namely as the temperature rises, the exergy efficiency decreases.

From this point of view as well, the heat pump operating with ammonia (R-717) refrigerant performs better, the exergy efficiency is higher in all cases, while in the case of R-134a refrigerant it is located between the two, but at high heat source temperatures it is almost equal to the exergy efficiency of ammonia refrigerant.

The most important thermal characteristics of a heat pump is the theoretical coefficient of performance (COP) µ and the actual coefficient of performance, μ_e.

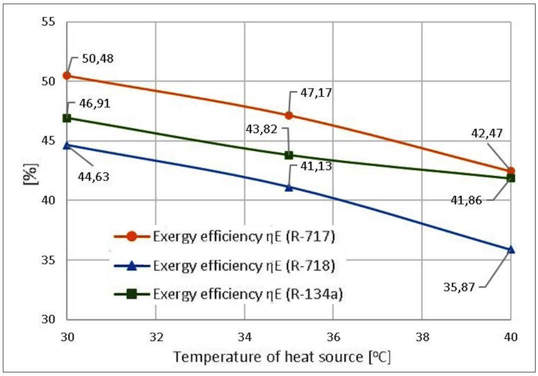

Fig. 6. *Exergy efficiency.*

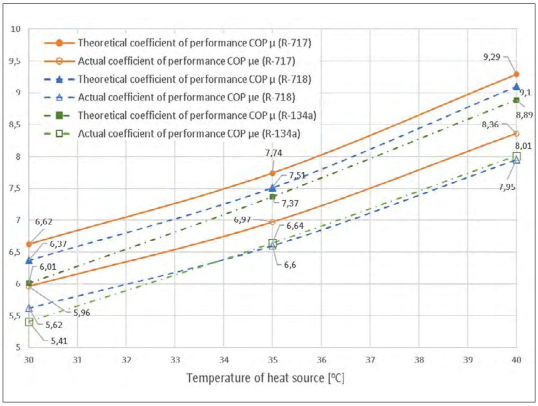

Fig. 7. *Theoretical and actual coefficient of performance (COP).*

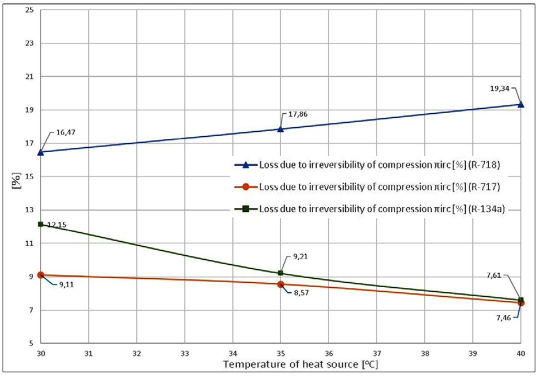

Fig. 8. *Exergy loss due to irreversibility of compression π_{irc}.*

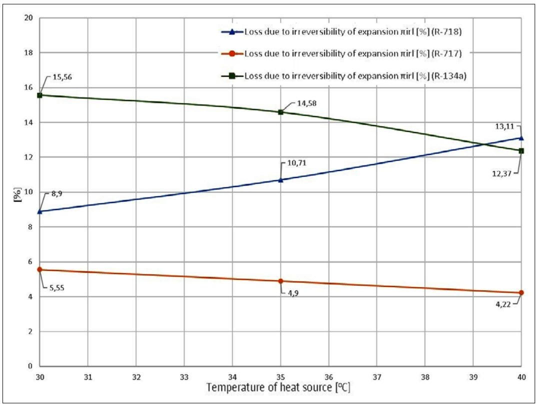

Fig. 9. *Exergy loss due to irreversibility of expansion π_{irl}.*

Figure 7 presents the variation of the theoretical COP μ and the actual COP μ_e as a function of the temperature of the heat source.

In case of the use of the three types of refrigerants, as the temperature of the heat source increases, the theoretical performance factor μ and the actual performance factor μe also increases.

As presented in **Figure 7** the theoretical performance factor is the highest for ammonia (R-717), followed by water vapour (R-718) and R-134a. In terms of actual performance, at higher heat source temperatures, R-134a has a better performance than R-718 refrigerant (water vapour).

Figures 8., **9.** and **10** highlight the following exergy losses: the exergy loss due to the irreversibility of the compression process π_{irc} [%], the exergy loss in the throttle and expansion valve π_{irl} [%], the exergy loss in the condenser due to the irreversibility of the heat transfer process $\pi\Delta T_c$ [%].

The exergy efficiency diagram presented in Figure 6 allows us to conclude that the ratio of losses remains the same, so the largest exergy losses will occur in the case of the heat pump operating with water vapor (R-718) refrigerant, followed by the heat pump operating with R-134a refrigerant, while in the case of the heat pump operating with ammonia (R-717) refrigerant the smallest exergy losses are expected.

This is also the case in **Figure 8** where the exergy loss due to the irreversible nature of the compression process π_{irc} is presented.

Value of exergy loss due to the irreversibility of the compression process π_{irc}, is the highest in the case of water vapor (R-718) refrigerant and increases with the temperature of the heat source, while it decreases in the case of R-717 and R-134a.

It should be noted that the construction of a heat pump using water vapor is much more complicated due to the refrigerant used, so only the losses that occur in each case are shown.

In **Figure 9** the order of magnitude of the losses due to irreversibility of expansion π_{irl} rises with

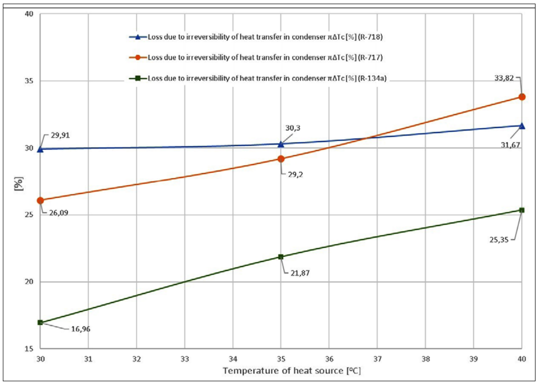

Fig. 10. *Exergy loss due to irreversibility of heat transfer in condenser, $\pi\Delta T_c$.*

the temperature of the heat source, for R-718 refrigerant, while for R-717 and R-134a decreases.

The schematics of the vapour compression heat pump using water vapour (R-718) as refrigerant shows there are two throttle valves.

This can lead to the conclusion that losses due to irreversibility of expansion have to be greater that one in the case of the heat pump using R-717 or R-134a refrigerant. But in **Figure 9**, it can be seen that only at high heat source temperatures, exergy loss due to irreversibility of expansion π_{irl} is higher. Correlating these with data in **Figure 5** where the power required to operate the cycle can be found, the conclusion is that the lower value of the loss due to irreversibility of expansion occurs due to the lower flow rate of refrigerant passing through the valves, when using R-718 refrigerant. The nature of variation shows that this loss is directly proportional to the temperature of the heat source.

In **Figure 10** exergy loss due to irreversibility of heat transfer in condenser, $\pi_{\Delta Tc}$ is presented.

Exergy loss due to irreversibility of heat transfer in condenser $\pi_{\Delta Tc}$ mrises for all types of refrigerants used.

For lower temperatures of heat source exergy loss due to irreversibility of heat transfer in condenser $\pi_{\Delta Tc}$ is higher for R-718 refrigerant, while at higher temperatures of heat source this type of loss is higher for R-717 refrigerant, while for R-134a is the lowest in all cases.

4. Conclusions

The thermodynamic characteristics of the heat pump operating with ammonia (R-717) refrigerant are better than the characteristics of the heat pump operating with water vapor (R-717) refrigerant, while the values of characteristics of the heat pump operating with R-134a refrigerant are usually in between.

An exception is the power required for operation of the cycle, which is much smaller in the case of a heat pump working with water vapour (R-718) refrigerant, approximately 2.5 times smaller. Values are: 3.59 kW for the heat pump operating with ammonia (R-717) refrigerant compared to the heat pump operating with water vapour refrigerant, which requires only 1.44 kW.

As for the heat pump working with R-134a refrigerant, the power required for operating the cycle is 3.75 kW.

The theoretical coefficient of performance (COP) μ in the case of the heat pump operating with ammonia refrigerant, according to the heat source temperature of 40 °C is 9.29, while in the case of the heat pump operating with water vapor refrigerant it is 9.1, so it is only 2% higher and is also very close in the case of R-134a, 8.89.

The actual coefficient of performance (COP) μ_e in the case of the heat pump operating with ammonia refrigerant according to the heat source temperature of 40 °C is 8.36, while in the case of the heat pump operating with water vapour refrigerant it is 7.95, which is 5.2% higher, and the value of the actual coefficient of performance for the heat pump working with R-134a refrigerant is 8.01, located between the two values.

These values of the coefficient of performance (COP) show that although the thermodynamic characteristics of the heat pump operating with ammonia refrigerant (R-717) are better, they are not significantly better than in the case of R-134a refrigerant, and in fact, they do not display large differences compared to the results of the water vapor refrigerant (R-718).

If the exergy efficiency is analyzed, the heat pump operating with ammonia refrigerant (R-171) displays better values, followed by R-134a and the R-718 refrigerant being in last place.

According to the heat source temperature of 40 °C the exergy efficiency of the heat pump operating with ammonia refrigerant is η_E=42.47 %, while in the case of the heat pump operating with water vapor refrigerant η_E=35.87 %, 18.4 % higher. In the case of using the modern R-134a refrigerant, this value is η_E=41.86%, which is barely perceptibly lower than the R-717 value.

The differences between the values (the actual coefficient of performance μ_e and exergy efficiency η_E) especially between R-718 and the other refrigerants, are higher than the tolerable margin of error for the preparation of the energy balance, which is 3% **[7]**, so they cannot be ignored.

There is one last comparison criterion left, the effect of the refrigerant on the environment.

From this point of view, the heat pump working with water vapour refrigerant (R-718) is by far the best choice, because, in the case of an accident, water vapor is completely neutral from an environmental point of view, while ammonia is particularly harmful being toxic, and moreover, can be explosive.

As for R134a, it is a modern refrigerant with a global warming potential (*GWP*) of 1430 (relative to CO_2) and an ozone depletion potential (*ODP*) of zero **[8]**. It should be mentioned here that although ammonia is toxic and explosive, its global warming potential (*GWP*) is zero and its ozone depletion potential (*ODP*) is also zero **[9]**.

So, in the event that it is necessary to use heat pumps in places where the risk of refrigerant leakage is unacceptable from a work safety regulations point of view, such as underground mines, tunnels, etc. the use of heat pumps with water vapor refrigerant is a perfect solution and does not generate much higher operating costs from an energy usage point of view.

References

[1] Radcenco, V. et. al.: *Processes in Refrigeration Equipment*. Didactică si Pedagogică Pulishing House, Bucharest, 1983, 372–390.

[2] Energy Department of the USA https://www.energy.gov/eere/buildings/downloads/water-source-heat-pumps (accessed on 2022 september 15)

[3] Dosa, I.: *Power Plant Waste Heat Recovery for Household Heating Using Heat Pumps*. Multiscience-XXVIII. microCAD International Multidisciplinary Scientific Conference, Miskolc, 10-11 april 2014, 1–8. https://doi.org/10.13140/rg.2.1.2616.2406

[4] Radcenco, V. et. al.: *Heat Pumps*. Tehnica Publishing House, Bucharest, 1985, 65–211.

[5] Radcenco, V. et. al.: *Refrigeration Installations and Cryogenics: Problems and Applications*. Tehnica Publishing House, Bucuresti, 1987,75–100.

[6] Laza I.: *Refrigeration Plants*. Universitatea Tehnica, Timisoara, 1995,60-125

[7] ***, *Guide to Development and Analysis of Energy Balance*. M.O. of Romania, part. I, nr.792/11.11.2003.

[8] Gasservei SA (accessed on: 2022. september 30.) https://gas-servei.com/shop/docs/technical-data-sheet-r-134a-gas-servei.pdf

[9] Danfoss (accessed on: 2022. september 30.) https://www.danfoss.com/en/about-danfoss/our-businesses/cooling/refrigerants-and-energy-efficiency/refrigerants-for-lowering-the-gwp/ammonia-nh3/