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Specific conditions for an optimal operation of air-water heat pumps

Condiții specifice pentru o funcționare optimă a pompelor de căldură aer-apă

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Abstract. The paper presents conditions required for an optimal operation of air-water heat pumps used for space heating and cooling. Designing such an installation able to reduce the greenhouse gas, *GHG* emission involve a prerequisite envelope improvement: its thermal performance is in a correlation with the seasonal performance factor, *SPF* resulting from the climatic conditions and from the heat pump setting having the primary energy factor, *PEF* together with the specific emission index for electricity generation, I_e as influencing factors. At the same time, the type of the fuel, (gas, coal, etc.) i.e., its *GHG* emission intensity, I_f and the efficiency, η_c of the original boiler that is to be replaced with the heat pump are important when analyzing the performance that can be achieved after this replacing. For air-water heat pumps an operation under the air temperature of +7 ºC seems to be not advisable from the efficiency and from the power consumption point of view.

Key words: air-water heat pumps

1. Introduction

Climate change, the result of global warming is evident by the increasingly frequent excessive phenomena: this increase of the global temperature is caused by the greenhouse gas emissions, *GHG* the main factor being carbon dioxide, CO_2. Energy "hunger", visible on a global scale, is an effect of the economy development: it requires an energy conversion, traditionally obtained through the burning process of fossil fuels.

Studies and research concerning the *GHG* emission from fossil fuels burning have been carried out in Europe and around the world having in mind that internal combustion engines and equipment used to provide thermal comfort in buildings are based on such burning processes. In Europe and beyond, buildings are the main energy consumer, i.e., about 40 per cent of the total energy is used by the building sector, being responsible of approx. 36 per cent of the CO_2 emission. Therefore, limiting the increase of the global temperature to 1.5 ^oC, set out in 2015 by the Paris Agreement, at COP21, in order to avoid a worsening of the effects due to climate change, involves an annual reduction of *GHG* emissions by 7.6% by 2030. It must be noted that global efforts to achieve this goal have so far proved insufficient. Decarbonization - including measures to reduce *GHG* emissions, aims to reduce and limit global temperature rise. Recently, on 14 July 2021, the European Commission proposed a package of measures on climate, energy, land use, transport and taxation policies to transform the EU economy and society in order to achieve climate ambitions, entitled *European Green Deal*: these policies aim to reduce net greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels. This will facilitate the necessary acceleration of measures aimed at reducing *GHG* emissions in the next decade by combining policies such as the application of emissions trading in new sectors with the tightening of the existing emissions trading system in the EU, along with an increased use of renewable energy sources and together with an improved energy efficiency, etc.

In fact, the UN Summit "COP 26" on climate change held in Glasgow, in the autumn of 2021 took into account the fact that "it is necessary for every company, every financial firm, every bank, insurer and investor to change in order to achieve our climate goals". This implies a wide financial mobilization: "we all have a role to play in combating climate change", the involvement of cities, regions, companies, investors and universities is needed. Achieving the proposed target i.e., limiting the increase in global temperature to 1.5 ^oC - implies an annual decrease in fossil fuel production of 6% for the current decade, while increasing the contribution of renewable energy. While 91% of the electricity currently generated is of solar and wind type (over 80% of new capacities appeared in 2020 were renewable), in the transport and in the space heating sector there has been a much slower progress or even a lack of the this progress.

Achieving climate change targets by the reducing of *GHG* emissions involves a significant change in the way they are heated and cooled. In this context, an increasing number of heating / cooling installation projects based on heat pumps and especially those that use atmospheric air as a source can be noted, given their attractiveness resulting from price, installation effort and commercial promotion.

It is therefore of interest to specify appropriate requirements that can ensure the optimal operation of these installations based on air-to-water heat pumps.

2. Energy performance of the envelope

Until recently it was considered within the EU, that limiting global temperature rise and reducing *GHG* emissions by 40%, respectively, could avoid the disastrous effects of climate change. In order to achieve a climate neutrality by 2050 the European Commission has set an intermediate step for cutting the *GHG*-emissions at least 55% by 2030. This package of proposals was launched mid-summer of 2021 under the name "Fit for 55" [1]. Even so, it has been scientifically proven that this target is still far from the level needed to limit the catastrophic impact specific to a global temperature increase of 1.5 ºC.

The mitigation of *GHG* emissions resulting from the burning of fossil fuels implies a reduction of energy consumption, mainly related to the heating and air conditioning of indoor spaces. This can be done through an improvement of the energy performance of the building envelope: the *energy consumption index* for heating, will be diminished from the current value $\boldsymbol{C_e}$ [kWh_{heat} / (m^2 year)] to a lesser-one, $\boldsymbol{C'_e}$ i.e., $\boldsymbol{C'_e < C_e}$. Increasing the energy performance of the envelope paves the way for the replacement of equipment based on the burning of fossil fuels, such as the boiler, with alternatives such as the heat pump. Considering the level of CO_2 emissions [$kgCO_2/(m^2$ year)] in case of a boiler $\boldsymbol{E_{GHG}^{boiler}}$ and that of the heat pump $\boldsymbol{E_{GHG}^{hp}}$ the *relative reduction of GHG emissions compared to 1990*, $\boldsymbol{RRE_{GHG}^{1990}}$ is,

$$RRE_{GHG}^{1990} = \frac{E_{GHG}^{boiler} - E_{GHG}^{hp}}{E_{GHG}^{boiler}} \tag{1}$$

The *GHG emission level intensity* of the boiler $\boldsymbol{E_{GHG}^{boiler}}$ depends on the *energy consumption index for heating* $\boldsymbol{C_e}$ and on *CO_2 emissions factor* specific for the fossil fuel used by the boiler, $\boldsymbol{I_f}$ [g $CO_{2\ eq}/kWh_{heat}$], and on the *efficiency of the boiler,* $\boldsymbol{\eta_b}$

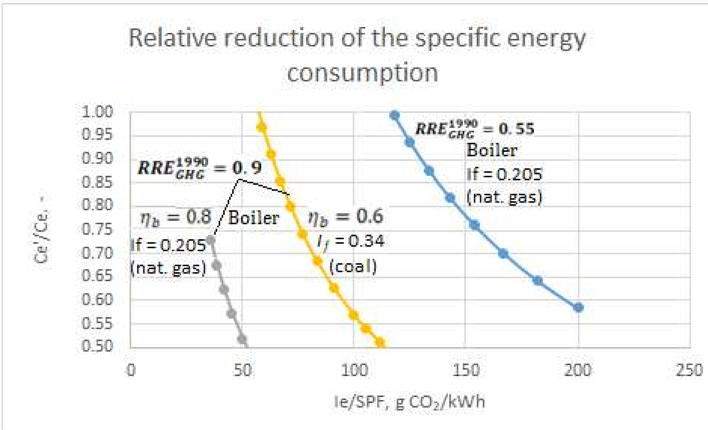
$$E_{GHG}^{boiler} = \frac{C_e}{\eta_b} I_f \tag{2}$$

In case of the heat pump the *GHG emission level* $\boldsymbol{E_{GHG}^{hp}}$ is related to the *energy consumption index for heating* the space having an improved energy performance of the envelope $\boldsymbol{C'_e}$ and to the *GHG emission intensity of electricity generation* $\boldsymbol{I_e}$ [g $CO_{2\ eq}/kWh_{el}$], and to the *seasonal performance factor SPF* of the heat pump

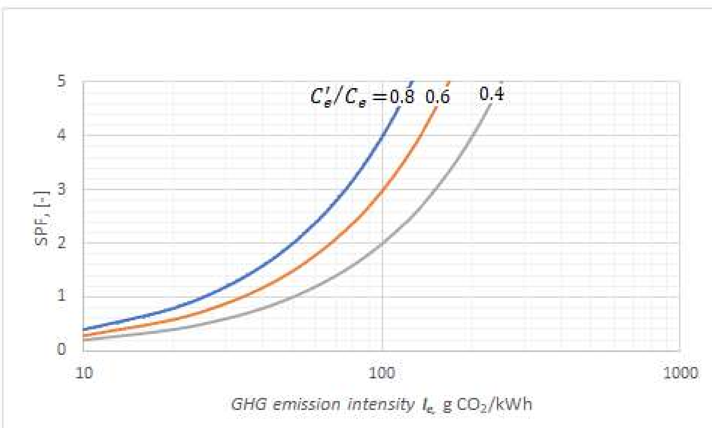
$$E_{GHG}^{hp} = \frac{C'_e}{SPF} I_e \tag{3}$$

Combining (1) with (2} and {3) a *relative reduction of the specific energy consumption* $\boldsymbol{C'_e / C_e}$ can be derived in correlation with characteristic elements of the boiler $\frac{I_f}{\eta_b}$ and that one's of the heat pump $\frac{I_e}{SPF}$, and with the relative emission reductions $\boldsymbol{RRE_{GHG}^{1990}}$

$$\frac{C_e'}{C_e} = \left(1 - \boldsymbol{RRE_{GHG}^{1990}}\right) \frac{I_f}{\eta_b} \frac{SPF}{I_e} \quad (4)$$



1.a. The relative reduction of the specific energy use of a building as a function the heat pump characteristic elements, and having the boiler characteristic elements as paramethers.



1.b. The seasonal performance factor of a heat pump necessary to be achieved for the 2050 condition depending on GHG emission intensity and on the relative reduction of the specific energy use as a paramether.

This correlation, presented in Figure 1a, shows that the target established through the project "Fit for 55" is feasible for the period until 2030 even if a 80%-efficiency, natural gas-boiler is to be replaced by a heat pump working with a ***SPF* > 2,5** when the electricity used for its electromotor is generated with a *GHG emission intensity* $\boldsymbol{I_e}$ **< 500 g $\mathbf{CO_2}$/kWh** ($I_e/SPF \leq 200$). In this situation a minimum 40 % relative reduction of the energy consumption resulting from an improvement of the building envelope is necessary: it corresponds to $\boldsymbol{C_e'/C_e} \geq 0{,}6$, that is a common situation.

On the other hand, under the conditions provided for 2050, as shown in Figure 1b, a relative emission reduction of $\boldsymbol{RRE_{GHG}^{1990} = 0.9}$ needs a heat pump working with a ***SPF*>3** when the supplied electricity was generated with a *GHG emission intensity* $\boldsymbol{I_e}$ **≤ 150 g $\mathbf{CO_2}$/kWh**, (I_e/SPF≤50): in such a situation the envelope must be insulated and sealed to get an improvement of 50% or higher for the *relative reduction of the specific energy consumption,* $\boldsymbol{C_e'/C_e \geq 0.5}$.

3. Electricity as a CO_2 generator

Usually heat pumps and those used in the residential sector are driven by electromotors i.e., electricity is required for their operation, resulting in *GHG* emission, as any technology used for the generation is responsible for this emission. In case of fossil-fueled generation the carbon footprint is higher than that of a renewable and nuclear process: *GHG* is produced in traditional electricity generation during the power plant operation, and not upstream of operation, i.e., during the construction phase of the plant, being an indirect emission. As a result, the *GHG emission intensity of electricity generation* $\boldsymbol{I_e}$ is a country- characteristic, as shown in Figure 2. It can be noted, that while in Scandinavian countries the values for the *GHG* emission are very low, under

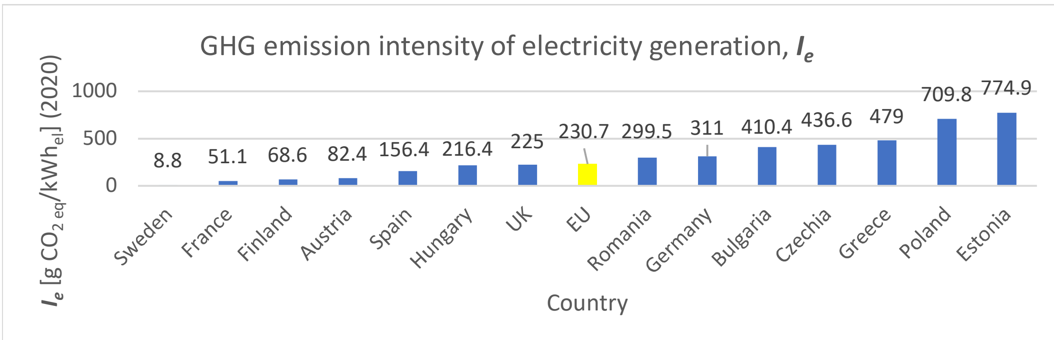


Fig.2. GHG emission intensity of electricity generation, I_e by country, in EU, 2020 [3]

50 g CO_2 -eq/kWh (even under 10, specific for hydroelectric, wind and nuclear) in the Central European area higher values of approx. 500 g CO_2 -eq/kWh (or even more) are still current (specific for natural gas and coal).

The general trend of the *GHG emission intensity of electricity generation* $\boldsymbol{I_e}$ is a downward one, and for 2030 the indicative level in EU is forecasted to be in the range of 110 to 118 g CO_2 -eq/kWh, as shown in Figure 3.

Reducing the *GHG* emission depends on the paradigm change, meaning a replacement of the traditional fossil-fuel based technologies with renewable-ones, as the solar-one release about 20 times less *GHG* than those coal-fired.

Beyond the generation of electricity and the associated *GHG* emission, it is necessary to consider its transport and distribution with the accompanying losses. The

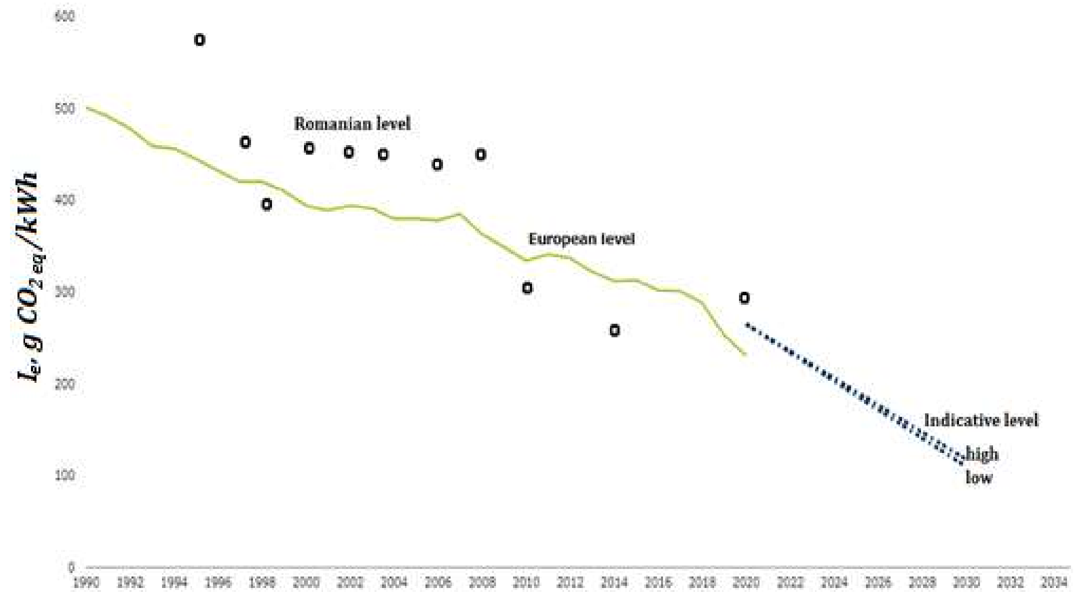


Fig.3. The progress of *GHG emission intensity of electricity generation, I_e* for the last three decades in EU, and with the 2030-prevision. Some values for Romania are indicated too [3].

Primary Energy Factor, PEF is defined as the raw primary energy required to provide for the electricity generation divided by the delivered electricity. *PEF* takes into account energy losses occurred during its production, transport and distribution. The efficiency of the entire process, η_{tot} is the reverse of the *PEF*

$$\eta_{tot} = 1/PEF \quad [5]$$

EUROSTAT has established for the EU a value of *PEF* = 2.5, which correspond to $\eta_{tot} = 0.40$. Recently, as the share of renewable energy sources *RES* has increased from 14,8% in 2005 to 30% in 2017 and a value of 49% being predicted for 2030, a lower *PEF* value was proposed. A detailed analysis carried out by COGEN Europe says that the revised value of *PEF* to be used in the framework of the Energy Efficiency Directive, *EED* for the period post 2020 should not be lower than **2.3** [3], leading to a mean efficiency of the power system of $\eta_{tot} = \mathbf{0.43}$. In fact, for the period 2018 - 2050 a linear increase of the efficiency is foreseen, so that at the end of this interval it reaches the value of $\eta_{tot}^{2050} = \mathbf{0.45}$ corresponding to a *PEF* = **2.22**.

4. Operating performance of the heat pump

The *seasonal performance factor, SPF* as the operating performance indicator of a heat pump working in a heating system is defined as the ratio of the total heat supplied to a building to the electricity used by the electromotor driving the compressor of this equipment, both of the energy amounts evaluated for the whole season. Considering the ANNEX VII from the DIRECTIVE 2009/28/EC [4], "Only heat pumps for which

$$SPF > 1,15 * 1/\eta \quad [6]$$

shall be taken into account in case of aerothermal, geothermal or hydrothermal heat pumps". The mean efficiency, η is calculated as an EU average based on Eurostat data, i.e., the ratio between total gross production of electricity and the primary energy consumption for electricity production. For the period post 2020 having a mean efficiency of the power system $\eta = \mathbf{0.43}$ a limit value for the seasonal performance factor *SPF* results: ***SPF*** **>2.65** as shown in Figure 4. This means that values of *SPF* from the red area are not accepted for an optimal heat pump operation.

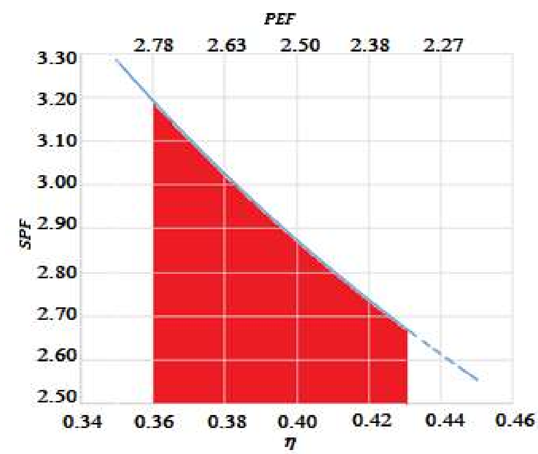


Fig.4. The correlation established by ANNEX VII, DIRECTIVE 2009/28/EC [4] between the seasonal performance factor *SPF* and the mean efficiency of the power system, η

SPF being a global indicator for the entire heating season do not reflect the influence of the momentary operating factors like the temperature of the source and that of the heated water supplied to the building by the heat pump. The *carnot coefficient of performance*, COP_{canot} is defined by these temperatures, that of the source - air in this case, T_{air} and that of the water supplied by the heat pump, T_w

$$COP_{carnot} = \frac{T_w}{T_w - T_{air}} \quad [7]$$

Higher values of COP_{canot} are possible only in cases when the temperature of water supplied by the heat pump is kept as close as possible to the source temperature, i.e., that of the air, as shown in Figure 5.

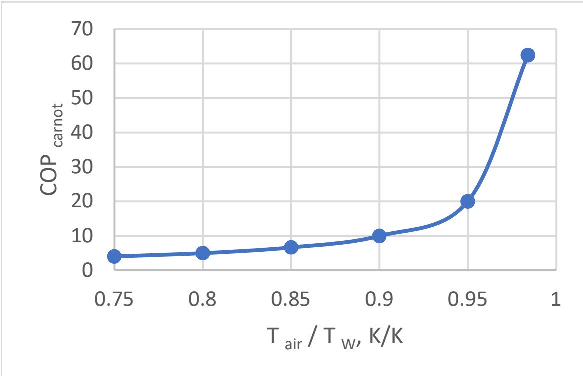


Fig.5. COP_{carnot} as a function of the temperatures ratio, the source one, T_{air} and water one, supplied by the heat pump, T_w.

The actual values of the coefficient of performance COP_{actual} are calculated as the ratio of the thermal power, P_{th} supplied by the heat pump and the electric power, P_{el} absorbed by its electromotor

$$COP_{actual} = \frac{P_{th}}{P_{el}} \quad [8]$$

In practice it is found that COP_{actual} is considerably smaller than the corresponding COP_{canot}

$$COP_{actual} < COP_{carnot} \quad [9]$$

This is due to the losses caused by the constructive-technological and operational factors that are described by the *exergetical coefficient of performance,* COP_{ex}

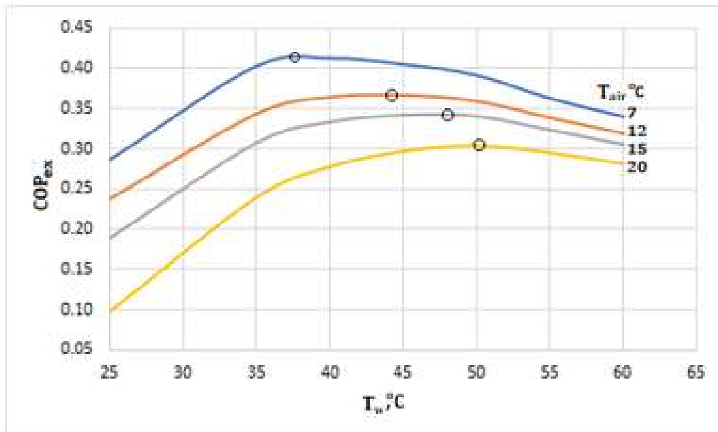
$$COP_{actual} = COP_{carnot} \cdot COP_{ex} \quad [10]$$

Usually, $COP_{ex}< 0.7$ and for heat pump capacity smaller than 20 kW, $COP_{ex} \approx 0.3 \ldots 0.5$, depending on the operating mode. Figure 6 shows the influence of the temperature of the water exiting the heat pump, T_w on the *exergetical coefficient of performance,* COP_{ex}, having as a parameter the temperature of the air at the entrance of the heat pump, T_{air}, for an equipment currently existing on the market. It is important to note that losses increase as the temperature of the air as a source rise from 7 ºC to 20 ºC, leading to a decrease of the maxCOP_{ex} from 0.41 to 0.30, as shown in Figure 6a. Similarly, when the air-temperature decrease from -7 ºC to -20 ºC a lowering of the maxCOP_{ex} from approx. 0.35 to 0.29 can be observed in Figure 6b. But even in the temperature range of +7 ºC…-7 ºC a diminution of maxCOP_{ex}, from 0.41 to 0.31 takes place, with the lowest values corresponding to a temperature close to 0 ºC.

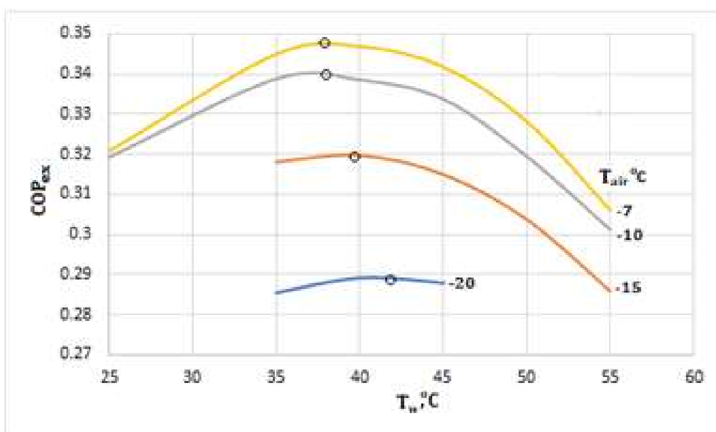
Improving the performance of a heat pump is an important step to win users / customers while choosing an equipment. That is why manufacturers assist air-source heat pumps with an electrical resistor to compensate the heat in case of low air-temperature. At the same time, controlling the flow of the thermal agent in the heat pump circuit by means of an inverter is able to adapt the heat supplied by the equipment to the heat use of the building.

Specific conditions for an optimal operation of air-water heat pumps

An optimal operation of air-source heat pumps will avoid air- temperature close to 0 °C in order to prevent water condensate, or even snow/ice deposit on the evaporator, as the heat transfer from the air to the thermal agent of heat pump is more difficult resulting in a supplementary cost. Data resulted from tests show that the maximal values of COP_{carnot} and COP_{ex} correspond to water temperature supplied by the heat pump in the range of 40 °C.



a)



b)

Fig.6. The influence of the hot water temperature at the exit of the heat pump, T_w on the exergetic efficiency of the heat pump, COP_{ex}, with the air temperature at the entrance to the equipment, T_{air} as a parameter.

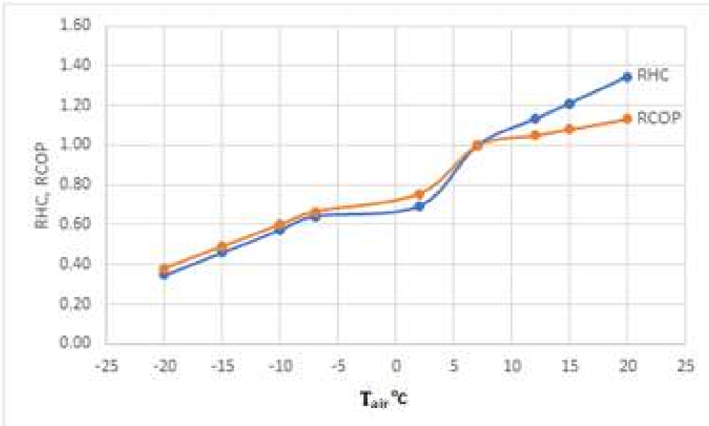


Fig.7. The relative heating capacity, *RHC* and the relative efficiency, *RCOP* on the air temperature T_{air}.

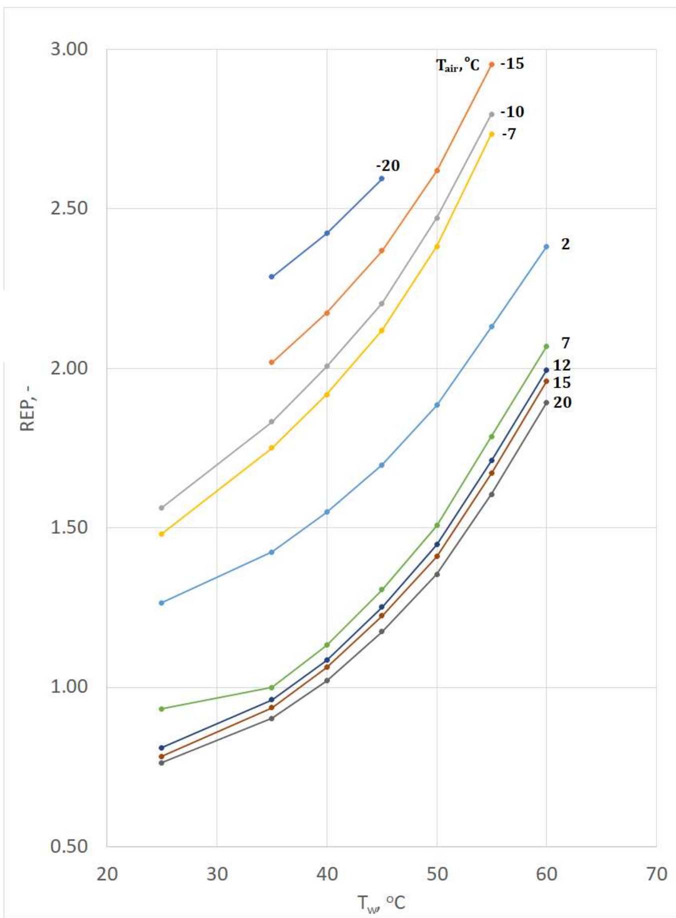


Fig.8. The relative electric power, *REP* correlated with the water temperature supplied by the heat pump and having the air temperature T_{air} as a parameter.

Moreover, air temperature under +7 ºC will cause besides a lowering of the *COP* a significant reduction in heating capacity. To estimate such effects, it is useful to compare the heating capacity with that specific for +7 ºC air temperature, the so-called *relative heating capacity, RHC*. Similarly, can be defined the *relative electric power, REP* and the *relative COP, RCOP*. Figure 7 shows the relative characteristics, *RHC* and *RCOP* resulted from specifications presented by data books of heat pumps currently existing on the market. It can be noticed, the most unfavorable air temperature interval, especially for *RHC* and *RCOP* decline, being between +7 ºC and +2 ºC, so that at +2 ºC *RHC* is diminished to 0.7 or *RCOP* to 0.8 compared to unity existing at +7 ºC. This trend continues when the air temperature drops, so at -20 ºC *RHC* and *RCOP* become almost one third of that measured at +7 ºC.

The analysis of data resulted from tests concerning the *relative electric power*, *REP* presented in Figure 8, shows that air temperatures over +7 °C will have a small influence, i.e., a reduction of *REP* from 10 to 20 %. However, the required temperature of the water delivered by the heat pump is of greater importance: when raising it from 35…40 °C to 60 °C this will double the electric power (the *REP* is becoming 2 instead of approx. 1). But when the air temperature drops from +7 °C to -15 °C or even -20 °C a significant increase in *REP* will result, i.e., 150 % to 200 %, and even more, if the water temperature is in the range of 35…40 °C. This increase in *REP* values will reach 300 % in case of a required water-temperature T_w of 60 °C.

5. Conclusions

Mitigation of *GHG* emissions aimed at limiting them in order to avoid the devastating effects of global warming requires urgent enforcement measures. Carbon dioxide, the main cause of global warming, is the result of fossil fuel combustion processes requiring the replacement of heating equipment based on this principle.

In this context, the heat pump can be an attractive solution, and the air-water variant is often presented as a "miraculous" answer, especially in the conditions of a partial knowledge of the specific operating conditions. Mitigation the *GHG* emissions with 55% by 2030 and at least with 90% by 2050 are landmarks for the limitation of the global temperature raise at 1.5 °C. The evaluations presented in the paper highlighted the need to reduce the specific energy use, primarily due to the improvement of the energy performance of the building envelope: reducing specific energy / heat use by 30% ... 50% is a feasible goal with current technologies and materials. Under these conditions, replacing a boiler based on fossil fuels (coal, liquid fuel, or natural gas) with an electrically operated heat pump can easily meet the condition of 55% reduction in GHG emissions if its operation is characterized by *SP*F> 2.5 and if the electric power used by its electric motor is generated under a specific emission index $I_e < 0.5$ kg CO_2 / kWh. However, the 90% reduction in *GHG* emissions set for 2050 imposes stricter conditions for both the heat pump, namely SPF>3 simultaneously with the thermal insulation measures of the building envelope that must be able to reduce the specific energy / heat use by about 50%. At the same time, it is necessary that the specific emission index for electricity generation be within the limit of I_e<0.150 kg CO_2 / kWh, which leads to national / European efforts to gradually replace traditional electricity generation with those based on renewable energy systems - photovoltaic, *PV* and wind. Romania is in the average area with 0.271 kg CO_2 / kWh compared to the Scandinavian countries emitting below 0.050 kg CO_2 / kWh, and the Central European ones exceeding 0.400 kg CO_2 / kWh, respectively. The efforts of EU countries to replace fossil fuels with renewable energy sources for electricity generation aim for a share of 49% by 2030. At the same time, for the year 2050, an efficiency of the entire process - production, transport and distribution of electricity is expected to achieve a value of $\eta_{tot}^{2050} = 45\%$, compared to the current value, which is currently about 36% in Romania.

With regard to the operation performance of the heat pump, Annex VII of the RES Directive, Directive 2009/28 / EC requires that "*Only heat pumps for which SPF > 1,15 * 1/η shall be taken into account*", which leads to values of SPF_{HP} >2,56. In addition to this condition, the losses that occur in the operating cycle of the heat pump and which are expressed with the help of COP_{ex} must also be taken into account. As shown by means of the characteristics extracted from data book of an equipment currently existing on the market, the lowest losses correspond to maximal values of the exergetical *COP*. For the analyzed case, maxCOP_{ex} = 0,41 and it occurs at an atmospheric air temperature of approximately T_{air} = +7 ºC and for a water-temperature at the outlet of the heat pump of T_w =37 ºC. But when the atmospheric air-temperature decreases below T_{air} = +7 ºC a higher energy loss appears which is manifested by the decrease of the exergetical *COP*, so that maxCOP_{ex} = 0.29, even in the case of the support provided by an auxiliary electrical resistance.

The increase in energy losses can be seen even at atmospheric air-temperatures exceeding the value of +7 ºC.

It is also important to note that the *relative electrical power* driving the electric motor is adversely affected by atmospheric air-temperatures below +7 ºC, meaning that the price of heat is rising and the associated CO_2 emitted in case of traditional generation of electricity is increased too.

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