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Structure and Environment 2021, vol. 13, (2), pp. 59-64, Article number: el 007
https://doi.org/10.30540/sae-2021-007

Structure and Environment
ISSN 2081-1500
e-ISSN 2657-6902
https://content.sciendo.com/sae
https://www.sae.tu.kielce.pl

sciendo

Kielce University of Technology

DOI: 10.30540/sae-2021-007

ANALYSIS OF THE CONVERSION OF PRIMARY ENERGY INTO HEAT FOCUSED ON A HEAT PUMP WITH A WORKING SUBSTANCE (REFRIGERANT) CO_2

ANALIZA KONWERSJI ENERGII PIERWOTNEJ W CIEPŁO PRZY ZASTOSOWANIU POMPY CIEPŁA Z CO_2 JAKO CZYNNIKIEM ROBOCZYM (CHŁODNICZYM)

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Abstract

The need for research in the field of energy efficiency and the ecological aspects of primary energy use is currently receiving considerable attention in the framework of European Union policy as well as in the Slovak Republic. It is necessary to deal with this issue not only for the needs of normal operations, but especially in the current situation, when due to the threat of the COVID-19 virus, the requirements for thermal energy are increased. A suitable way to achieve this is the use of renewable resources, in Slovakia mainly biomass, solar, wind, water and geothermal energy. Ambient air, ground heat, heat contained in groundwater and various other waste heat from technological processes represent a huge potential for the use of low-potential energy. The article is focused on solving the problem of conversion of primary energy into heat using thermodynamic cycles and compressor circulation with working substance (refrigerant) CO_2.

Keywords: primary energy, heat pump, CO_2 refrigerant, energy efficiency, energy demand

Streszczenie

Potrzeba badań w obszarze efektywności energetycznej i ekologicznych aspektów wykorzystania energii pierwotnej skupia obecnie dużo uwagi w ramach polityki Unii Europejskiej, jak również w Republice Słowackiej. Konieczne jest zajęcie się tym problemem nie tylko dla zapewnienia normalnego funkcjonowania, ale szczególnie w obecnej sytuacji, gdy w związku z zagrożeniem wirusem COVID-19 wzrastają wymagania i zapotrzebowanie na energię cieplną. Odpowiednim sposobem na osiągnięcie tego jest wykorzystanie zasobów odnawialnych, na Słowacji głównie biomasy, energii słonecznej, wiatrowej, wodnej i geotermalnej. Powietrze atmosferyczne, ciepło ziemi, ciepło zawarte w wodach gruntowych i różne inne rodzaje ciepła odpadowego z procesów technologicznych stanowią ogromny potencjał wykorzystania energii niskotemperaturowej. W artykule skupiono się na rozwiązaniu problemu konwersji energii pierwotnej na ciepło za pomocą obiegów termodynamicznych sprężarkowych z czynnikiem roboczym (chłodniczym) CO_2.

Słowa kluczowe: energia pierwotna, pompa ciepła, CO_2, czynnik chłodniczy, efektywność energetyczna, zapotrzebowanie na energię

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1. INTRODUCTION

The use of energy in the built environment is one of the most important aspects that will need to be addressed in the near future. About 40% of primary energy in Europe is in the construction industry. In order to achieve the targets of the Kyoto Protocol, energy use in the built environment must change. So far, most of our air conditioning systems have made a significant contribution to global warming. In order to reduce greenhouse gas emissions, it is necessary to introduce large-scale environmentally friendly heating systems. Eco-labeling of such environmentally friendly systems is one way to encourage and guide customers when choosing products.

One of the most promising technologies for reducing greenhouse gas emissions is electric heat pumps. Heat pumps offer an energy-efficient way of providing space heating and domestic hot water. Although the technical know-how of heat pumping technology is well established, it has not yet gained public recognition worldwide. In Europe, a sustainable market has only been introduced in small countries such as Sweden, Switzerland and parts of Austria. As a result of rising oil and electricity prices combined with rising energy taxes and growing environmental problems, the heat pump market has begun to grow across Europe.

The research by Fang Wanga et al. dealt with energy and exergy analysis of working substances (refrigerants) R744/R32 on a heat pump. This study examined the volume heat capacity, condensing pressure, discharge temperature, compression ratio and performance of the R744/R32 refrigerant mixture and was compared with the parameters of the R22 refrigerant under the same conditions. The authors found that R744/R32 refrigerant mixtures have a positive effect on energy efficiency, volumetric heating capacity and discharge temperature in a heat pump. An interesting finding was also that at a certain concentration of mixtures (15/85 by mass) the heat pump system shows better performance and COP and energy efficiency reach a peak value [1].

The study by M. Pitarch et al. was focused on the theoretical analysis of cycles of air-water heat pumps R744 for heating applications up to 80°C. The present study investigated the performance of different transcritical thermodynamic cycles working with CO_2, from a theoretical point of view by means of the commercial software EES (F-Chart Software). The authors found that the use of heat pumps for the production of sanitary hot water has some differences compared to the use of heat pumps for air conditioning; the final water temperature is quite high (60°C), and the water temperature lift is large (50°C), i.e. the difference between the water temperature inlet and outlet in the hot side is high. These two facts make that the use of CO_2 in transcritical conditions has some technical advantages beyond environmental arguments in comparison to the use of HFCs [2].

The research by V. K. Venkatesh et al. was focused on experimental evaluation of heat pump performance using CO_2 as a refrigerant. The authors chose CO_2 refrigerant as a working substance due to it's properties. The experiment was performed for two different condensers by varying mass flow rate and pressure. The authors evaluated various parameters such as COP (Coefficient of Performance), LMTD (Logarithmic Mean Temperature Difference) and outlet water temperature of condenser. The maximum COP and outlet temperature of water got in the experiments are 4.46 and 48°C and it was got for the condenser-2. The CO_2 refrigerant performance shows better efficiency and reduced environmental impact. So, the CO_2 refrigerant is best replacement for globally used artificial refrigerants [3].

These studies focused on the analysis of R744 refrigerant and the performance of transcritical thermodynamic cycles. However, they did not address the factors of primary energy conversion for different energy carriers and their impact on the environment. Based on the findings of the research, it is important to analyze energy sources in terms of their impact on the environment. This analysis will be the subject of this study.

2. PRINCIPLE OF LOW POTENCIAL HEAT RECOVERY AND TRANSFORMATION

The word heat pump is a collective term for a wide range of products using the same working principle. However, there are many different types of heat pumps that are best suited for different applications. Heat pumps are generally divided into different types depending on the heat source and cooler for which they are intended. All types have their own advantages and disadvantages, as well as the impact on the environment. The most important aspects to consider when evaluating different heat sources are; availability, temperature, annual temperature fluctuations and investment costs associated with the choice of heat source.

Ambient air is by far the most common source of heat for heat pump applications worldwide.

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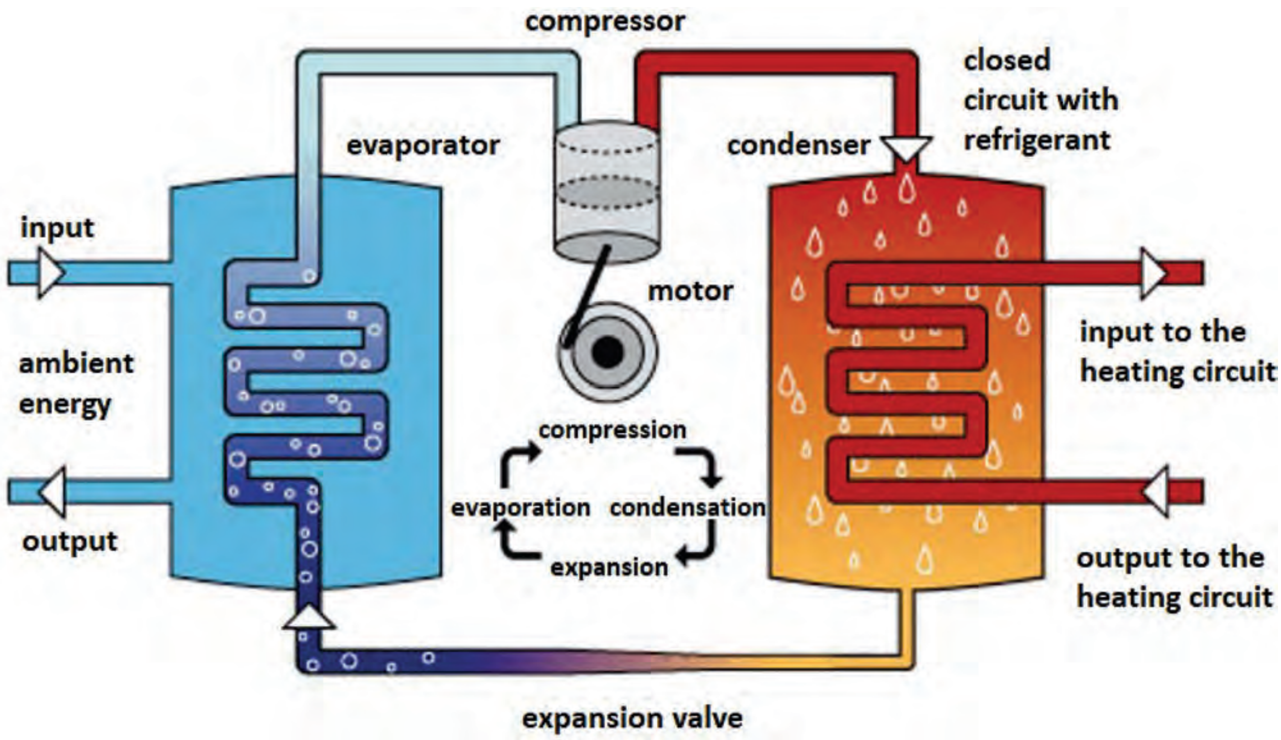

Fig. 1. Air-to-water heat pump principle (own source)

The reason is unlimited availability, which allows uncomplicated and fast installation. In most European climates, the ambient air temperature changes significantly depending on the season. The fact that the output of the heat pump decreases with decreasing temperature of the heat source leads to unfavorable properties. The output of the ambient air heat pump will decrease as the heat demand increases. At some point, the temperature difference between the heat source and the radiator will be large for the heat pump to work at all, and the heat pump must be stopped. For most heat pumps with ambient air, this occurs at temperatures between -15°C and -20°C. In cold climates, this increases the demand for an additional heating system that is designed for the maximum thermal load of the building. Heat pumps are unique in the sense that one and the same appliance is able to provide both heating and cooling. Given that more than 15 000 people died during the 2003 heat wave, cooling space in many parts of Europe is not just a matter of comfort, but a necessity for human well-being. The main number of all heat pumps with air source are designed for dual use, for heating and cooling. Cooling can be achieved by simply reversing the cycle. Small air heat sources sold in the southern part of Europe are mainly used for cooling, while the same unit sold in the northern part of Europe will be used for heating.

The basis of the air-to-water heat pump is a closed circuit filled with refrigerant. The heat pump or cooling circuit has four basic parts:

Evaporator: Low potential heat is supplied to the evaporator by the ambient air. The heat supplied causes the refrigerant to evaporate, the refrigerant vapors become the carrier of thermal energy and are transferred to the compressor. The air flowed through the evaporator by the axial fan or fans is cooled. The air path represents the primary circuit of the heat pump.

Compressor: sucks in steam from the evaporator, compresses it and pushes it into the condenser. The work to drive the compressor is converted into heat, which is added to the heat supplied to the evaporator.

Condenser: the energy supplied to the condenser by the refrigerant vapor from the evaporator and the compressor is transferred to the circulating heating medium (heat pump secondary circuit). The transferred heat heats the heating medium.

Throttle (expansion) valve: liquid refrigerant that has condensed in the condenser at a higher (condensing) pressure is injected into the evaporator to evaporate again at a lower (vaporized) pressure.

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The use of soil as a heat source for heat pumps allows the use of renewable energy stored in the soil or subsoil. The earth serves as a seasonal storage of solar energy. At a depth of 0.9-1.5 m, the amplitude of the temperature change due to changes in the outdoor temperature is damped and delayed. The result is very favorable working conditions for a heat pump that obtains energy from the ground. The heat exchanger can be designed for horizontal installation in the ground or vertical installation. Vertical heat exchangers are most often installed in deep boreholes in the built-in subsoil. Installing horizontal loops is generally cheaper than vertical systems. However, vertical systems require a much smaller area. The ground can additionally serve as a cooler for cooling applications or, as in some systems that are designed for "free cooling", provide comfortable cooling with almost no electrical input. Waste air, groundwater and surface water (such as a lake, river or pond) are other examples of commonly used heat sources.

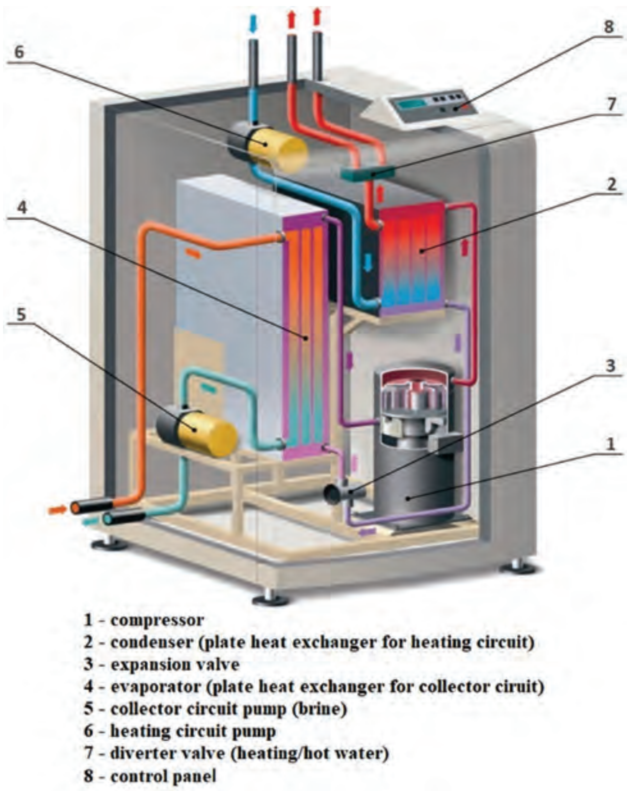

Fig. 2. Ground-water heat pump section (own source)

The overall efficiency of a heat pump system, called the power factor (COP), does not only depend on the efficiency of the system. One and the same appliance will generate completely different annual efficiency factors depending on the temperature levels of the heat source and the heat distribution system. The performance of the unit is tested according to the European standard EN-14511 by accredited testing institutes. The growing interest in this technology has intensified research and development, which has led to significant efficiency gains over the last decade. Compared to a conventional boiler, a highly efficient heat pump system will reduce the use of fossil fuels and reduce hazardous emissions locally. Depending on the production of electricity, emissions occur in operation. However, utility plants generally produce lower emission rates than small domestic furnaces. Indirect emissions from heat pumps both depend on the efficiency of the heat pump system as well as on the efficiency of the electricity generation plant. Emission mitigation is the most significant environmental benefit offered by heat pumps. The range of possible benefits will vary depending on local electricity generation.

3. METHODS FOR ASSESSING THE ENVIRONMENTAL IMPACT OF A HEAT PUMP

However, heat pumps contribute to direct emissions through refrigerant leakage throughout their life cycle. In addition to the leak that occurs during operation, losses will also occur during the demolition of the device. The impact of these losses on the environment will depend on the refrigerant used. The most commonly used refrigerants today are fluorocarbons (HFC). These refrigerants have no ozone depleting potential (ODP), but they contribute to global warming and should therefore be used with caution. Heat pumps have one huge advantage over other types of heating. Heat pump motors (compressors) don't generate all the heat on their own. They only increase the coolant temperature. Most of the heat is taken from the surrounding environment (air, earth, water). The heat pump with natural CO_2 refrigerant (R744) is an ecological alternative to R410A and R32 refrigerants. Fluorocarbon-free climate-friendly technology supports international climate gas commitments. Refrigerant R744 has an ozone depletion potential (ODP) = 0 and a global warming potential (GWP) = 1. CO_2 heat pumps use a compressor that uses R744 refrigerant, which is carbon dioxide (CO_2). Refrigerant R744 (carbon dioxide) used to produce heated and cooling air is a gas that is less harmful to the environment than fluorinated refrigerants.

Environmental assessments of heat pump applications must take into account the indirect

environment

Table 1. Primary energy factors in selected energy carriers (STN EN ISO 52000-1)

Energy carrier	Non-renewable factors PE - $f_{p,nren}$ (Slovak legislation) /STN EN ISO 52000-1	Renewable factors PE - $f_{p,ren}$ (Slovak legislation) /STN EN ISO 52000-1	Factors overall PE - $f_{p,tot}$ /STN EN ISO 52000-1
Natural gas, coal, coke	1.1	0.0	1.1
Wood pellets	0.2	1.0	1.2
Wood chips	0.15	1.0	1.15
Piece wood	0.1	1.0	1.1
Solar, geothermal energy	0	1.0	1.0
Electricity	2.2 / 2.3*	0.2	2.5

* factor $f_{p,nren}$ according to STN EN ISO 52000-1:2017

emissions related to the production of electricity used to operate the heat pump as well as the direct emissions of the refrigerant. Much research has been done on introducing an integrated method for calculating the contribution of greenhouse gas emissions from refrigeration and heat pump applications. The most famous TEWI (Total Equivalent Warming Impact) method was developed at the Oak Ridge National Laboratory in the early 1990s. The TEWI calculation integrates direct and indirect lifetime greenhouse gas emissions into a single number expressed in mass equivalents of CO_2. The TEWI concept is used in the newly developed criteria for the environmental labeling of electrically driven heat pumps within the "Der blaue engel" in Germany [4].

Estimating CO_2 emissions is a basic exercise in assessing environmental behavior. However, there are other measures to compare the performance of the different systems available. The concept of the primary energy ratio (PER) is only the relationship between the useful energy output divided by the required energy input. This value provides a direct value of the overall efficiency of the whole system, taking into account the losses associated with electricity generation. For a conventional combustion plant, the PER value is equal to the total efficiency of the system [1].

4. THE IMPACT OF THE PRIMARY ENERGY NEED ON THE ENERGY CLASS

When analyzing the need for primary energy, it is important to take into account the energy intensity of heat production and transport using the distribution and transformation factor (simply put – the efficiency of converting the energy carrier into heat). So it depends on which heat source we choose – for example, gas condensing has an efficiency of about 105%, a heat pump can have up to 300% (compared to the heat produced consumes only about a third of electricity) [5].

The total energy demand for heating and hot water preparation is divided in the following table based on the Slovak legislation STN EN ISO 52000-1 according to energy carriers (gas, electricity, etc.) and their values are multiplied by the relevant factors. From this, the value of the global indicator, ie primary energy, is obtained. For example, in the case of wood and wood pellets, this factor is close to 0, so that the primary energy requirement is very low. For gas, the primary energy factor is 1.1, for electricity it is 2.2, because its production represents a high environmental burden. Therefore, if you heat with electricity, even with a very low heat demand for heating, you will reach a relatively high value with primary energy [6].

The need for energy for heating and hot water is actually the basis for calculating the cost of operating the house, the primary energy in turn expresses the environmental burden. Although most people look at investing in a heating system mainly through money to run a house and procure technology, the requirement for primary energy must be met by law. If this indicator is not in the required energy class, you will not approve the house. The value of primary energy can be significantly affected by the choice of heat source - even if the total energy demand of the house is in class B, with an ecological heat source (e.g. biomass boiler, heat pump, etc.) the global indicator can get into the right category.

In the case of primary energy, the environmental aspect, i.e. CO_2 emissions, is also taken into account. To put it simply, the energy needed to produce fuel is also taken into account in its calculation. It is essential to classify the house in the energy class according to the value of the global indicator, i.e. primary energy (since January 2021 "A0" energy class is required).

5. CONCLUSIONS

Thanks to the CO_2 refrigerant, the outlet water temperature is adjustable between 60°C and 90°C. While today's best heat pumps can operate at outdoor temperatures of -20°C to -25°C, the R744 models equipped with compressors allow trouble-free operation down to -30°C, at which the heat pump can still reach an outlet temperature of 90°C with a relatively low power drop. Unlike conventional heat pumps, it can be the only source of hot water all year round, so that the produced amount and temperature of water is not reduced at extremely low outdoor temperatures. Carbon dioxide as a heat transfer medium has much better properties than synthetic refrigerants used in pumps. This difference is particularly pronounced in cold climates with a lower outdoor temperature and in hot water supplies with a temperature of around 90°C. CO_2 refrigerant increases energy efficiency compared to traditional pumps, so they can be used even in colder periods and climates. Carbon dioxide heat pumps have a higher energy efficiency than other heat pumps and can also be used in colder climates and periods. CO_2 refrigerant is a natural refrigerant and is the future of refrigeration without HFCS refrigerants.

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Acknowledgements
The research is supported by project 021ŽU-4/2021 "Primary energy conversion into heat/cold using thermodynamic cycles and compressor cycle with working substance (refrigerant) CO_2".