TERMODINAMIČKA OPTIMIZACIJA KASKADNE TOPLOTNE PUMPE

THERMODYNAMIC OPTIMIZATION OF CASCADE HEAT PUMP

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Razvoj industrije i tehnologije u svetu doveo je do povećanja potreba za energijom i sve većeg sagorevanja fosilnih goriva kako bi se te potrebe zadovoljile. Usled brojnih nedostataka i negativnog uticaja na okolinu koje sa sobom nosi sagorevanje fosilnih goriva,obnovljivi izvori nergije a među njima i toplotne pumpe stavljaju se u sve veći fokus kada je u pitanju dobijanje energije za grejanje. U okviru ovog rada izvršena je termodinamička optimizacija kaskadne toplotne pumpe u pogledu kombinacije radnih fluida i maksimizacije koeficijenta grejanja. Radi sprovođenja termodinamičke analize napisan je softverski program koji koristi referentnu bazu podataka radnih medijuma. Prilikom sprovođenja analize varirana je srednja temperatura kaskadnog razmenjivača toplote koja predstavlja ključan parametar pri analizi i projektovanju kaskadnih toplotnih pumpi. Variranjem ove temperature u opsegu od 0ºC do 25ºC određena je optimalna srednja vrednost temperature pri kojoj se ostvaruje maksimalni koeficijent grejanja. Analizirana je toplotna pumpa koja bi služila za grejanje prostora različite namene u predelima Srbije kod kojih spoljna projektna temperatura iznosi do -20ºC. Kaskadna toplotna pumpa bi se koristila u kombinaciji sa radijatorskim sistemom grejanja koji radi u temperaturnom režimu 70ºC/50ºC. Optimizacija je izvršena za kaskadnu toplotnu pumpu vazduh-voda kod koje je temperatura isparavanja iznosila -25ºC, a temperatura kondenzacije 75ºC. Nakon sprovedene optimizacije, izvršena je analiza uticaja stepena dobrote kompresora na koeficijent grejanja.

Ključne reči: *Toplotne pumpe; koeficijent grejanja; radni fluidi; termodinamika; optimizacija*

In today's modern world, development of industry and technology has led to the increase in energy demand. Hence, more fossil fuels are burnt in order to cover this demand. Due to the multiple disadvantages, as well as the negative impact that burning of fossil fuels has on the environment, heat pumps are gaining more importance when providing energy for heating. This paper is aimed at conducting thermodynamic optimization of cascade heat pump in terms of different working fluid combinations and calculating maximum COP. In order to perform thermodynamic analysis, a software program that uses database of working fluids, was developed. The intermediate temperature within cascade heat exchanger represents a crucial parameter when analyzing and designing cascade heat pumps. Thus, when performing thermodynamic analysis, the intermediate temperature was varied in the range from 0ºC to 25ºC and the optimal temperature that provides maximum COP was defined. The analysis was performed on an air-to-water heat pump, that could be used for heating different types of buildings in places in Serbia where the outdoor design temperature is -20ºC. The cascade heat pump would be used alongside radiator heating system operating at temperatures 70ºC/50ºC. Due to the high temperature difference between heat source and heat sink, cascade heat pumps have advantages over single stage or multi stage heat pumps. The optimization was performed on an air-to-water cascade heat pump where the evaporation and condensation temperatures were -25ºC and 75ºC, respectively. Following the conducted optimization, the analysis of the impact that isentropic efficiency of compressor has on COP was examined.

Key words: *Heat pump; COP; working mediums; thermodynamics; optimizations*

1 Introduction

The development of industry and technology has led to an increase in energy demand. Consequently, the use of fossil fuels has increased in order to fulfill that demand. Fossil fuels application when producing energy for heating brings along various disadvantages. Some of the main issues are waste heat, pollution and greenhouse gases' emission. Due to these disadvantages, as well as the growing need for environmental protection, heat pumps are more and more put into focus.

In order to improve energy efficiency of the existing heating systems, i.e. to reduce primary energy consumption and emission of greenhouse gases, high-temperature heat pumps could be applied [1]. These types of heat pumps can operate as a single-stage, double-stage or a cascade heat pump. Traditional heat pumps perform well when combined with the low-temperature heating system, i.e. underfloor heating, low-temperature radiators or fan convection heaters [2]. When single-stage heat pumps are applied, the compression ratio is relatively high when the temperature lift between the heat source and destination exceeds 60ºC [1]. The high value of compression ratio results in low values of isentropic and volumetric efficiency which, consequently, reduces the coefficient of performance (COP) [3]. Hence, when the temperature difference between the heat source and the heat sink is higher, cascade heat pumps could be applied in order to overcome above mentioned disadvantages of single-stage systems. A representative case of this scenario is in high-temperature heating systems where cascade heat pump application represents economically acceptable solution [4] and performs better than double-stage heat pumps [5]. Cascade heat pump can have multiple number of

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cascades, although the most common is the system consisting of two cascades. In principle, conventional cascade heat pump consists of two separate single-stage cycles interconnected by a cascade heat exchanger [6]. These cycles are often referred to as a low stage (LS) cycle and a high stage (HS) cycle of a cascade heat pump. Each stage has a different working fluid that is optimal in the respective temperature range. In that way more suitable selection of working fluids can be performed. Moreover, cascade heat pumps compared to the single-stage heat pumps, are able to provide higher temperatures of the heating medium (e.g. hot water), therefore providing more energy for heating with less losses.

Given the fact that today's world is shifting towards more environmentally friendly solutions, the concept of providing renewable energy and sustainable energy is gaining importance. On one hand, heat pumps present a solution that extracts heat from the renewable energy source (e.g. air, water). While, on the other hand, they are producing sustainable energy since the same input power for heat pump generates much more useful energy compared to a traditional heating system [7]. Even though energy produced by heat pumps is renewable and thus environmentally friendly, it is also crucial to select appropriate working fluids. There are various criteria that could be applied in working fluid selection. However, different directives focused around environmental protection have posed some limitations when certain working fluids are concerned. In that regard, Serbia is one of the countries following guidelines specified within the Vienna Convention and the Montreal Protocol [8]. Hence, the usage of working fluids that have Ozone Depletion Potential (ODP) or a high value of Global Warming Potential (GWP) is limited or restricted. Analysis within this paper included six working fluids, two of which are HFCs (R404A, R410A) while the rest (R7171, R744, R1270, R290) are natural, environmentally friendly fluids.

In 2017, the final energy consumption by households in European Union was 27.2%, while 64.1% of that energy was used for heating [9]. Considering this fact, as well as all previously presented facts within this paper, a conclusion may be drawn that heat pump's application definitely has its potential and they should be widely used.

2 Methodology

Figure 1 presents schematic of a cascade heat pump that consists of two cascades. Low stage cycle is labeled with Arabic numerals, while the high stage cycle is labeled with Roman numerals. It can be observed that each stage includes four main components of a heat pump – a condenser, an expansion valve, an evaporator and a compressor. The connection between stages is established through the cascade heat exchanger that serves as an evaporator for a high stage cycle and as a condenser for a low stage cycle. Furthermore, evaporator of the low stage is connected to a heat source, while the condenser of the high stage has a connection to a heat sink.

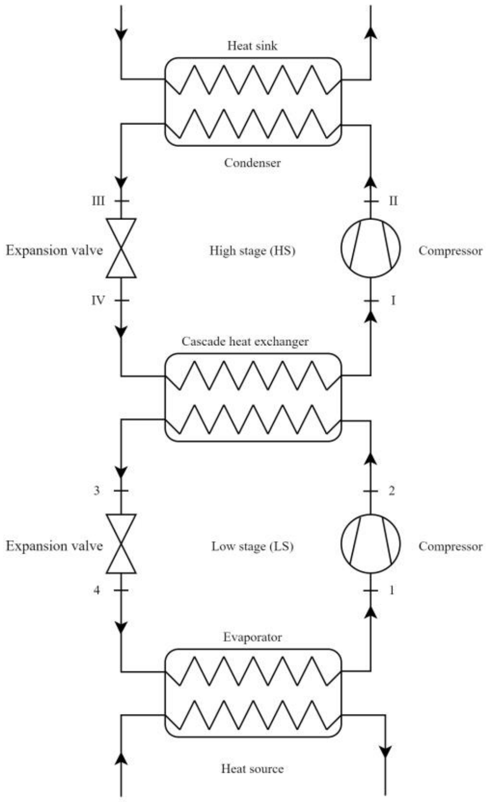

Figure 1 Cascade heat pump schema

Figure 2 presents log*p*-*h* diagram of the cascade heat pump analyzed in this paper. The low stage cycle is presented with the blue color, while the high stage cycle is presented with the red color. The cascade heat pump analyzed in this paper is an air to water heat pump intended to be used in areas with the outdoor air temperature of -20ºC. Places in Serbia that comply to this condition are Sjenica, Kopaonik, Prijepolje, Trstenik, etc. Additionally, the heat pump is used in combination with the radiator heating that operates in 70ºC/50ºC regime. This way, evaporation temperature within the low stage cycle is defined and equals to -25ºC (5ºC lower than outdoor air temperature), as well as condensing temperature within the high stage cycle which equals to 75ºC (5ºC higher than temperature of hot water in the radiator).

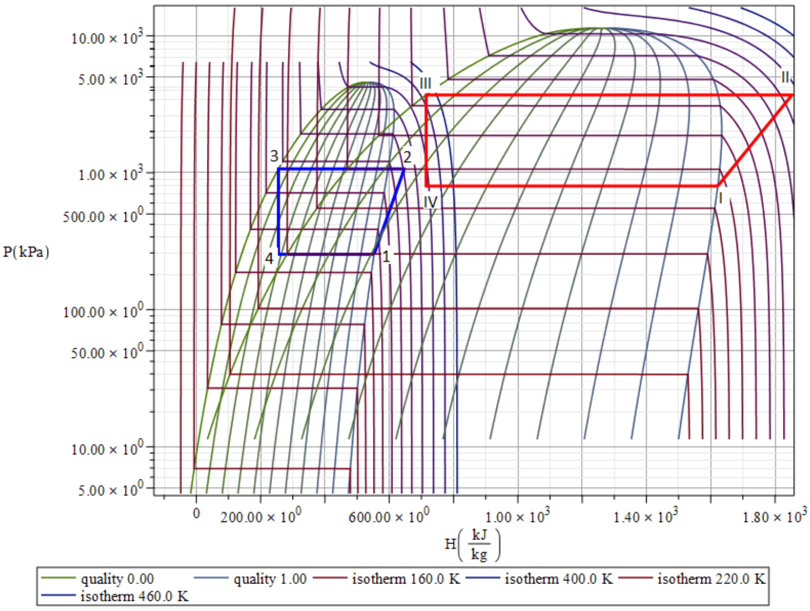

Figure 2 logp-h diagram of a cascade heat pump cycle

Crucial parameters when designing cascade heat pumps are intermediate temperature, temperature difference in the cascade heat exchanger as well as LS evaporating temperature and HS condensing temperature. Moreover, all of these parameters are interconnected and interdependent. In that regard, the optimal intermediate temperature depends on HS evaporating temperature and LS condensing temperature as well as on the temperature difference in the cascade heat exchanger [10]. Thus, this temperature was varied for different fluid combinations in the range from 0ºC to 25ºC and the optimal temperature was determined. The term optimal temperature here refers to the intermediate temperature which provides the maximum value of COP for the given working fluid combination. COP of a cascade heat pump can be calculated as a ratio between useful heat extracted from the condenser and total power consumed in compressors:

$$\mathrm{COP} = \frac{\mathrm{Q}_{Cond}}{\mathrm{P}_{LS} + \mathrm{P}_{HS}} \tag{1}$$

Apart from calculating total COP of a heat pump, COPs for each one of the stages can be determined. It can be observed that COP of a low stage cycle will deteriorate with the increase of intermediate temperature. On the other hand, COP of a high stage cycle will increase along with the increase in value of intermediate temperature.

Moreover, temperature difference in the cascade heat exchanger is set to be 4ºC, while the cascade heat pump capacity was set to 100 kW. The analysis was conducted over six working fluid pairs and those were: R1270-R717, R744-R1270, R744-R717, R744-R290, R404A-R717 и R410A-R717 where the first fluid was used in the low stage and the second one in the high stage cycle.

A software program was written for performing thermodynamic analysis. Additionally, the program uses coefficients from Nasa database and CoolProp library. After determining optimal intermediate temperature, the analysis of the impact that isentropic efficiency of a compressor has on COP was conducted. In this case, isentropic efficiency had the same value for both compressors and was varied in the range from 0.7 to 1. The general data based on which all other parameters were calculated within the algorithm was outdoor air temperature ($t_{ot}=-20^oC$), temperature difference in the cascade heat exchanger ($\Delta t=4^oC$) and temperature of distribution medium used for heating, i.e. hot water temperature ($t_w=70^oC$). Considering the way Arabic and Roman numerals were used when illustrating low stage and high stage cycles in Figure 1 and Figure 2, the algorithm implemented when performing thermodynamic analysis is presented below. Equations (2-5) were used for calculating low stage cycle parameters, while the numbers next to the parameters correspond to numbers in Figure 1 and Figure 2.

$$t_1 = t_{ot} - 5^\circ C;\ p_1 = f(t_1);\ s_1 = f(t_1, x_1 = 1);\ h_1 = f(t_1, x_1 = 1) \tag{2}$$

$$p_2 = p_3;\ s_2 = s_1;\ t_2 = f(p_2; s_2);\ h_2 = f(p_2, t_2) \tag{3}$$

$$t_3 = t_{it} + \frac{\Delta t}{2};\ p_1 = f(t_3);\ s_3 = f(t_3, x_3 = 0);\ h_3 = f(t_3, x_3 = 0) \tag{4}$$

$$h_4 = h_3;\ t_4 = t_1;\ p_4 = p_1;\ x_4 = f(h_4);\ s_4 = f(x_4) \tag{5}$$

On the other hand, equations (6-9) were used for high stage cycle parameter calculations.

$$t_I = t_3 - \Delta t;\ p_I = f(t_I);\ s_I = f(t_I, x_I = 1);\ h_I = f(t_I, x_I = 1) \quad (6)$$

$$p_{II} = p_{III};\ s_{II} = s_I;\ t_{II} = f(p_{II}; s_{II});\ h_{II} = f(p_{II}, t_{II}) \quad (7)$$

$$t_{III} = t_w + 5^{\circ}C;\ p_{III} = f(t_{III});\ s_{III} = f(t_{III}, x_{III} = 0);\ h_{III} = f(t_{III}, x_{III} = 0) \quad (8)$$

$$h_{IV} = h_{III};\ t_{IV} = t_I;\ p_{IV} = p_I;\ x_{IV} = f(h_{IV});\ s_{IV} = f(x_{IV}) \quad (9)$$

3 Results and discussion

3.1 Analysis of optimal intermediate temperature

The analysis included six working fluid pairs that were selected as optimal for the relevant temperature range. Figure 3 presents summarized results of the analysis of optimal intermediate temperature.

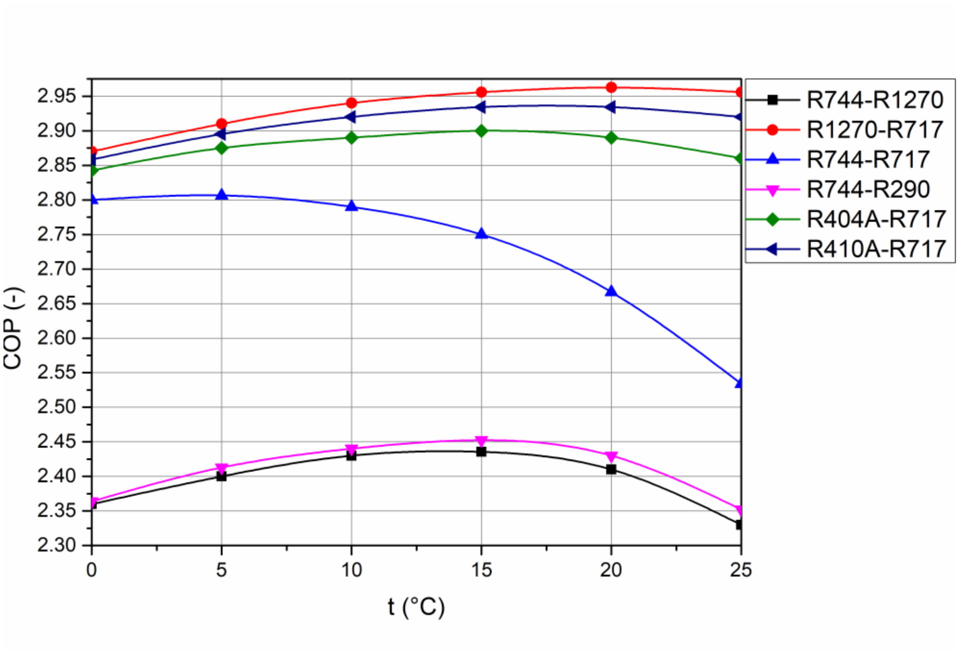

Figure 3 Results of the optimal intermediate temperature analysis

The results of the analysis have shown that the highest value of COP is achieved when using working pair R1270-R717. The value of that maximum COP equals to 2.96 and corresponds to the intermediate temperature of 20°C. Along with R1270-R717, the analysis of R404A-R717 and R410A-R717 revealed similar results with the latter one showing higher values of COP. However, these working fluid pairs contain R404A and R410A which are HFCs and thus have high values of GWP. Not only does the pair R1270-R717 have the highest value of COP for the given circumstances, but it also represents combination of natural fluids that are not polluting the environment.

The Figure 3 also shows lower values of COP achieved when carbon-dioxide (R744) was used as one of the working fluids. This comes due to the fact that carbon-dioxide operates better when temperatures are lower than the ones in scope of this analysis. When using combination ammonia and carbon-dioxide (R744-R717), the optimal intermediate temperature is achieved at lower values compared to the other pairs. In this case, the optimal intermediate temperature equals to 4°C while it exceeds 14°C for every other analyzed pair of working fluids.

Finally, it can be concluded that the lowest values of COP are achieved when using R744 in combination with R290, as well as R744 with R1270, with the first one performing better than the latter one.

3.2 Analysis of the impact that isentropic efficiency has on COP

When performing previous analysis, the isentropic efficiency of both compressors was set to 1. However, this is an ideal case and more realistic cases should be examined. The analysis of the impact that isentropic efficiency has on COP has shown noticeable deterioration in COP when isentropic efficiency reduces. Figure 4 represents summarized results for different working fluid pairs. It can be concluded that the relation between COP and isentropic efficiency is linear and always results in decrease of COP when isentropic efficiency is reduced. Deterioration of COP can be visualized and presented with the fact that COP for the combination R1270-R717 equals to 2.21 when isentropic efficiency is 0.7. As it can be deduced, COP value in that case deteriorates by approximately 25%. This applies to all other working fluid pairs that were analyzed in scope of this paper.

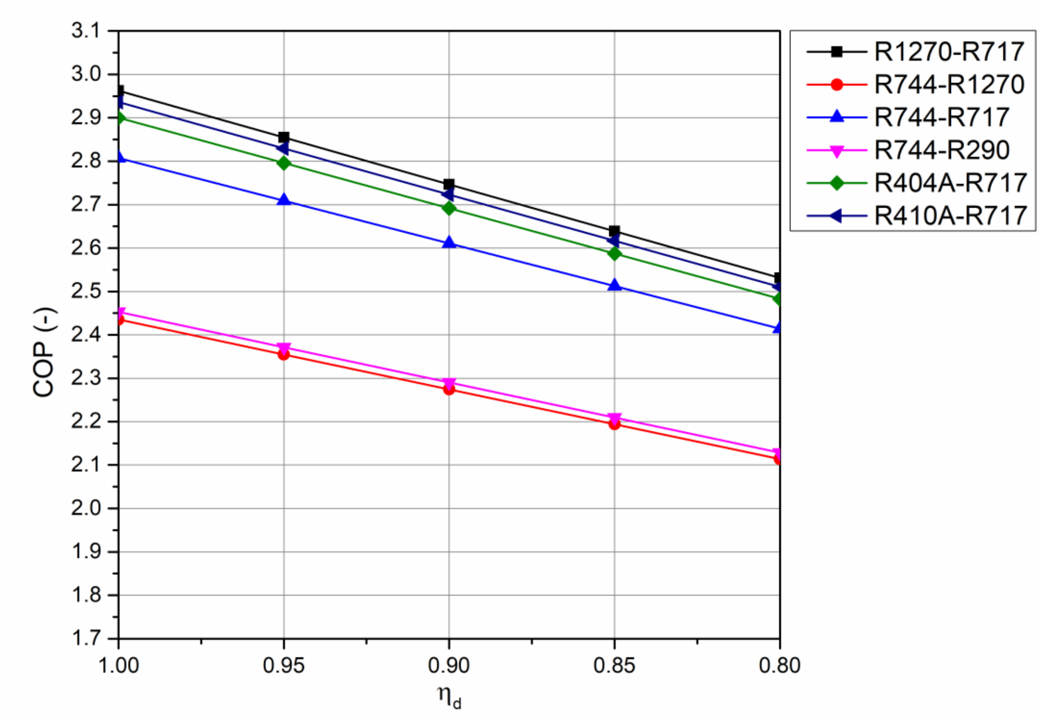

Figure 4 Analysis of the impact isentropic efficiency has on COP

4 Conclusion

This paper presented results of thermodynamic analysis and optimization of an air to water cascade heat pump. The analyzed cascade heat pump was intended to be used in combination with radiator heating and with very low outdoor air temperatures. The paper covered analysis of optimal temperature with which maximum value of COP is achieved. Furthermore, the impact that isentropic efficiency has on maximum COP was also investigated. The results of the analysis were presented and showed that the maximum value of COP was achieved when using R1270 in low stage cycle and R717 in high stage cycle. Moreover, when analyzing impact of isentropic efficiency, it was concluded that its reduction leads to almost linear deterioration of COP.

5 References

[1] **Xiaoqiong L., Yufeng Z., Xuelian M., Na D., Zhendong J., Xiaohui Y., Wei L.,** Performance analysis of high-temperature water source cascade heat pump using BY3B/BY6 as refrigerants, Elsevier, 2019

[2] **Ivanovski, I., Gorianec, D., Salamuni, J. J., and agar, T.,** Strojniki vestnik - Journal of Mechanical Engineering 64, 2018

[3] **Bansal P.K., Jain S.,** Cascade systems: past, present, and future, ASHRAE Transactions. 2007 Winter Meeting. *Volume* 113

[4] **Goricanec, D. et al.,** Cascade type geothermal heat pump – economic analysis and environmental impact, in KGH Conference Proceedings, pages 140–146, SMEITS, 2008

[5] **Bertsch, S. S. and Groll, E. A.,** International Journal of Refrigeration 31 (2008) 1282, doi:10.1016/j.ijrefrig.2008.01.006.

[6] **Venus Lun Y. H., Dennis Tung S.L.,** Heat Pumps for Sustainable Heating and Cooling, Springer, 2020

[7] **Boahen S., Choi J. M.,** A Study on the Performace of a Cascade Heat Pump for Generating Hot Water, energies, 2019

[8] **Markoski M.,** Rashladni uredjaji prvi deo, Mašinski fakultet, Beograd, 2013

[9] Eurostat 2019, European Commission, accessed 29 July 2020, https://ec.europa.eu/

[10] **Kim, D. H., Park, H. S., Kim, M. S.,** Optimal temperature between high and low stage cycles for R134a/R410A cascade heat pump based water heater system, Experimental Thermal and Fluid Science, Vol. 47 pages 172-179.