Thermodynamic analysis of a high-temperature heat pump using low GWP natural working fluids for upgrading district heating to process heating

Mohsen Sadeghi[a], Tage Petersen[b], Zhenyu Yang[c], Benjamin Zühlsdorf[d], Kim Stenholdt Madsen[e] and Ahmad Arabkoohsar[f]

[a] AAU Energy, Aalborg University, Esbjerg, Denmark, msad@energy.aau.dk
[b] Energy and Climate, Danish Technological Institute, Aarhus, Denmark, tagp@teknologisk.dk
[c] AAU Energy, Aalborg University, Esbjerg, Denmark, yang@energy.aau.dk
[d] Energy and Climate, Danish Technological Institute, Aarhus, Denmark , bez@teknologisk.dk
[e]DIN Forsyning A/S, Esbjerg, Denmark, ksm@dinforsyning.dk
[f]AAU Energy, Aalborg University, Esbjerg, Denmark

Abstract:
High-temperature heat pump (HTHP) is a promising technology for decarbonization of process heating through electrification and energy efficiency. Exploiting the potentials requires a simultaneous optimization of the cycle layout and the working fluid. This paper proposes an efficient cascade HTHP and optimizes its thermodynamic performance. Using steam for high-temperature loop and use of alternative hydrocarbons for low-temperature loop are examined. On the application level, district heating is considered as a heat source and evaluated for different supply temperatures, including 80 °C, 70 °C and 40 °C.
The results reveal that pentane with highest critical temperature among the suggested hydrocarbons, shows the best energy performance to be paired with steam in the proposed cascade HTHP system. However, concerning the hydrocarbon compressor volumetric heating capacity (VHC) and safety issues, butane is an excellent candidate. In addition, when the heat available in the main transmission lines of district heating unit is considered as the source cooled from 80 °C down 70 °C, the highest value of coefficient of performance (COP) is achieved as 2.74 for the sink condensation temperature of 160 °C.

Keywords:
High-temperature heat pump, Low GWP working fluids, Steam, Hydrocarbons, District heating.

1. Introduction

High-temperature heat pump (HTHP) technology using renewable electricity is a promising solution to decarbonize the industrial process heat supply; which is mainly based on fossil fuels and contributes with 36.8 % to the CO_2 emissions in industry [1]. In this regard, optimizing the performance of the HTHP systems concerning various configurations and working fluids is a vital issue.

Chen et al. [2] investigated performance of an improved vapor injected cascade heat pump system for high-temperature applications, from the viewpoints of thermodynamics and exergoeconomics. Considering zero Ozone Depletion Potential (OPD) and low Global Warming Potential (GWP) as the main environmental criteria, they examined the use of R1233zd(E), R1336mzz(Z) and R245fa in the high-temperature loop and R1234yf, R290 and R134a through the low-temperature loop, meeting the required target temperatures. The highest coefficient of performance (COP) value of 2.3, when the evaporation and condensation temperatures are 10 °C and 100 °C, respectively, was achieved.

Performance of simple vapor compression HTHP system with condensation temperature up to 125 °C using low GWP working fluids of R1234ze(E) and R1234ze(Z) was compared by Fukuda et al. [3]. It was discussed when the condensation temperature is about 20 °C below the corresponding working fluid critical point, the COP is maximized, which is higher also for R1234ze(Z). In another study by Kondou et al. [4], again R1234ze(Z) showed promising performance among other low GWP refrigerants such as R1234ze(E), R717 and R365mfc for high-temperature applications of heat pumps up to 160 °C. In addition, performance of dual pressure condensation HTHP using 10 different working fluids including R600a, R1234ze(Z), R1224yd(Z), R245fa, R1233zd(E), R245ca, R601a, R1336mzz(Z), R365mfc and Isohexane was carried out and compared to the single-stage, two-stage and cascade systems, by Dai et al. [5]. It was revealed that the system using R1234ze(Z) shows the highest COP of 4.16, which is about 9 % higher than that of the conventional HTHP configurations.

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In a semi-empirical work by Mateu-Royo et al. [6], they demonstrated that in a HTHP system covering the wide range of sink temperatures of 110- 140 °C, using HCFO-R1224yd(Z) shows promising performance from the energy efficiency and environmental perspectives and could be replaced with R245fa.

R1233zd(E) also was introduced as promising working fluid in heat pumps with high-temperature applications by Arpagaus et al. [7] and Frate et al. [8]. Mateu-Royo et al. [9] focused on the effects on the heat pump performance of superheating degree in an internal heat exchanger. They concluded that using HCFO-R1233zd(E), HFO-R1336mzz(Z) and HCFO-R1224yd(Z) instead of R245fa leads to an improvement of 27%, 21% and 17% in COP, respectively. In similar study, Mateu-Royo et al. [10] conducted experimental study of HTHP system to upgrade the heat from 60 °C to 80 °C to the temperature of 90 °C to 140 °C. Performance of the system was compared using different refrigerants such as R245fa, R1224yd(Z), R1233zd(E), and R1336mzz(Z). They reported that under the same operating condition, using R1336mzz(Z) leads to higher COP values and reduction in CO_2 emissions up to 57 %, compared to a natural gas boiler.

However, through another work, Mateu-Royo et al. [11] showed that using pentane as a hydrocarbon working fluid in heat pumps with condensation temperature up to 150 °C leads to higher COPs than for using R1233zd(E), R1336mzz(Z) and R245fa. Following the promising performance of using hydrocarbon refrigerants, a comprehensive study on the performance prediction of water source HTHP system screening various working fluids were performed by Yan et al. [12]. The results revealed that butane as hydrocarbon working fluid with a low GWP value, also shows a better performance than HFCs and HFOs. In addition, Mota-Babiloni et al. [13] reported that in a cascade HTHP system, butane and pentane are the best choices for the low-temperature and high-temperature loops, respectively. A 20 kW capacity cascade heat pump using such hydrocarbons as propane and butane in the low and high-temperature cycles, respectively, was investigated by Bamigbetan et al. [14]. It was revealed that recovering waste heat at 30 °C, the heating COP could reach 3.1 for the temperature lift of above 70 °C. Bai et al. [15] also reported that R600 (butane), R1224yd(Z), R1234ze(Z) and R1233zd(E) show high COPs and smaller compressor sizes in high-temperature applications of heat pumps.

However, despite the promising performance of heat pumps for high-temperature applications using hydrocarbons such as butane and pentane and also hydrofluoroolefins in particular R1234ze(Z), R1233zd(E) and R1336mzz(Z), steam as zero GWP working fluid showed a better performance with higher COP through the study conducted by Wu et al. [16]. Steam also was successfully used and recommended by Zühlsdorf et al. [17] in a cascade multi-stage HTHP system for steam generation and process heat supply up to 280 °C.

On the other, based on the recent reports, more than 6000 district heating networks operate in Europe and supply 11 % to 12 % of the total domestic heat demand [18]. District heating systems can be categorized in five generations, as summarized in Table 1 [18,19].

Table 1. Different district heating networks and their characteristics [18].

DH Network	Operating temperature	Main drawback
1G	120 °C to 200 °C	High implementation and maintenance costs and huge amount of thermal losses up to 30 %.
2G	120 °C to 160 °C	
3G	70 °C to 100 °C	
4G	35 °C to 70 °C	Emergent technologies and high electricity and HP costs.
5G	10 °C to 35 °C	

As briefly discussed in Table 1, due to the inefficient distribution processes for 1G and 2G DH networks, 4G and 5G DH systems are the most considered and dominant DH generations. They do not suffer from large thermal losses and as results sharp thermal stresses as well as high pressure drops in the pipelines [18]. In addition, comparing the traditional heating systems based on natural gas boiler, the CO_2 emissions could decrease up to 45%, which allies with the decarbonization of the heating sector, as well [18]. Regarding the promising environmental performance of new generation DH networks and their temperature range of operation, heat pumps (HP) can be effectively integrated with them to decarbonize the district heat sector.

Using R245fa and R134fa, thermodynamic and economic analyses of booster heat pump in low-temperature district heating was carried out by Roh et al. [20]. It was concluded that the economic feasibility of using heat pumps in the DH networks strongly is affected by the electricity and district heat prices. The optimum combination of booster heat pumps in a very low-temperature district heating was performed and compared with low-temperature district heating by Ommen et al. [21]. They reported that using central heat pump, the performance of the system is improved up to 12 %. Combining a ground source central heat pump and local boosters, Yang et al. [22] proposed and analyzed a system for domestic hot water production. According to the exergy analysis results, the low-temperature district heating operating at 55 °C showed higher efficiency than high-temperature DH at 70 °C. Use of modern heat pumps in the existing district heating networks was investigated by Kontu et al. [23]. Possibility of utilization of various heat sources in the HP-boosted DH networks was introduced as one of the main advantages. However, it was outlined that using heat pumps in DH networks is very sensitive to the heat source and electricity prices.

Various scenarios on the integration of heat pumps with district heating concerning heat pumps location, connection and operations mode was studied by Sayegh et al. [24]. They reported that, higher share of heat pumps in district heating networks yields less emissions, and environmental impacts. Pieper et al. [25] evaluated integrating three different heat sources of groundwater, seawater and air with heat pumps to supply district heating. They reported that the most appropriate heat source to be integrated by heat pump is changed seasonally and using multi-source heat leads to the maximum COP. In addition, Arabkoohsar et al. [26] proposed a new generation of district heating system using booster heat pumps and triple pipes. They reported that the new system shows a better energy efficiency, especially during winter days.

In all aforementioned studies, the district heating was considered as the sink and the heat pump was supposed to supply or boost the required heat for the DH network. However, referring to Table 1, 4G DH networks, which provide heat up to 70 °C, can be considered as heat source for heat pumps, to supply heat for medium or high-temperature process applications. The main benefit of this integration is that the district heat is always available as a source. In this regard, the present study aims to evaluate the performance of a cascade heat pump system integrated with district heat. In addition, on the HTHP system configuration level, reviewing the literature outlines those hydrocarbons such as butane and pentane as natural working fluids shows competitive performance with synthetic hydrofluoroolefins. However, using steam could lead to higher COPs in the high-temperature applications. Since, considering the special environmental characteristics of steam (zero ODP and zero GWP), it turns into a very interesting choice, as the working fluid in HTHP systems. However, for industrial applications with high-temperature lifts, using single-stage steam heat pump brings about some serious challenges, in particular high superheating degrees at the compressor discharge. Therefore, this work also aims to address these challenges and then find solutions through proposing efficient system design and choosing appropriate natural low GWP working fluids.

2. System description and modelling

Selecting the optimal cycle layout and working fluid for a given application must consider a variety of thermodynamic and technical parameters, such as temperatures, pressures, and main operating parameters for the equipment. Steam is found to be an optimal working fluid for applications above around 100 °C, due to the high required volume flow rates, high pressure ratios and high superheating during compression for lower temperatures, as depicted in Figure 1. Therefore, a cascade system is suggested, consisting of a single-stage bottom cycle using a hydrocarbon and a steam compression as top-cycle.

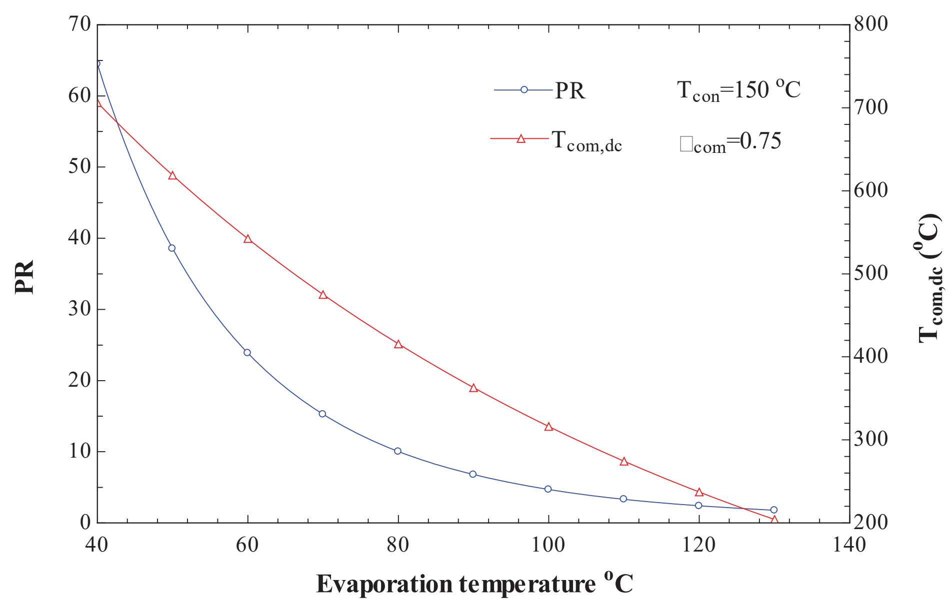

Figure 1. Steam compressor pressure ratio (PR) and discharge temperature ($T_{com,dc}$) of varying evaporation temperatures and a fixed condensation temperature

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A schematic of the proposed cascade heat pump system is presented in Figure 2. In the proposed HP system, the high-temperature loop is not closed and steam as non-flammable and non-toxic fluid could be directly delivered to the sink after discharging from the compressor. The steam is generated through the steam generator, which receives thermal energy from the bottoming cycle. In the bottoming cycle, the working fluid absorbs heat in the evaporator and then is superheated through the internal heat exchanger. Then passing through the compressor, the pressurized hot stream cools down through the condenser and is throttled in the expansion valve.

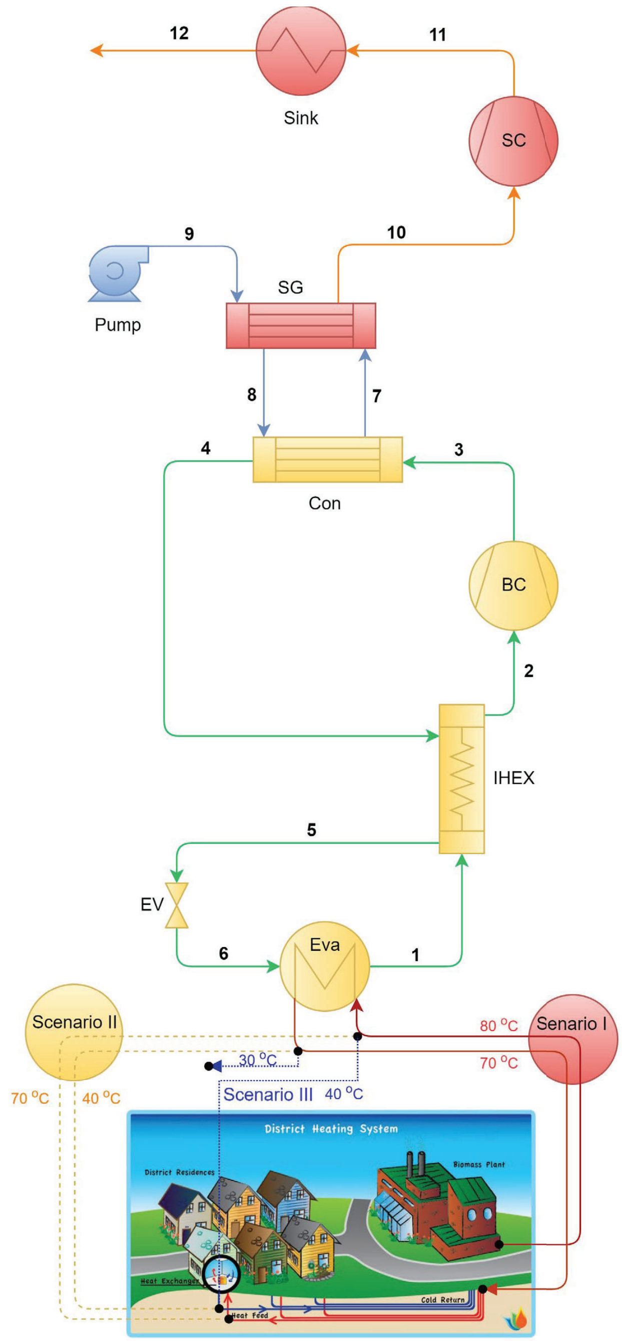

Figure 2. Proposed cascade high-temperature heat pump system (red and yellow lines: heat source, blue lines: water, green lines: alternative hydrocarbons, orange lines: steam)

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For the low-temperature cycle, hydrocarbons with high enough critical temperatures above 130 °C are considered as the low GWP natural working fluids. The selected working fluids and their properties are listed in Table 2.

Table 2. Properties of the selected working fluids for the cascade HTHP system [1].

Working fluid	Safety group	ODP	GWP	P_{cri} (bar)	T_{cri} (°C)	Auto-ignition temperature (°C)
Steam (R718)	A1	0	0	220.6	374	-
Pentane (R601)	A3	0	5	33.64	196.6	260
Isopentane (R601a)	A3	0	5	33.7	187.2	420
Butane (R600)	A3	0	4	37.96	152	405
Isobutane (R600a)	A3	0	4	36.4	134.7	460

In addition, as illustrated in Figure 2, the HTHP system uses the heat available from district heating as the source through three different scenarios, which is explained in detail in Table 3.

Table 3. Three different scenarios for integrating the heat pump system with district heating.

Scenario	$T_{source,in}$ (°C)	$T_{source,out}$ (°C)	T_{eva} (°C)	Description	Connection
I	80	70	65	High-quality and expensive heat source	Main transmission line from biomass plant
II	70	40	35	Moderate heat source	DH Distribution lines
II	40	30	25	Cheapest heat source but low-quality	DH Return lines

Using Engineering Equation Solver (EES) and based on the input data given in Table 4, thermodynamic steady state model has been implemented using a control volume approach with energy and mass balances for each control volume. The heat exchangers are modelled with a defined minimum pinch point temperature difference and the compressor is based on an isentropic efficiency.

Table 4. The input data for modelling the HTHP system

Parameter	Value
Sink condensation temperature, T_{12}	160 °C
Superheating degree in IHEX, T_2-T_1	10 K
Pinch point temperature difference in HEXs except IHEX	5 K
Intermediate water circuit temperature difference, T_7-T_8	5 K
Feed water temperature, T_9	105 °C
Cascade temperature, T_{10}	105 °C (1.21 bar)
Compressors isentropic efficiency, η_{is}	75 %

Considering that high-temperature superheated steam is completely condensed through the sink, and is subcooled up to the feedwater temperature (105 °C), the COP and VHC of the compressors are defined, as follows:

$$COP = \dot{Q}_{sink}/(\dot{W}_{BC} + \dot{W}_{SC}) \tag{1}$$

$$VHC_{SC} = \dot{Q}_{sink}/\dot{V}_{10} \tag{2}$$

$$VHC_{BC} = \dot{Q}_{con}/\dot{V}_2 \tag{3}$$

Here, $\dot{Q}_{sink}$, $\dot{W}_{BC}$ *and* $\dot{W}_{SC}$ are the heat transfer rate delivered to the sink and power consumption of the hydrocarbon and steam compressors, respectively.

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3. Results and discussion

The HTHP system has been simulated for the three scenarios with 4 different refrigerants in the bottom cycle. The COP of the HTHP system is depicted in Figure 3. Referring to this figure, the HTHP system gets higher COPs, when is integrated with district heating based on scenario I. This is because; considering the 5 K pinch point temperature difference in the evaporator, it could operate at 65 °C under scenario I, which is much higher than 35 °C and 25 °C in scenarios II and III, respectively. Therefore, the temperature lift of the cascade HTHP system in scenario I is lower than that of the other scenarios, which leads to a significant reduction in the pressure ratio and power consumption of the compressors as shown in Figures 4 and 5, respectively.

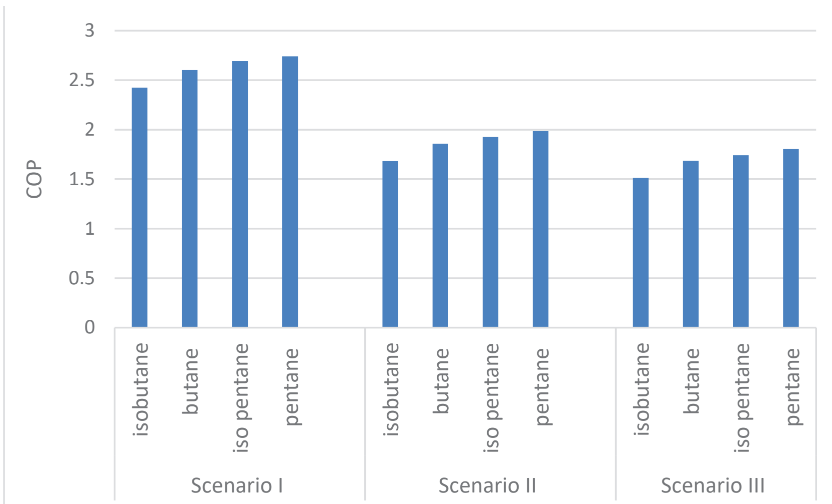

Figure 3. COP of the HTHP system using various hydrocarbons in the low-temperature loop based on the three different scenarios

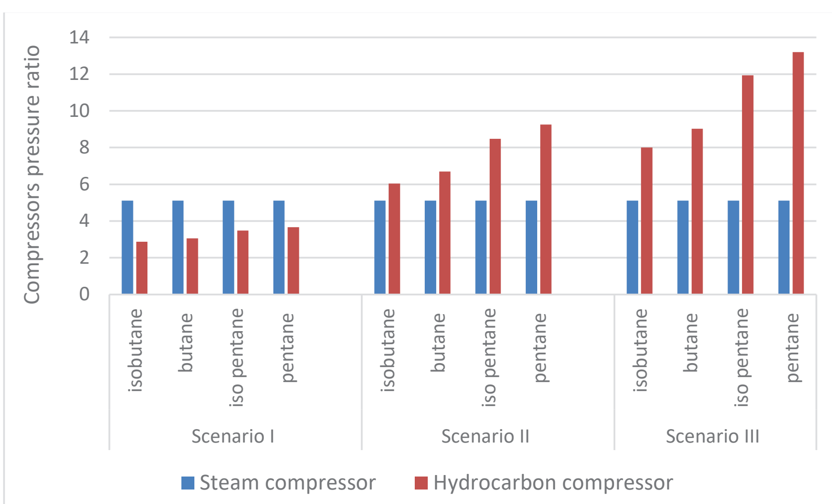

Figure 4. Pressure ratio of the compressors using various hydrocarbons in the low-temperature loop based on the three different scenarios

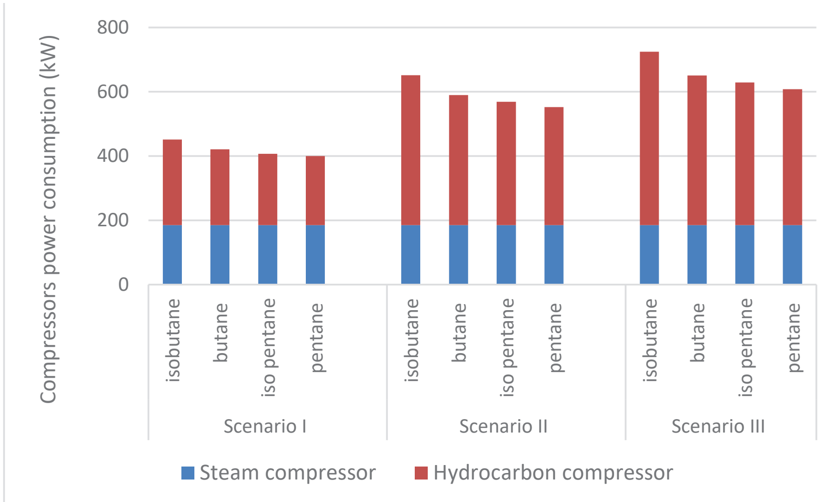

Figure 5. Power consumption of the compressors using various hydrocarbons in the low-temperature loop based on the three different scenarios

Referring to Figures 4 and 5, the pressure ratio and power consumption of the steam compressor in all the cases does not change (5.1 and 185 kW, respectively). This is due to the constant evaporation pressure of the steam generator.

However, referring to Figure 4, in all the scenarios, pentane compressor shows higher pressure ratios, which is mainly due to the higher critical temperature of pentane compared to the other hydrocarbons. Though, thanks to the relatively smaller mass flow rate of pentane through the compressor, the hydrocarbon compressor consumes less power in the case of using pentane, as depicted in Figure 5.

In conclusion, the HTHP system achieves the highest COP of 2.74, when is integrated with district heating based on scenario I and uses pentane as the working fluid in the low-temperature loop, as shown in Figure 3. Therefore, from the energy point of view, pentane is the best candidate to be used as the working fluid in the bottoming loop.

However, Figure 6 shows that pentane has a higher specific volume compared to the other hydrocarbons, meaning that the volumetric flow rate of pentane in the compressor suction is larger, requiring a bigger hydrocarbon compressor. Thus, from the viewpoint of sizing, butane is introduced as a good candidate with almost twice VHC compared to pentane, just in the expense of about 5 % reduction in the HTHP COP. In addition, using butane could be safer, as well, due to its higher auto-ignition temperature compared to pentane (405 °C Vs 260 °C).

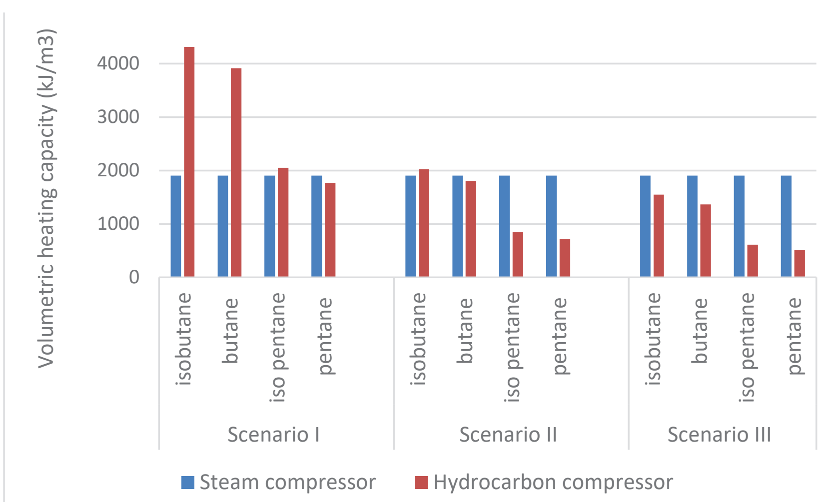

Figure 6. VHC of the compressors using various hydrocarbons in the low-temperature loop based on the three different scenarios

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Moreover, as shown, in Figure 6, the steam compressor VHC is a constant value in all the cases, due to the unchanged operating condition of that.

All in all, depending on the objective function, either maximizing the COP or minimizing the sizing and auto-ignition risk, pentane and butane are recommended, respectively, as the low-temperature loop working fluids to reach out a promising HTHP system performance.

However, in all the twelve case studies, the steam compressor discharge temperature is a high value. In this regard, some technology improvements e.g. water injection and re-designing the system could enhance the COP, as well.

4. Conclusions

Thermodynamic analysis of a cascade high-temperature heat pump using steam in the high-temperature loop and low GWP hydrocarbons including isobutane, butane, isopentane and pentane in the low-temperature loop, was carried out. The importance and advantages of using steam as well as the necessity of using cascade layout was discussed. On the application level, there different scenarios for integrating the proposed HTHP system with a district heating unit were studied and compared, in terms of the COP, pressure ratio, power consumption and VHC of the compressors. The most significant results of the present study are summarized, as follows:

- Integrating the HTHP system with district heating based on scenario I- which suggests the use of district heat available in the main transmission line at 80 °C cooled down 70 °C - leads to the higher COP values compared to the other scenarios.
- Among the suggested hydrocarbons, pentane shows the most promising performance from the energy perspective, leading to high COP values.
- The highest COP value of 2.74 is achieved for the case based on scenario I and using pentane as the low-temperature loop working fluid.
- Concerning the hydrocarbon compressor sizing criterion, butane is introduced as a good candidate; with VHC value of about two times more than that of pentane, in the expense of just about 5 % reduction in the HTHP COP.
- Considering the high auto-ignition temperature of butane, it is also suggested for the high-risk applications.
- Regarding the high discharge temperature of the steam compressor, technology improvements e.g. water injection or proposing more effective layouts are recommended for the future works.

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Nomenclature

Symbols

P Pressure, bar

T Temperature, K

$\dot{V}$ Volumetric flow rate, m^3/s

$\dot{W}$ Power, kW

Abbreviations

BC Butane compressor

Com Compressor

Con Condenser
COP Cofficient of perfromance
EV Expansion valve
Eva Evaporator
HEX Heat exchnager
IHEX Internal heat exchanger
PR Pressure ratio
SC Steam compressor
SG Steam generator
VHC Volumetric heating capacity, kJ/m3

Subscripts
cri Critical point
dc Discharge
is Isentropic

Greek symbols
ε Effectivness
η Efficiency

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