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Multiparametric Analysis of Novel Multilevel Temperature Heat Pumps (LEAP) for Multi-Sink Heating

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Abstract

Industrial sectors are currently seeking ways to decarbonize their processes which rely primarily on fossil fuel boilers. Heat pumps offer high-quality heating that could substitute boilers due to their high coefficient of performance (COP) for moderate temperature lifts. It is proven that the heat pump efficiency deteriorates with increased temperature lifts. This paper examines multilevel heat pumps (LEAP) as an efficient way to produce high and/or variable-level sink temperatures. The LEAP concept operates between 0°C and 160°C with three heating levels at 60°C, 110°C, and 160°C. With a two and three-stage independent layered heat pump system, the sink heat exchanger is divided into two heat exchangers at each stage. One is used to supply the external load requirements, and the other is to cover the source or internal load on the higher consecutive stage cycle. The external load heat exchangers can be connected in series or parallel to control the desired load output temperature. A multi-parameter selection analysis was conducted using EES software to evaluate several natural and synthetic refrigerants with low values of the Global Warming Potential (GWP) index. For different scenarios, selected low GWP refrigerants were investigated based on their thermophysical properties. The multiparametric analysis shows that for each stage a COP of 3.5 was achieved and a total COP of 2.5 can be obtained for the LEAP concept. This is equivalent to an increase of about 40 % more than a single heat pump can provide. The best synthetic refrigerants were R-1234ze (Z), R-1224yd (Z), R-1233zd (E), and R1366mzz (Z). On the other hand, the best natural refrigerants were R-600 (n-Butane), R-600a (Isobutane), R-601 (n-Pentane), and R-601a (Isopentane).

Keywords: Hydrocarbon; Synthetic refrigerants;Natural refrigerants, low GWP; Hydrofluooroolefin (HFO); multi-stage; cascade

1. Introduction

Decarbonization of commercial and industrial processes is a requirement for a sustainable future. There is a great interest in increasing the use of waste heat, making efficient use of thermal energy and replacing fossil fuel boilers with other cleaner technologies. Heat pump systems are considered a greener alternative to fossil fuel boilers because electricity with a high share of renewable sources can power the system. Moreover, in the absence of waste heat sink sources, the heat must be extracted from near ambient temperatures. This would lead to higher temperature difference between both heat source and heat sink reservoirs, therefore; penalizes the system's energy performance and decreasing its environmental benefits.

Multilevel heat pump applications are scarce [1]. The most common solution for increasing energy performance in high-temperature lift applications is using multilevel vapor compression configurations. The LEAP concept, with the multi-layered configuration, offers flexibility in the operation and adaptation to the application. The potential of two-stage heat pump cycles compared to single-stage has been evaluated in terms of energy performance and heating capacity [2]. A two-stage cascade system has been investigated with appropriate configurations for 60 K and 80 K temperature lifts compared to other technologies, such as ejector or parallel compression. In each stage, efforts are mainly devoted to its optimization in terms of intermediate

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temperature and refrigerants [3]. The use of natural refrigerants Butane (R-600) and Isobutane (R-600a), respectively, in a cascade system appeared to be the most viable working fluids in terms of COP for the low-temperature circuit, while R-601a (n-Pentane) and R-1336mzz (Z) were the most promising for the high-temperature stage [4]. Uusitalo et al. studied combinations of refrigerants and concluded that the temperature level in the cascade heat exchanger has a significant effect on the COP [5]. Wang et al. explored the applicability of an auto-cascade heat pump for heating in cold climates. The research found that R-134a / R-600 with a mass ratio of 0.8/0.2 could get a COP of 2.15 [6]. Yu et al. presented a novel auto-cascade heat pump for electric vehicles. Theoretical analysis indicated that the proposed system with CO_2/R-290 improved the COP by 12.3 % compared to a single-stage compression system using CO_2 [7]. Chen et al. proposed a novel vapor injection auto-cascade heat pump for high–temperature water heating, which introduced the liquid branch after the partial condensation into the injection port through a cascade internal heat exchanger based on the conventional auto-cascade cycle [8]. A most recent study investigated a three-stage cascade for very low-temperature refrigeration [9]. They studied different operating, energetic, and exergetic parameters and obtained the most suitable refrigerant combination. They found that this system has an optimum condensation temperature for each intermediate temperature.

R-134a and R-245fa refrigerants will be used as a base reference to select an appropriate refrigerant for each stage since they will be replaced in the upcoming years to prevent the usage of hydrofluorocarbons with high GWP. Dawo et al. investigated and showed that three low GWP refrigerants could replace R-245fa at a constant heat source temperature of 120°C with small variations in efficiency and heating output [10].

Several literature studies show that most multi-layered heat pumps only consider a two-stage system. They do not use the intermediate levels to satisfy other heating consumptions. This paper presents a multiparametric analysis of multilevel temperature heat pumps (LEAP) to obtain multilevel sink temperatures for variable heating applications.

2. LEAP configuration with multilevel sink temperatures.

The multi-layered heat pump concept is used to overcome the problems of decreasing compressor efficiencies and power consumption due to high-temperature lifts and give the user the freedom to choose the required sink temperature for different applications. To reach high-temperature outputs from a low-temperature heat source, moderate steps of temperature lifts can be utilized. This gradual increase is enough to cover greater temperature lifts. If no waste heat source is available, then the heat sink can be the same as ambient or even below ambient temperature. Therefore, additional stages should be considered for operating between ambient and industrial high temperatures. Usually, cascades are designed in two stages with the same working fluid, and this solution is enough to cover greater temperature lifts, for example, commercial refrigeration or air source heat pumps.

However, high-temperature industrial applications can reach 150°C, so additional stages should be carefully considered when operating between ambient and industrial high temperatures. When selecting the refrigerant, it is necessary to consider the thermodynamic and thermophysical properties, the environmental issues, and safety characteristics. Fig. 1 shows the temperature-entropy diagram of an ideal three-stage multi-layered heat pump, in which the different temperature levels in this system are visible.

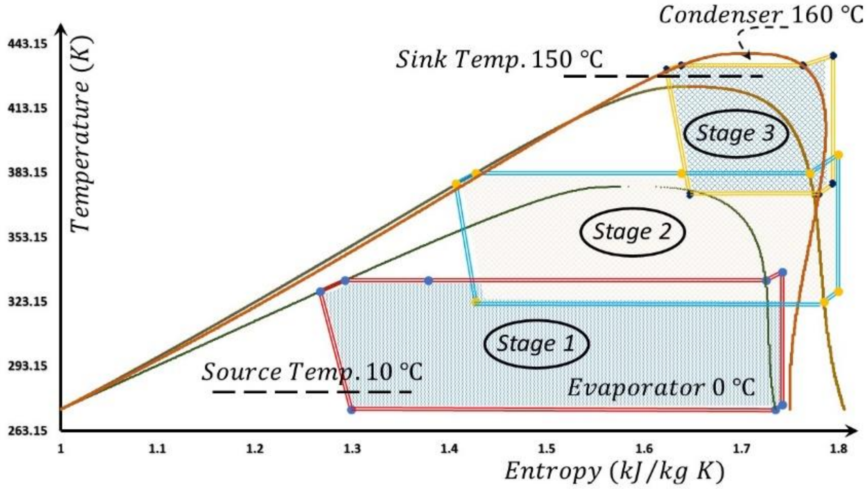

Fig. 1: T-s Diagram for LEAP Concept.

Fig. 2 illustrate the conceptual structure of the LEAP idea where the condenser in the internal cycles is divided into two or several heat exchangers with equal loads. The first heat exchanger will cover the load of the evaporator in the successive cycle, whereas the remaining heat exchangers will supply the external users with the required loads at specific temperature. The external load heat exchangers can be connected in series or parallel to control the desired output temperature. Therefore, this system possesses excellent flexibility in covering different heating consumptions in buildings or industrial applications such as HVAC or domestic hot water systems.

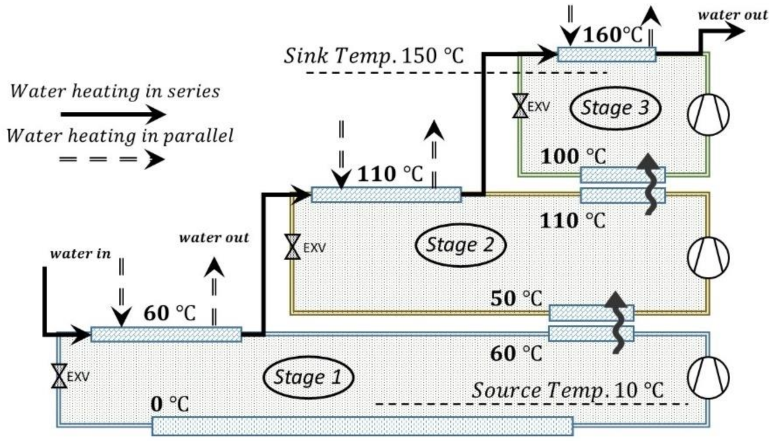

Fig. 2: Components of the LEAP with multiple heating levels.

The main assumptions for each LEAP concept start with an initial source load of 200 kW as the base load for the whole system, an isentropic efficiency of 70% for each compressor within the system, isenthalpic expansion within the expansion valve, constant and equal temperature lifts for each stage, no internal heat exchanger, and pressure drops and heat transfer to the ambient are neglected.

2.1. Low-GWP refrigerants for LEAP concept.

This section provides the various criteria considered to identify the refrigerant with the best thermophysical and thermodynamic properties, which maximizes the system's performance and minimizes the environmental impact. A variety of refrigerant types have been considered in order to choose the best refrigerant for the LEAP concept.

Fig. 3 shows the families of synthetic refrigerants obtained from natural ones and how the chemical processes would be done to obtain the required synthetic refrigerant.

Fig. 4 represents the triangle of elements, Hydrogen on the top, Carbon on the bottom left, and Fluorine on the bottom right. From the triangle, we can locate flammable, toxic, and long atmospheric lifetime (fully halogenated) areas. We can also find areas where refrigerants have high GWP values and high ozone depletion potential (ODP) rates.

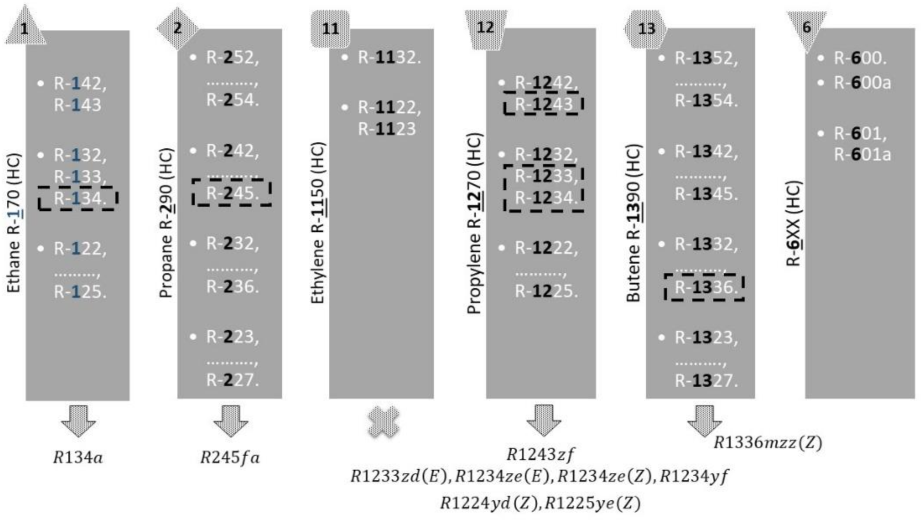

Fig. 3: Synthetic refrigerants families.

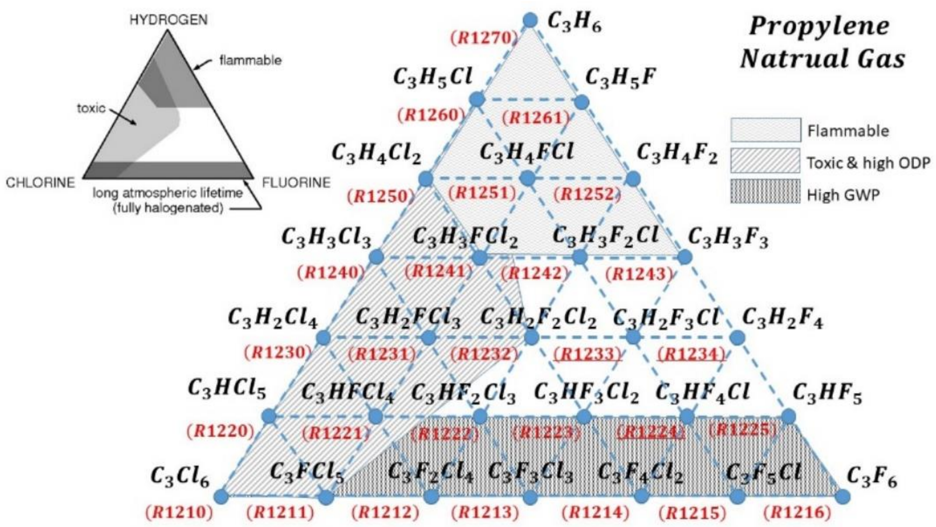

Fig. 4: Synthetic from natural refrigerants (series 12)

All refrigerants will be investigated for a single-stage heat pump with different temperature lifts to eliminate and choose the right media for different stages in the LEAP concept. Table 1 illustrates the refrigerants under investigation in this paper. It shows the trend of increasing the critical temperature of the refrigerants and states the molar mass of the refrigerants' molecules. It is clear from the table that some refrigerants are limited in substituting R-134a and R-245fa, and some are superior thermodynamically. All refrigerants in the table have a GWP around unity and almost zero ODP rates; therefore, their direct impact on climate change can be considered ultra-low.

Table 1: Investigated synthetic & natural refrigerants.

Refrigerants		MW	T_{BP}		T_{cr}		P_{cr}
		$kg/kmol$	(°C)	(K)	(°C)	(K)	kPa
R-1270 (Propylene)	HC	42.08	-47.72	225.43	92.42	365.57	4665
R-1234yf	HFO	114	-29.49	243.66	94.7	367.85	3382
R-290 (Propane)	HC	44.1	-42.1	231.05	96.68	369.83	4247
R-134a	HFC	102	-26.09	247.06	101	374.15	4059

R-1243zf	HCFO	96.05	-25.43	247.72	103.8	376.95	3518
R-1225ye (Z)	HFO	132	-19.54	253.61	106.9	380.05	3528
R-1234ze (E)	HFO	114	-19.28	253.87	109.4	382.55	3632
R-600a (Isobutene)	HC	58.12	-11.68	261.47	134.7	407.85	3640
R-1234ze (Z)	HFO	114	9.72	282.87	150.1	423.25	3531
R-600 (n-Butane)	HC	58.12	-0.52	272.62	152	425.15	3796
R-245fa	HFC	134	15.18	288.33	154	427.15	3651
R-1224yd (Z)	HCFO	148.5	14.61	287.76	155.5	428.65	3337
R-1233zd (E)	HCFO	130.5	18.32	291.47	165.6	438.75	3573
R-1336mzz (Z)	HFO	164.1	33.47	306.62	171.3	444.45	2900
R-601a (Isopentane)	HC	72.15	27.85	301	187.2	460.35	3370
R-601 (n-Pentane)	HC	72.15	35.87	309.02	196.5	469.65	3364

2.2. Refrigerants' selection for each stage.

Simulating a single-stage heat pump with different temperature lifts of 30, 40, 50, 60, 70, and 80K for the same conditions mentioned above, we notice that the heating loads for all "drop-in" refrigerants vary between -8% and 6% for R-134a as base refrigerant and between -14% and 2% for R-245fa as base refrigerant. Similarly, the COP ranges between -17% and 14% for R-134a and between -5% and 24% for R-245fa. Fig. 5 illustrates the COP trend for all refrigerants with a constant temperature lift of 60 K. The evaporator temperature starts with the boiling point temperature of the selected refrigerant with a gradual increase of 2K. The COP values decline as we go higher in the evaporator temperature as we go closer to the critical temperature. It also shows the available refrigerants that can substitute R-134a and R-245fa with respect to COP values.

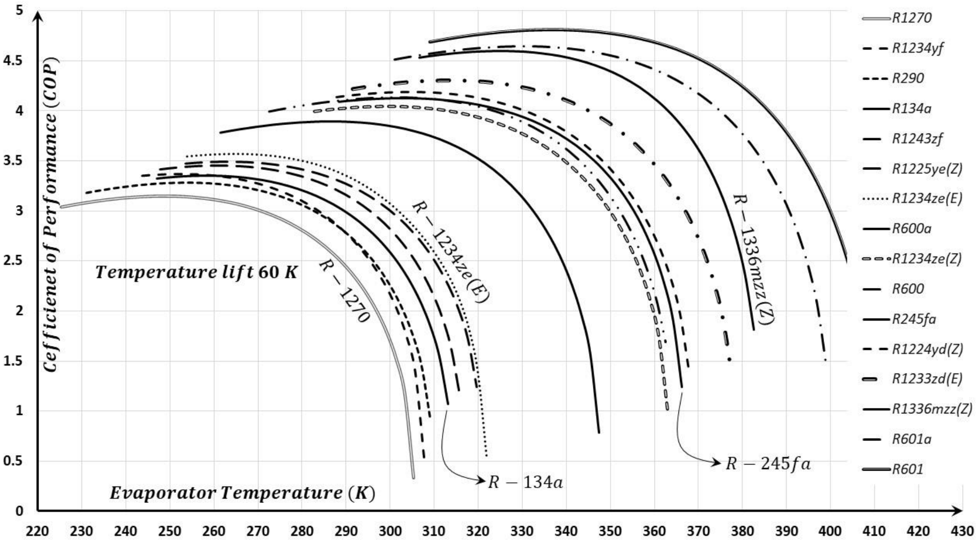

Fig. 5: COP trend for all refrigerants.

Table 2 indicates the variation of COP and heating load (HL) for all investigated refrigerants in a single-stage heat pump with a temperature lift of 60 K as a sample parameter. These values are given in equations (1) and (2) for R-134a and R-245fa as the base refrigerants. We notice from the table that the base refrigerants can be replaced with several refrigerants with an increased COP values and some variation in the heating load on the sink side. The trend is more stable in R-245fa with increasing temperature lifts where the COP values increased while the heating load capacity decreased for all refrigerants. This trend is not clear for R-134a.

Table 2: Data for single-stage heat pump for 60 K temperature lift.

Refrigerants	R-134a		Refrigerants	R-245fa	
	COP%	HL%		COP%	HL%
R-1234ze (Z)	-9.2	1.9	R-1234ze (Z)	-2.7	0.5
R-601 (n-Pentane)	-9.0	-0.8	R-601 (n-Pentane)	-2.5	0.6
R-1233zd (E)	-8.4	1.8	R-1233zd (E)	-2.0	0.3
R-601a (Isopentane)	-7.4	1.7	R-601a (Isopentane)	-1.0	0.3
R-600 (n-Butene)	-6.1	1.4	R-600 (n-Butene)	0.2	-0.1
R-1224yd (Z)	-6.1	1.4	R-1224yd (Z)	0.2	-0.1
R-1336mzz (Z)	-4.9	1.2	R-1336mzz (Z)	1.4	-0.3
R-600a (Isobutene)	-2.8	0.7	R-600a (Isobutene)	3.3	-0.8
R-1234ze (E)	1.0	-0.1	R-1234ze (E)	6.8	-1.6
R-1243zf	1.3	-0.2	R-1243zf	7.1	-1.7
R-290 (Propane)	2.3	-0.6	R-290 (Propane)	8.1	-2.2
R-1270 (Propylene)	2.4	2.1	R-1270 (Propylene)	8.2	-2.3
R-1225ye (Z)	2.6	-0.6	R-1225ye (Z)	8.4	-2.1
R-1234yf	7.7	-1.7	R-1234yf	13.2	-3.2

$$COP\% = \frac{COP_{ref} - COP_{base}}{COP_{base}} \quad (1)$$

$$HL\% = \frac{LH_{ref} - LH_{base}}{LH_{base}} \quad (2)$$

The first stage in the LEAP concept work between 0°C and 60°C and 10°C for the heat source, the second stage operate between 50°C and 110°C, and between 100°C and 160°C for the third stage. This means that the maximum temperature for the heat sink is 150°C. If we take the critical temperature of the refrigerant as a base for comparison with positive COP values and a temperature lift of 60K, several candidates for the first stage, as per Table 2, can be selected. If we, however, open the selection for all COP values, the option to select a suitable refrigerant can widen, and the choice will vary for each LEAP stage.

Table 3 shows the selected refrigerants for each stage with boiling temperature below 0°C and critical temperature above 60°C for the first stage, below 50°C and above 110°C for the second stage, and below 100°C and above 160°C for the third stage.

Table 3: LEAP refrigerants for each stage.

<table>
<tr><th>First Stage
(0°C and 60°C)</th><th>Second Stage
(50°C and 110°C)</th><th>Third Stage
(100°C and 160°C)</th></tr>
<tr><td colspan="3">Synthetic</td></tr>
<tr><td></td><td>R-1336mzz (Z)</td><td></td></tr>
<tr><td></td><td>R-1233zd (E)</td><td></td></tr>
<tr><td colspan="2">R-1224yd(Z)</td><td></td></tr>
<tr><td colspan="2">R-1234ze(Z)</td><td></td></tr>
<tr><td>R-1234ze (E)</td><td colspan="2"></td></tr>
<tr><td>R-1225ye (Z)</td><td colspan="2"></td></tr>
<tr><td>R-1234yf</td><td colspan="2"></td></tr>
<tr><td>R-1243zf</td><td colspan="2"></td></tr>
<tr><td colspan="3">Hydrocarbons</td></tr>
<tr><td>R-290 (Propane)</td><td colspan="2"></td></tr>
<tr><td>R-1270 (Propylene)</td><td colspan="2"></td></tr>
<tr><td colspan="2">R-600 (n-Butene)</td><td></td></tr>
<tr><td colspan="2">R-600a (Isobutene)</td><td></td></tr>
<tr><td></td><td colspan="2">R-601 (n-Pentane)</td></tr>
<tr><td></td><td colspan="2">R-601a (Isopentane)</td></tr>
</table>

3. Results & Discussions

3.1. LEAP results with 2-layered heat pump.

Running the simulation software EES for variable combinations of refrigerants between the first and the second stage starting from the boiling point of the refrigerant, we notice that no matter what the selection would be for the first stage, the second stage will output increasing COP values, as seen in Table 4, and fluctuating heating load values.

Table 4: The 2-layered heat pump results.

First Stage (0°C and 60°C)		Second Stage (50°C and 110°C)	
Refrigerant	COP	Refrigerant	COP
R-1234yf	3.065	R-600a (Isobutane)	3.159
R-1270 (Propylene)	3.202	R-600 (n-Butane)	3.449
R-1225ye (Z)	3.202	R-1224yd (Z)	3.501
R-290 (Propane)	3.208	R-1336mzz (Z)	3.532
R-1243zf	3.242	R-1234ze (Z)	3.603
R-1234ze (E)	3.252	R-601a (Isopentane)	3.617
R-600a (Isobutane)	3.355	R-1233zd (E)	3.675
R-600 (n-Butane)	3.448	R-601 (n-Pentane)	3.722

The structured array of increasing COP values in the second stage is composed of the following refrigerants: R-600a, R-600, R-1224yd (Z), R-1336mzz (Z), R-1234ze (Z), R-601a, R-1233zd (E), and R-601. The best combination for the 2-layered heat pump is R-600 with a COP of 3.448 for the first stage and R-601 with a COP of 3.722 for the second stage. If the choice is to use only synthetic refrigerants, then that R-1234ze (E) with a COP of 3.252 for the first stage and R-1233zd (E) with a COP of 3.675 for the second stage. In the 2-layer heat pump, we obtain two levels of temperatures, 50°C and 100°C, or we can increase the sink source temperature from 10°C to 100°C in one step

If a single-stage heat pump is supposed to deliver the same sink temperature of 100°C from a 10°C source temperature, then the temperature lift is 110 K. By looking at the refrigerants' thermophysical properties, we can see that only R-600 and R-600a will comply, and the COP values will be 1.6 and 1.4 respectively compared to a total COP value of 2.56 for the LEAP two stages. Using a 2-layered heat pump will therefore lead to energy savings of almost 40%.

3.2. LEAP results with 3-layered heat pumps.

In the third stage layer, the compressor enthalpy discharge values will land in the vapor-liquid mixture zone instead of the superheated zone due to the positive slope of the vapor line in the P-h chart. To overcome these discrepancies, the superheat and subcooling temperatures will be increased to overcome the false values.

Using the same analogy from the 2-layered heat pump, Table 5 summarizes the refrigerants that can be selected for each stage. For the first and the second stage, the array of refrigerants is the same. Considering the third stage, fewer options are available. The best option is R-600 for the first and the third stages, with COP values of 4.143 and 5.877 respectively, and R-601 for the second stage with a COP value of 4.527. If a single-stage heat pump is supposed to deliver the same sink temperature of 150°C from a 10°C source temperature, then the temperature lift will be 160K. In this case, only R-601 and R-601a will comply, and the COP values will be 1.336 and 1.264 respectively with high-power compressors. The total COP value for the LEAP three stages is 2.539. The increase in using a 3-layered heat pump is an energy saving of almost 48%.

Table 5: The 3-layered heat pump results.

First Stage (0°C - 60°C)		Second Stage (50°C - 110°C)		Third Stage (100°C - 160°C)	
Refrigerant	COP	Refrigerant	COP	Refrigerant	COP
R-1234yf	3.801	R-600a (Isobutane)	4.11	R-1233zd (E)	5.704
R-1270 (Propylene)	3.907	R-600 (N-butane)	4.315	R-1336mzz (Z)	5.841
R-1225ye (Z)	3.926	R-1224yd (Z)	4.348	R-601a (Isopentane)	5.85
R-290 (Propane)	3.918	R-1336mzz (Z)	4.368	R-600 (n-Pentane)	5.877
R-1243zf	3.959	R-1234ze (Z)	4.441		
R-1234ze (E)	3.973	R-601a (Isopentane)	4.435		
R-600a (Isobutane)	4.06	R-1233zd (E)	4.475		
R-600 (N-butane)	4.143	R-601 (N-pentane)	4.527		

4. Conclusions

This paper analyzes the performance of a three-stage heat pump with multilevel heating based on different working fluids for taking advantage of the flexibility of heat pumps in comparison with other heating technologies. The most suitable low GWP refrigerants for condensing temperatures of 60°C, 110°C and 160 °C (at the evaporation temperature of 0°C, 50°C, and 100 °C respectively) have been studied in terms of operational and thermodynamic potential. The highest heating production is set at 150 °C, and the nominal heating capacity is 200 kW. The heat transfer to the external flow in the intermediate and low condensing temperature depends on the cycle selection.

Refrigerants have been classified according to the critical temperatures, pressures, and working pressure-temperature relationship. R-1224yd (Z), R-1234ze (Z), R-1234ze (E), R-1225ye (Z), R-1234yf, R-1243zf, R-290, R1270, R600, R00a with positive COP values have been proposed at the first stage to replace R134a; R-1336mzz (Z), R-1233zd (E), R-1224yd (Z), R-1234ze(Z), R-600, R-600a, R-601, and R-601a at the second stage; R-601, R-601a, R-1336mzz (Z) and R-1233zd (E) at the third stage. From that list, carbon dioxide, water, and ammonia have not been considered for this study because of the significant difference in critical temperatures and safety requirements to HFCs traditionally used (R-134a and R-245fa).

Refrigerants with a higher coefficient of performance capacity have been selected for each cycle. R-1234ze (E) and R-1233zd (E) as synthetic refrigerants, and R-600 and R-601 as natural refrigerants for a 2-layered heat pump with a total COP of 40% more than using the single-stage heat pump. R-1234ze (E), R-1233zd, R1336mzz (Z) as synthetic refrigerants, and R-600, R-601, and R-600 as natural refrigerants for 3-layered heat pump with a total COP of 48% more than using the single-stage heat pump. These values of COP are promising since it makes the heat pump a valuable alternative to natural gas boilers in most European countries.

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