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Performance Analysis of a Heat Pump Using Different Refrigerants to Supply Heat to Industrial Processes

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In a coupled system heat pump-solar thermal energy, the heat pump represents 50 % of the total cost, while the compressor represents 92 % of the total heat pump cost. Refrigerant and mass flow rate directly determine the cost and the operation of the compressor. In this work, a thermo-economic study of a heat pump coupled to solar thermal energy was carried out to determine the minimum energy cost, depending on the mass flow, varying the degree of subcooling and guaranteeing for each flow rate and three selected refrigerants, the heat load and the target temperature required by an industrial process. The three selected refrigerants were: R600a (ODP=0, GWP=3), R245fa (ODP=0, GWP=1030) and R1234ze(Z) (ODP=0, GWP=1.4). A pulp bleaching process for paper production was used as a case study. The heat pump uses a network of low-temperature solar collectors as a heat source, it reaches a temperature of 70 and 80 °C and operates with an irradiance of 443 W/m^2. For each refrigerant, the minimum cost was calculated based on the degree of subcooling and the mass flow rate. Refrigerant R1234ze(Z) produces the lowest levelized cost ($LCOE_t$) of 0.06058 $/kWh with a mass flow rate of 1.33 kg/s, a subcooling degree of 9 °C and a coefficient of performance (COP) of 3.19. The highest COP was 4.01 for the same refrigerant with a subcooling degree of 30 °C. By varying the mass flow rate of the refrigerant R1234ze(Z), the total cost of the heat pump can be reduced by up to 7 % and using other refrigerants by up to 26 % (R600a). Determination of the lowest total cost of the heat pump by varying the mass flow of the refrigerant allows reducing the energy cost by up to 19 %, making competitive the use of heat pumps feed with solar thermal energy for heat production.

1. Introduction

One of the largest energy consumers worldwide is the industrial sector, which in 2022 consumed 166 EJ that corresponds to 37 % of global energy consumption (IEA, 2023). In the same year and for the same sector, 65 % of the energy consumed was produced by burning fossil fuels. By burning, 9 Gt of CO_2 are released into the environment, the industrial emissions values correspond to a quarter of the total CO_2 emissions in the world (IEA, 2023). The integration of low temperature solar thermal systems is a feasible option for processes around 100 °C. The implementation of solar thermal devices in the industrial sector presents a high capital cost, derived from the large installation areas and the continuous supply of heat to the industrial process for 24 h (Farjana et al., 2018). Solar assisted heat pumps (SAHP) are devices that consist of a solar thermal energy source and a heat pump coupled together. Díaz-de-León et al. (2022) carried out a study where the thermal storage system was reduced by 44 % using a heat pump and the refrigerant R1234ze(E). Martínez-Rodríguez et al. (2023) conducted a thermo-economic analysis of a coupled system heat pump – solar thermal installation applied to a pair of processes, dairy and a second generation bioethanol (2 G). The results obtained were a competitive levelized energy cost of 0.0799 and 0.0409 $/kWh for the dairy and 2G bioethanol processes respectively, compared to the cost of fossil fuels (0.293 $/kWh).

In other studies, was analyzed the heat pump performance with variable operating conditions where the mass flow and the thermodynamic characteristics of the selected refrigerant are involved. The main aspects to be considered in the selection of the working fluid are thermal stability, critical temperature greater than 150 °C,

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critical pressure less than 30 bar or 3,000 kPa, zero value in ODP and GWP, toxicity and flammability, efficiency and availability (Arpagaus et al., 2018). Wu et al. (2020) conducted an experimental study of a high thermal heat pump (HTHP) using R718 at different operating conditions. For an evaporation temperature of 85 °C and a condensation temperature between 115 and 150 °C, the mass flow varied from 0.133 to 0.078 kg/s and the COP varied from 6.1 to 1.96. Navarro-Esbrí and Mota-Babiloni (2023) carried out an experimental analysis of a HTHP using R1336mzz(Z). Source temperatures were 83 to 107 °C, sink 102 to 158 °C, and subcooling -255.4 to -240.8 °C. For evaporation temperatures between 70 and 80 °C, the mass flow varies from 0.075 to 0.11 kg/s. The latter influences inversely the operation of the heat pump, decreasing heating from 12.3 to 9.2 kW and COP from 4.4 to 1.9.

A study of the potential of the industrial heat pump market in Europe was carried out by Marina et al. (2021), who estimated and found that there are not many studies that report the costs associated with heat pumps for industrial applications. Meyers et al. (2018) collected specific cost data of industrial heat pumps, the costs range from 300 to 1000 EUR/kW_{proc}, with an average value of around 400 EUR/kWproc. Schlosser et al. (2020), reported an average specific cost of the heat pump of 420 EUR/kW. In Annex 48 (EIA, 2019), were identified 25 heat pump manufacturing companies for steam production up to 280 °C, with specific costs ranging from 200 to 2000 EUR/kW_{proc}, these differences are attributed to the different technologies used. Kosmadakis et al. (2020) carried out a techno-economic analysis of heat pumps for industrial applications, the cost of the equipment was determined through correlations that depend on the geometric and operating characteristics of the main components of the heat pump: heat exchangers, compressor and receiver tank. Navarro-Esbrí and Mota-Babiloni (2023) experimentally evaluated the thermal performance of a heat pump (COP) using the refrigerant R1336mzz(Z) and varying the mass flow. To date, the relationship between the cost of energy and the mass flow and degree of subcooling of a heat pump powered by solar thermal energy, guaranteeing the heat load and the degree of subcooling demanded by an industrial process, has not been reported in the open literature.

In this work, 11 mass flow values were evaluated that vary inversely with the respective degree of subcooling for each flow and for 3 refrigerants. The refrigerant with the lowest energy cost of the three evaluated was R1234ze(Z) with 0.06058 USD/kWh. The present work seeks to minimize the cost of thermal energy production through the coupled system heat pump - solar thermal installation under operating conditions to guarantee the supply of the heat load required by a pulp bleaching process in the paper production industry. The mass flow rate of each refrigerant is determined based on the variation of the subcooling temperature of the refrigerant in the heat pump.

2. Determination of the minimum energy cost by varying the degree of subcooling for three refrigerants

The focus of this work is to determine the refrigerant mass flow rate of a heat pump that allows obtaining the lowest levelized cost of energy ($LCOE_t$). For the sizing of a coupled system heat pump – solar thermal installation, the design of the heat pump was carried out under the conditions that guarantee the supply of the heat load at the target temperature required by the industrial process. The pump design must ensure continuous delivery of a constant heat load to the condenser regardless of the working fluid being used. For the case study pulp bleaching process for paper production, it was considered that for the three refrigerants evaluated R600a (ODP=0, GWP=3) (Longo et al., 2022), R245fa (ODP=0, GWP=1030) (Dawo et al., 2021), and R1234ze (Z) (ODP=0, GWP=1.4) (Thu-Huong et al., 2022), condensation is carried out at 130 °C, with a temperature gradient of 10 °C between the condenser and the process (which is at 120 °C). The evaporation temperature in the heat pump was set at 50 °C, which is the temperature at which the minimum levelized energy cost was obtained (Martínez-Rodriguez et al., 2023). A schematic of the proposed device can be seen in Figure 1. The low temperature solar thermal installation is the heat source of the pump evaporator and the heat load required by the pulp bleaching process for paper production is removed in the heat pump condenser.

2.1 Case study: a pulp bleaching process for paper production

The bleaching process in the paper industry is a crucial stage in which the lignin that causes coloration to the final product is eliminated and the cellulose is left free. During the operation, the bleaching process is carried out twice per day, for a daily production of 1 t. The heat flux required per ton of product is 2.78 MWh (Lipiâinen et al., 2022) at the target temperature of 120 °C, considering an operation of 16 h per day and a daily production of 1 t of product. To design the industrial heat pump, the heat load required by the process that is supplied in the heat pump condenser is used as a starting point. The thermal load on the condenser is $\dot{Q}_{condHP} = 173.75$ kW and must be supplied at a temperature of 130 °C. The mass flow rate of the refrigerant, $\dot{m}_{ref}$, (kg/s) is a function of the degree of subcooling in the condenser, which varies in the range from 0 to 12 °C in intervals of 3 °C.

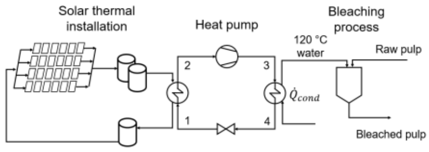


Figure 1: Simplified diagram of the proposed device

From the degree of subcooling, the condensation enthalpies of the refrigerants to be evaluated were determined. The mass flow rate of each refrigerant was determined by Eq(1).

$$\dot{Q}_{condHP} = \dot{m}_{ref}(h_3 - h_4) \tag{1}$$

Where h_3 is the enthalpy of the refrigerant at the outlet of the compressor, kJ/kg; while h_4 corresponds to the enthalpy at the condenser outlet of the heat pump. The enthalpies of the evaporation process depend on the degree of subcooling while the enthalpies of the compression process depend on the isentropic efficiency, reported to be 90 % (Yang et al., 2019). From these operating conditions, the power consumed by the compressor and the heat load on the evaporator were determined. The evaporation temperature is 50 °C for the three refrigerants, the degree of superheat is 10 °C for R600a and R1234ze(Z) and 14 °C for R245fa. To determine the performance of the heat pump, the COP was evaluated in each case.
The design of the solar collector network was carried out using the methodology proposed by Martínez-Rodríguez et al. (2019) based on the average irradiance levels that occur in winter (443 W/m^2). The solar collector network supplies 70 and 80 °C, 11 light h, an ambient temperature of 17.3 °C and a wind velocity of 2.87 m/s. ΔT=10 °C is considered between the hot water from the solar collector network and the superheated refrigerant (R600a and R1234ze(Z)) in the evaporator and for R245fa the ΔT=16 °C.

2.2 Cost calculation

The investment cost is a function of heat pump equipment. The cost of the storage system is estimated from the required volume of hot water to supply the heat load of the industrial process; a tank available on the market was used (13,280 USD per 15.4 m^3 tank). The cost of solar thermal energy is a function of the absorber area of the solar collector network, which depends on the heat load and the temperature level at which it must be supplied (Martínez-Rodríguez et al., 2023b). The average useful life of solar collectors is 25 y according to what is reported on the consumer power portal (The power of the consumer, 2024). In this case the collector cost was 350 USD/m^2. To estimate the compressor cost was used Eq(2) (Calado, 2012).

$$C_{comp}(\$) = 4896.57\dot{W}_{compHP}^{0.8} \tag{2}$$

Where C_{comp} is the cost of the compressor, USD; and $\dot{W}_{comp}$, is the power consumed by the compressor, kW.
The costs of the heat exchangers (condenser and evaporator) were determined using the expression reported by Selbas et al. (2006), Eq(3).

$$C_{hexc}(\$) = 516.621A + 268.45 \tag{3}$$

Where C_{hexc} is the heat exchanger cost, USD; and A is the heat exchanger area, m^2. To determine the heat transfer area, it is calculated from the general heat exchange design equation.

$$Q = UA\Delta T_{lm} \tag{4}$$

Because the working fluids are water and organic liquids, as reported by Sinnot et al. (2005), the overall heat transfer coefficient for shell and tube type heat exchangers is $U = 900$ W/m^2 °C, (evaporator and condenser). ΔT_{lm} is calculated for each case considering the temperatures of the streams that exchange heat.
The levelized cost of energy production of the system is determined by Eq(5) and represents the profitability of the proposed system.

$$LCOEt = \frac{(C_{inv})CFR + C_{op} + C_{maint} + C_{auxserv}}{\dot{E}_{sys}} \tag{5}$$

Where C_{inv} is the investment cost of the equipment, CFR is the capital recovery factor considered for a period of 25 y and an interest rate of 8 %, $C_{auxserv}$, are the costs of auxiliary services (electricity price = 0.3435 USD/kWh), $\dot{E}_{sys}$, is the energy produced. Additional costs for operation, maintenance and overhead are considered as a percentage of the investment costs, so that $C_{op} = 0.15C_{inv}$ (raw materials, protective equipment, operating personnel, etc.), $C_{maint} = 0.1C_{inv}$ (cleaning, lubrication and protection of equipment;

repairs and replacement of parts; among others) and $C_{gen} = 0.75 C_{op}$ (office payrolls, tax payments and commissions, advertising, etc.) To verify the feasibility of the proposed system, a comparison was made between the levelized cost obtained with that reported using natural gas to produce energy, which was 0.075 $/kWh for business consumption (GlobalPetrolPrices, 2023).

The simple payback is also estimated, this indicator relates the investment cost of the proposed system, C_{inv}, and the savings obtained by replacing the natural gas consumption of the current system, USD/y, Eq(6). Where, $S_{fossil\ fuel}$, are the annual savings from the use of fossil fuel since the current system operates with natural gas.

$$Payback = C_{inv}/S_{fossil\ fuel} \quad (6)$$

3. Results

The results were obtained from the thermal energy requirement of the paper bleaching process, which is 173.75 kW. The operating conditions of the heat pump are 50 °C for evaporation and 130 °C for condensation. To achieve the required degree of superheating of the refrigerant, two source temperatures were used, 70 °C for R600a and R1234ze(Z), and 80 °C for R245fa.The compressor raises the pressure from 630 kPa to 3326 kPa in the case of R600a, for R245fa it is increased from 340 kPa to 2400 kPa and for R1234ze(Z) it is increased from 40 kPa to 1400 kPa.

Table 1 shows the costs for each refrigerant at different subcooling temperatures. As the degree of subcooling in the condenser increases, the refrigerant mass flow decreases for all three refrigerants. The mass flow of the refrigerant directly impacts the size of the equipment in the heat pump and the solar collector network, and therefore, the investment costs of the equipment. By increasing the mass flow of the refrigerant, the heat load on the evaporator decreases and the work required on the heat pump compressor increases. The opposite occurs when the mass flow of refrigerant decreases.

Table 1: Cost estimation for each refrigerant.

R600a					R245fa				R1234ze(Z)			
T_{sub} (°C)	C_{compHP} ($)	C_{hexc} ($)	C_{invHP} ($)	C_{invSN} ($)	C_{compHP} ($)	C_{hexc} ($)	C_{invHP} ($)	C_{invSN} ($)	C_{compHP} ($)	C_{hexc} ($)	C_{invHP} ($)	C_{invSN} ($)
0	220,577	6,112	226,689	145,719	144,552	7,811	152,362	262,546	135,063	7,883.65	142,947	247,799
3	193,778	7,075	200,854	179,011	139,071	8,293	147,364	269,402	129,587	8,344.69	137,932	253,885
6	175,630	8,069	183,699	200,915	134,036	9,007	143,043	275,647	126,205	8,990.65	135,195	257,596
9	162,242	9,942	172,184	216,734	128,508	10,743	139,251	282,433	120,000	10,646.28	130,647	264,381
12	151,530	15,683	167,213	229,139	124,277	16,250	140,528	287,575	116,458	17,467.89	133,926	268,327
15	142,784	17,319	160,103	239,119	119,595	17,783	137,378	293,219	113,142	19,293.50	132,436	271,883
18	135,446	19,249	154,695	247,372	115,984	19,634	135,618	297,532	110,638	21,320.53	131,959	274,551
21	129,162	21,750	150,911	254,352	112,610	22,074	134,684	301,533	107,107	24,026.49	131,133	278,289
24	123,715	25,182	148,897	260,333	109,449	25,459	134,908	305,254	103,820	27,782.70	131,602	281,741
27	118,918	30,263	149,181	265,548	107,060	30,492	137,551	308,049	101,751	33,362.55	135,114	283,899
30	114,657	38,657	153,315	270,135	104,233	38,857	143,090	311,335	99,773	38,940.51	138,713	285,952

The cost of the heat pump using R600a represents 61 % of the total investment cost for T_{sub}=0 °C and 42 % for T_{sub}=12 °C, using R1234ze(Z) the percentage is 58 % and 49 % for the subcooling temperature from 0 and 12°C. The cost of the compressor represents 90 % of the total cost of the heat pump when using R600a and 86 % for R1234ze(Z) for T_{sub}=12 °C.

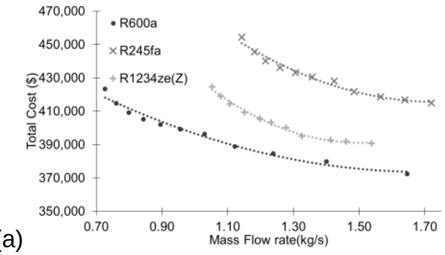
Table 2 shows the results obtained from the coupled system heat pump – solar thermal installation for each refrigerant: the mass flow rate, the COP, the levelized cost of energy, and the payback in function of the degree of subcooling (T_{sub}). It can be seen that for the refrigerant R600a the minimum value of $LCOE_t$ corresponds to a subcooling temperature of 12 °C with a mass flow of 1.03 kg/s. For the refrigerants R245fa and R1234ze(Z), the minimum $LCOE_t$ values were obtained for a subcooling temperature of 9 °C in both cases, with a mass flow rate of 1.49 and 1.33 kg/s. It is observed that the mass flow rate decreases as the subcooling temperature increases, this is because the difference in condensation enthalpies increases by guaranteeing the supply heat load. The decrease in the refrigerant mass flow rate directly affects the compression process, which also decreases, causing the COP value to increase. For the lowest energy cost (LCOE=0.06058 $/kWh) the cost of the heat pump represents 50 % of the total investment and the compressor represents 91.8 %.

Regarding the investment cost using R1234ze(Z), a 7 % reduction occurs when the subcooling temperature increases from 0 °C to 12 °C, and for R245fa and R600a refrigerants the cost reduction is 8 % and 26 % with the same subcooling range, because the compressor size is reduced. The R1234ze(Z) has the lowest payback at 1.8 y.

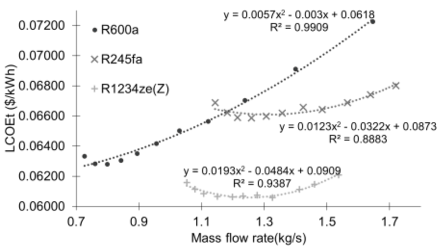
Table 2: Results of the coupled system heat pump - solar thermal installation for each refrigerant.

T_{sub} (°C)	R600a $\dot{m}_{ref}$ (kg/s)	COP	$LCOE_t$ ($/kWh)	Payback (y)	R245fa $\dot{m}_{ref}$ (kg/s)	COP	$LCOE_t$ ($/kWh)	Payback (y)	R1234ze(Z) $\dot{m}_{ref}$ (kg/s)	COP	$LCOE_t$ ($/kWh)	Payback (y)
0	1.65	1.49	0.07225	3.1	1.72	2.53	0.06802	2.1	1.54	2.75	0.06208	2.0
3	1.40	1.75	0.06911	2.8	1.64	2.65	0.06741	2.0	1.46	2.89	0.06147	1.9
6	1.24	1.98	0.06703	2.5	1.57	2.78	0.06688	2.0	1.41	2.99	0.06113	1.9
9	1.12	2.19	0.06563	2.4	1.49	2.93	0.06642	1.9	1.33	3.19	0.06058	1.8
12	1.03	2.38	0.06502	2.3	1.42	3.05	0.06658	1.9	1.28	3.31	0.06100	1.8
15	0.96	2.56	0.06416	2.2	1.36	3.20	0.06620	1.9	1.23	3.43	0.06082	1.8
18	0.89	2.74	0.06350	2.1	1.31	3.33	0.06598	1.9	1.20	3.53	0.06076	1.8
21	0.84	2.91	0.06304	2.1	1.26	3.45	0.06587	1.8	1.15	3.67	0.06066	1.8
24	0.80	3.07	0.06280	2.0	1.22	3.58	0.06589	1.8	1.11	3.82	0.06072	1.8
27	0.76	3.22	0.06283	2.0	1.18	3.68	0.06621	1.9	1.08	3.92	0.06114	1.9
30	0.73	3.37	0.06333	2.1	1.14	3.80	0.06689	2.0	1.05	4.01	0.06158	1.9

Figure 2(a) shows the curve that relates the total cost to the mass flow rate of the three refrigerants and presents a quadratic behavior that tends towards a horizontal asymptote as the mass flow rate increases. The total cost increases at lower mass flow because the network of solar collectors increases due to the load required on the heat pump evaporator. There is a design space where there are several mass flows with a minimum total cost of the proposed system. For each of the refrigerants, a minimum is observed that represents the mass flow with the minimum energy cost. Figure 2(b) represents the relationship of the levelized cost of energy for the three refrigerants considered in the study (LCOEt) versus the variation of the mass flow for each refrigerant. There is a region of mass flow values that can be selected since the energy cost does not vary significantly. The behavior of the three refrigerants is represented by a quadratic equation, the value of the coefficient of determination (R2) indicates the percentage of dependence of the LCOEt on the mass flow rate. In the trend curves, the coefficients of the polynomials are small, so the curvature is also small, however, in all quadratic functions a minimum of the energy cost is observed for each of the refrigerants. The variations in the minimum energy cost between the three refrigerants are not significant, as they do not exceed 10 %. The lowest energy cost for the case study was 0.06058 $/kWh and was obtained for the coupled system heat pump - solar thermal installation that operates with R1234ze(Z), operating conditions are: Tevap in=50 °C, Tcomp in=60 °C, Tcond in=135 °C y Texpvalv in=121 °C, pressure ratio (Pcond/Pevap) is 14/4 (bar).



(a)



(b)

Figure 2: Behavior of: (a) total cost and (b) $LCOE_t$ as a function of the mass flow rate of each refrigerant.

4. Conclusions

The total cost of the coupled system heat pump – solar thermal installation for the three refrigerants decreases as the mass flow increases and the energy consumption in the compressor increases with increasing mass flow rate. Comparing the three refrigerants, the minimum total cost is for R600a with a value of $372,408 and a mass flow rate of 1.65 kg/s where the compressor represents 61% of the total cost. The best scenario with the minimum energy cost was obtained with the refrigerant R1234ze(Z) (ODP=0 and GWP=1.4); the system operates with a mass flow of 1.33 kg/s for a degree of subcooling of 9 °C; it has a LCOEt of 0.06058 $/kWh and a payback of 1.8 y. Also, it has the lowest impact on the environment with 197 tCO2/y that are no longer emitted into the atmosphere. Likewise, it has the highest performance compared to other refrigerants (COP=3.19).

The need to handle different mass flow rates requires different degrees of subcooling that significantly impacts the total cost, energy cost and payback. On the other hand, it is implicit, in addition to the cost, to minimize the impact on the environment. The application of the use of different mass flow rates is due to the variability of the solar resource that occurs on an hourly, daily and seasonal basis. Some of the variations in the irradiance level can be absorbed by the storage tank, however the irradiance varies significantly.

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