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PERFORMANCE OF LOW GWP FLUIDS IN HEAT PUMP SYSTEMS

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ABSTRACT

Heat pumps are increasingly gaining popularity as the world is moving towards low-carbon energy systems. Use of heat pumps for domestic heating and hot water is widely seen as a sustainable option, and a step further from conventional fuel dependence. In spite of being 'green' in terms of carbon-pollution, there is a need to move towards low GWP working fluids in heat pump systems to ensure minimal impact to the environment.

Low GWP fluids and mixtures have been emerging in the light of sterner legislations being introduced to limit, if not to totally prevent, further use of high GWP fluids. Replacement fluid has to satisfy a number of criteria, primarily to perform similarly to the original fluid. We have compared high and low GWP fluids, as well as several mixtures, as working fluids in the same operational scenario. Low GWP fluids are fundamentally different from conventionally used one, but their performance has some promising features.

INTRODUCTION

With global energy demand being on the rise, energy efficiency and alternative energy supply are firmly embedded in the centre of scientific research. Whilst pursuing efficient power and heat production systems, there is a requirement for suggested solutions to be sustainable and environmentally friendly. With impact of global warming being more prominent, greater pledges are made towards reduction in CO_2 emissions and pollution in general.

Heat pumps and refrigeration systems have long been known and successfully employed in numerous commercial and industrial applications. With developing countries becoming more affluent, a sharp rise in air-conditioning demand is likely, potentially accelerated by the climate change. Use of heat pumps is widely seen as a low carbon option, especially for domestic heating and hot water supply [1]. Heat pumps require only moderate electricity input to power the compressor, and heat can be sourced from a variety of mediums. Air source heat pump, which absorbs heat from ambient air (exhaust air heat pumps have also been developed), is a popular option due to low installation and capital costs. Performance is limited and the running costs can be high. Ground source heat pump extracts heat from the ground, where the temperatures are relatively constant (around 10°C all year round). Typical performance is better compared to air source heat pump, but access to land is required and capital costs are higher.

Various water source heat pumps are building a reputation. Reversible heat pumps, which can provide heating during the winter and cooling during the summer, are gaining popularity in countries where climate varies greatly across the year. Currently, there are large discrepancies in heat pump market shares globally. Probably the most important reason heat pumps are not more popular in developed countries is their cost relative to the most common alternatives [2]. Continuous improvement of heat pump technology and better performance may eventually entice the market [3]. However, even with novel system designs and installation there is no expectation of a dramatic improvement to heat pump performance [4].

Montreal protocol initiated the worldwide phase-out of ozone-depleting chlorofluorocarbons (CFCs). Subsequently, a schedule was established for gradual caps on consumption and production of hydrochlorofluorocarbons (HCFCs), whose Ozone Depletion Potential (ODP) cannot be overlooked. Hydrofluorocarbons (HFC) have no adverse effect on the stratospheric ozone layer, yet their Global Warming Potential (GWP) is of concern. Kyoto protocol outlines minimization of high GWP of working fluids as one of the priorities. With continuous efforts to reduce greenhouse gas emissions and raising environmental concerns, the future of HFCs in heat pump systems is uncertain. Since Montreal and Kyoto protocols, a number of pure fluids and fluid mixtures have been suggested as suitable replacement fluids for R22, amongst others R134a, R407C, and R410A, whose GWP is considerable. Furthermore, R134a is being phased out in Europe, and the initiative to completely ban most uses of HFCs in developed countries is well under way. Low GWP refrigerants are available, and more are being developed to replace the current generation of HFCs. Hence, it is not surprising they are in the spotlight on current scientific research [5, 6] (and references therein). Presently a range of hydrofluoroolefin (HFO) looks promising.

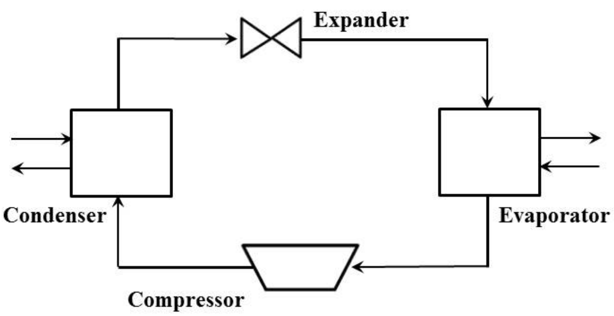

Figure 1. Schematic of a simple heat pump unit.

SYSTEM MODEL

Heat pump operation was modelled assuming steady-flow, steady-state system, with negligible kinetic and potential energy losses. Pressure drops in all cycle elements were ignored, with pressure changes occurring only during compression and expansion processes. Schematic of a simple heat pump system is given in Figure 1. Main processes can be outlined as: adiabatic compression, isobaric cooling in the condenser, isenthalpic expansion in the throttle, and isobaric heating in the evaporator. Saturated liquid state at the condenser outlet, and saturated vapour state at the inlet of the compressor were assumed in all cases. Evaporator operational pressure was determined as the saturation pressure at ambient temperature, which was varied in 273K – 300K range. Condensation temperature was fixed at 333K. Compressor isentropic efficiency of 80% was assumed.

Heat and work exchanges were calculated as enthalpy gradients between relevant points of the cycle, as outlined below:

$$q_E = h_1 - h_4 \tag{1}$$

$$q_C = h_2 - h_3 \tag{2}$$

$$w_{comp} = h_2 - h_1 \tag{3}$$

where numbering depicts the relevant points of the cycle: 2 and 3, for condenser inlet and outlet states, and 4 and 1, for evaporator inlet and outlet conditions, respectively. All fluid properties were evaluated by REFPROP 9.1. Coefficient of performance (COP) and exergetic efficiency were calculated as:

$$COP_{HP} = \frac{q_C}{w_{comp}} \tag{4}$$

$$\eta_{ex} = \frac{q_C\left(1 - \frac{T_0}{T_C}\right)}{w_{comp} + q_E\left(1 - \frac{T_0}{T_E}\right)} \tag{5}$$

where T_E, T_C, and T_0 are temperatures of the evaporator, condenser and dead-state, respectively. Maximum temperature difference in operational temperatures of the cycle was calculated as shown below. Exergy destruction in individual cycle components was evaluated from the exergy balance:

$$ex_{in} + q\left(1 - \frac{T_0}{T}\right) = ex_{out} + w + i \tag{6}$$

$$\Delta T = T_2 - T_E \tag{7}$$

Three groups of fluids were considered. Firstly, historically used pure refrigerants, with high GWP and ODP: R12 and R22. These harmful fluids are included in the study for comparison purposes only. Suggested R22 replacement fluids [7], R134a and R245fa, were considered. Despite being widely used nowadays, high GWP fluids are expected to face bans in not too distant future as more low GWP fluids are being developed and their use encouraged due to environmental concerns and global warming effects.

Second group comprised of selected mixtures, which have been developed to address high GWP fluids phase out whilst maintaining satisfactory performance characteristics. Nearly azeotropic mixtures, R404A (44% R125 + 52% R143a + 4% R134a) and R410A (50% R32 + 50% R125) have been designed to be used as R22 replacements. Zeotropic mixture R407C (23% R32 + 25% R125 + 52% R134a) is a similar blend with higher critical temperature, where three components deliver desired heat capacity, reduced flammability and pressure. It must be noted that the mixtures contain very high GWP fluids, R143a and R125 (GWP of 4300 and 3450, respectively). Overall GWP is lower due to the presence of more moderate GWP fluids, R32 (GWP = 650) and R134a (GWP = 1300). However, they still present a considerable environmental concern. In particular, R404A is the most widely used gas in the EU in stationary refrigeration systems, yet revised f-gas regulations will introduce a ban on the use of virgin HFCs with a GWP higher than 2500 from 2020.

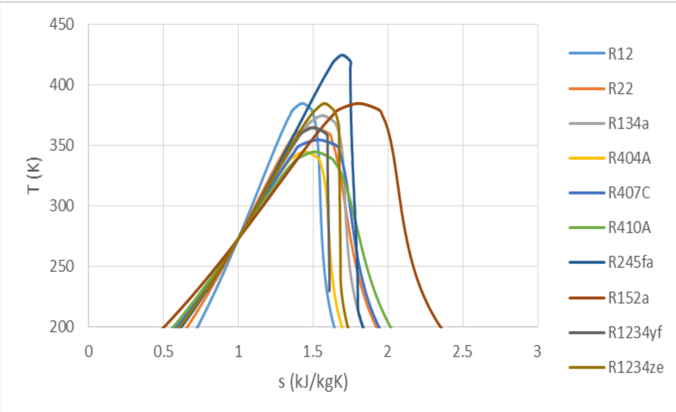

Figure 2. Saturation curves of selected fluids.

Table 1. Basic thermodynamic properties of selected fluids.

Fluid	*M*	T_b	T_c	p_c
	(kg/kmol)	*(K)*	*(K)*	*(MPa)*
R12	120.91	243.40	385.12	4.1361
R22	86.47	232.34	369.30	4.9900
R134a	102.03	247.08	374.21	4.0593
R245fa	134.05	288.29	427.16	3.6510
R404A	97.604	226.93/227.68*	345.27	3.7349
R407C	86.204	229.53/236.52*	359.29	4.6394
R410A	72.585	221.71/221.79*	349.49	4.9012
R152a	66.051	249.13	386.41	4.5168
R1234yf	114.04	243.70	367.85	3.3822
R1234ze	114.04	254.18	382.51	3.6349

* Liquid/Vapour phase temperature at saturation at atmospheric pressure

In the light of stringent environmental regulations a number of low GWP fluids entered international refrigerant market and quickly gained popularity. R152a has been seen as a potential replacement for R134a due to the similarity in operational parameters, but R152a GWP is one tenth of R134a one. Furthermore, family of hydrofluorolefins (R1234 group) has been developed to fully replace R134a. Their GWP is extremely low; however, there are flammability issues. Basic thermodynamic parameters of the considered fluids are given in Table 1. Ozone depletion potential and global warming potential, as well as ASHRAE flammability and toxicity classifications are given in Table 2.

As shown on Figure 2, R152a is a slightly wet fluid, with the widest curve. Saturated vapour side is practically vertical for R245fa, R1234yf and R1234ze. Thus, these are isentropic fluids. With the highest critical temperature, R245fa saturation dome is obvious. Compared to R1234yf, R1234ze has higher critical point and generally larger saturation curve. Majority of fluids fall into A1 category. Low GWP fluids typically have higher flammability; hence, A2 and A2L classification. The only high toxicity fluid (B) fluid considered is R245fa.

Table 2. Environmental and safety properties of selected fluids.

Fluid	*ODP***	*GWP****	*ASHRAE Class*****
R12	1	4000	A1
R22	0.05	1700	A1
R134a	0	1300	A1
R245fa	0	1030	B1
R404A	0.04	3300	A1
R407C	0	1610	A1
R410A	0	1725	A1
R152a	0	120	A2
R1234yf	0	4	A2L
R1234ze	0	<1	A2L

** ODP: Ozone depletion potential, relative to R11;
*** GWP: Global warming potential, relative to CO_2;
**** ASHRAE Standard 34 – Refrigerant safety group classification. 1: No flame propagation; 2: Lower flammability; 3: Higher Flammability; A: Lower Toxicity; B: Higher Toxicity.

RESULTS AND DISCUSSION

Evaluation of heating performance of different refrigerants is presented in Figure 3 as a function of the evaporator temperature. Coefficient of performance increased with evaporator temperature similarly for all fluids. However, larger variations were observed for higher evaporator temperatures. Notable lower COP values were found for the mixtures, with R404A showing poorer performance than the other two. Best performing fluids, R245fa and R152a, reached COP values above 7 for the highest evaporator temperatures, outperforming R12, while R1234ze showed identical COP rise as R134a. COP of R1234yf cycle was higher than those of the mixtures, yet lower than any pure fluid. Interestingly, the difference between R1234 fluids was practically constant (0.5) across the temperature range. Our model is in agreement with Gorozabel Chata et al.[8] results, showing poorer performance of mixtures compared to high GWP pure fluids. Our results for R410A are somewhat lower than those reported by Palmiter et al. [9], yet this is presumably due to different assumption for compressor efficiency. Superb performance of R245fa has confirmed by Pan et al. [10], who suggested R245fa/R600 mixtures for high temperature conditions.

Further differences in fluid behaviour were observed through comparison of the required compressor input. Specific work of compression is presented in Figure 4. By far the highest compressor work was needed for R152a; a third higher than the second highest compression work for R407C and practically twofold of the lowest work input of R12. Due to very low compressor demand R12 and its replacement R404A were historically favoured; our results identified identical behaviour of R1234yf, and somewhat higher values for R1234ze. Required work input of R245fa was marginally higher than that of R134a. Interestingly, R22 required higher compressor work than any of the suggested replacement fluids, including low GWP ones. Mixtures, R407C and R410A, also showed significant compressor input.

Figure 5 depicts the magnitude of heat delivered to the condenser as the function of the evaporator temperature. Heat load varied largely for different fluids, with R152a again reaching an immense value. Having high compressor work and high heat input, it is not surprising R152a had very high COP. Heat delivered by R22 was the second highest below 14°C. Above this temperature threshold, R245fa showed marginally better performance. Both fluids also reached comparable COP values. However, R245fa is showing the best overall performance whilst requiring the lowest compressor work. The lowest amount of heat rejected was identified for R404A case. Low condenser outputs were also evaluated for R1234yf, R12, and R1234ze. Compared to R1234yf, R1234ze heat rejection load was higher. R1234ze compressor work was greater as well, and overall performance was better. Conversely, R1234yf had the lowest work requirement, but also the poorest performance of all pure fluids. Two R1234 refrigerants needed lower compressor input, but also absorbed less heat during evaporation compared to R134a. Hence, the performance was poorer and less heat available to the condenser.

Maximum temperature difference, between the compressor inlet and outlet states, as specified in Eq. 7, presented in Figure 6 allows for three distinct groupings. R12, R404A and R134a showed virtually identical decrease in compressor outlet temperature. Other two mixtures, R407C and R410A, as well as R22, have reached notably higher temperatures at the end of compression step. Temperatures calculated for R152a compression were slightly lower than those of the top group, but still significant. On the other hand, R245fa and R1234 refrigerants achieved modest temperature lift, on average 10K lower than the intermediate group, and up to 30K lower than the high temperature group.

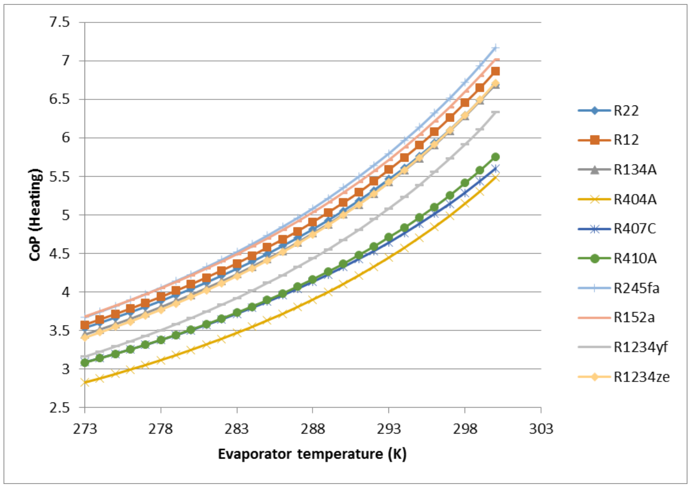

Figure 3. Coefficient of heat pump performance of selected refrigerants as a function of evaporation temperature.

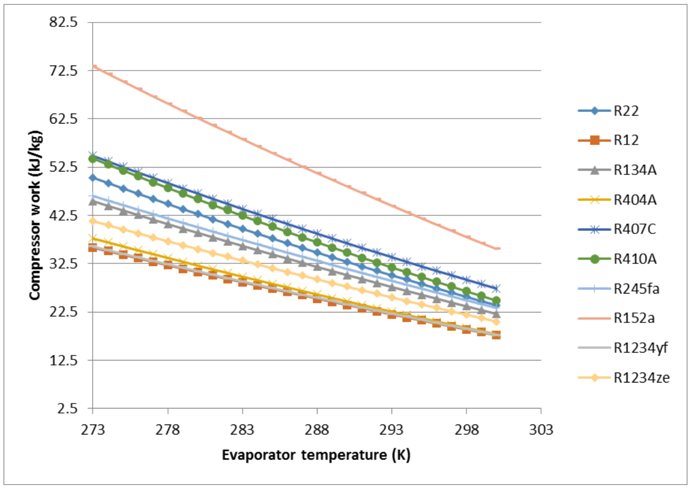

Figure 4. Required compressor work for different refrigerants as a function of the evaporator temperature.

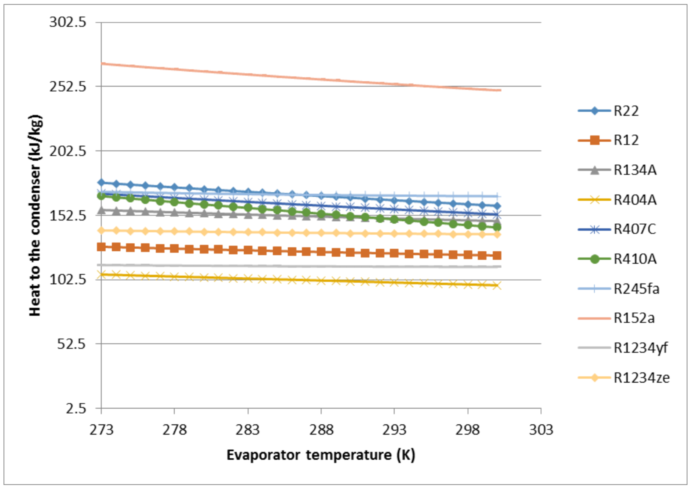

Figure 5. Specific heating load of different refrigerants as a function of the evaporator temperature.

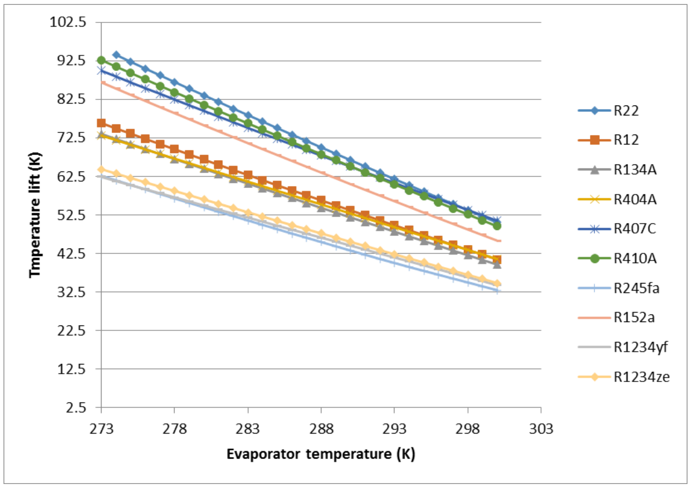

Figure 6. Temperature lift in different refrigerant systems as a function of the evaporator temperature.

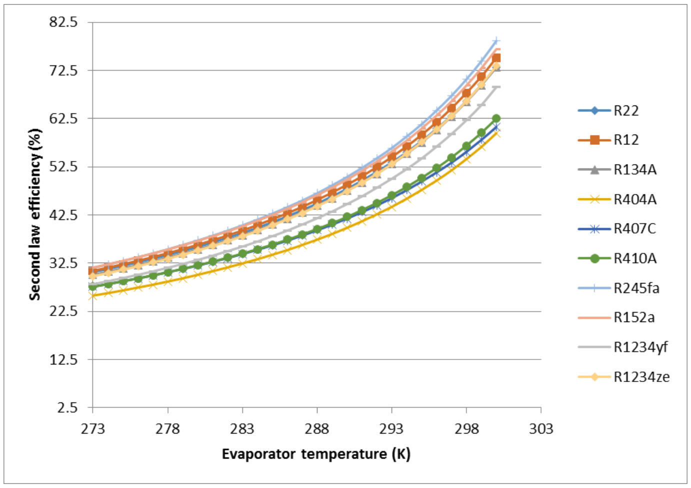

Figure 7. Exergetic efficiency of different refrigerants as a function of the evaporator temperature.

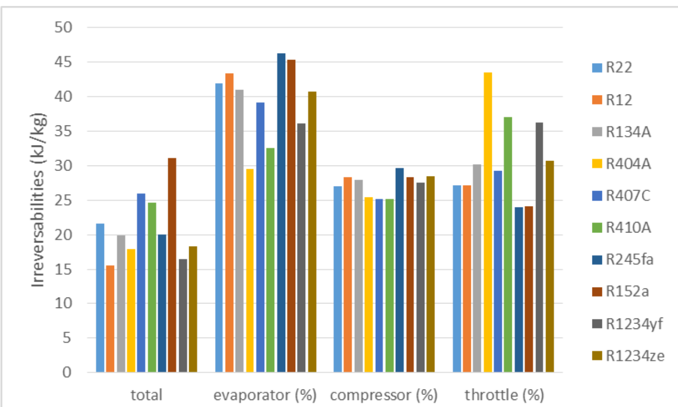

Figure 8. Overall exergy destruction and its distribution across cycle components for different refrigerants at T_E = 15 °C.

In terms of exergetic performance, our selected fluids can be roughly divided into two groups, as shown in Figure 7. Tested mixtures generally showed lower exergetic efficiency than pure fluids, with R1234yf being the worst performing fluid in the latter category. While pure fluids showed very similar increase of exergetic efficiency with evaporator temperature, slightly larger values were found for R245fa and R152a, with R1234ze yielding identical efficiencies as R134a. Nevertheless, comparison of overall exergy destruction values paints a different picture. Total irreversibilities varied greatly; R22, R404A and R1234 fluids had low exergy destruction rates, whilst the highest one was observed for R152a. Distribution of exergy destruction in individual cycle components is of interest. Approximately 25% of irreversibilities occurred during the compression for all mixtures, and up to 30% for pure fluids. However, exergy destruction in the evaporator and the throttle were very dissimilar for different fluids. The expansion process was the primary cause of irreversibilities for R404A, R410A and R1234yf. On the other hand, for R245fa and R152a more than 45% of destroyed exergy can be contributed to the evaporation.

Table 3. Additional properties of selected fluids.

	Thermal conductivity (mW/mK)		*Kinematic viscosity (cSt)*	
	T_E = 15 °C	T_C = 60 °C	T_E = 15 °C	T_C = 60 °C
R22	9.70	55.18	0.4026	0.1101
R12	10.48	67.11	0.3618	0.1049
R134a	12.85	66.16	0.4773	0.1176
R404A	14.50	50.64	0.2408	0.0860
R407C	13.43	67.72	0.3704	0.0992
R410A	13.84	70.86	0.2681	0.0823
R254fa	12.22	77.00	1.7088	0.2066
R152a	13.58	83.48	0.7131	0.1360
R1234yf	12.91	53.29	0.3786	0.1057
R1234ze	12.75	62.85	0.6135	0.1267

Further fluid properties were also taken in account when evaluating suitability of low GWP refrigerant to be used in heat pump systems. Thermal conductivity is essential to ensure effective heat transfer, while low viscosity is desirable to avoid frictional losses in cycle elements. Selected fluid properties are presented in Table 3 for T_E = 15 °C and T_C = 60 °C. Thermal conductivity of mixtures was higher at lower temperatures making them good working fluids in low temperature environments. However, at condenser temperature significantly higher thermal conductivity values were found for R152a and R245fa; R1234 fluids had lower values which may cause issues in heat transfer in the condenser. Additionally, R152a and R245fa have notably higher kinematic viscosities than pure fluids, which could prove to be problematic, primarily for compressor operation, but also for the system on the whole. Nonetheless, R1234 fluids had lower viscosities, similar to those of pure high GWP fluids, and with appropriate thermal properties [11] must be considered as likely replacement for conventional working fluids in heat pump systems.

CONCLUSION

Gradual phase out of high GWP fluids threatens to affect current systems performance unless suitable low GWP replacement fluids are found. We have assessed the behavior of various fluids, concentrating on potential low GWP replacement fluids for R134a. Coefficient of performance of R152a and R245fa is somewhat higher than that of R134a. However, R152a requires substantial compressor work, while R245fa, despite comparable heat and work exchanges, is a highly toxic fluid. R1234 fluid family is also promising. R1234ze shows similar thermal performance and exergetic efficiency. Additionally, these fluids exhibit very modest exergy destruction rates and they may have an important role in the search for high GWP replacement fluids

NOMENCLATURE

ex	specific exergy (kJ/kg)
h	specific enthalpy (kJ/kg)
i	specific irreversibility (kJ/kg)
M	molecular mass (kg/kmol)
p	pressure (MPa)
q	specific heat (kJ/kg)
s	specific entropy (kJ/kgK)
T	temperature (K)
w	specific work (kJ/kg)
η	efficiency (%)

Subscripts

0	reference state
1, 2, etc.	states of the cycle
b	normal boiling point
c	critical
comp	compressor
C	condenser
E	evaporator
ex	exergetic
in	inlet
HP	heat pump
out	outlet
p	pressure
T	turbine
th	Thermal

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