International Journal of Advance Research and Innovation
Vol. 3(1), Jan-Mar 2015, pp. 187-194
Doi: 10.51976/ijari.311533
www.gla.ac.in/journals/ijari

Article Info
Received: 02 Feb 2015 | Revised Submission: 20 Feb 2015 | Accepted: 28 Feb 2015 | Available Online: 15 Mar 2015

Thermal Analysis & Optimization of Two Stages Vapour Compression Refrigeration Systems Using Sixteen Ecofriendly Refrigerants

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ABSTRACT

This paper mainly deals with comparative computation performance evaluation of sixteen ecofriendly refrigerants used in the two stage vapour compression refrigeration system based on energetic and exergetic principles for findingsystem and components irreversibilities . Performance parameters have been evaluation using entropy generation concept. The numerical computation was carried out for finding rational exergy destruction ratio based on system exergy input in terms of total work dene by compressors as will as exergy destruction ratio based on exergy of product out and first law efficiency in terms of COP . The second law efficiency in terms of exergetic efficiency is also computed at different input variations . It was found Flash chamber responsible for highest exergy destruction for all refrigerants taken under consideration . R123 shows best first law efficiency and R125 shows lowest first law performance among selected sixteen ecofriendly refrigerants The first and second law performance of using R1234ze (of GWP =6) is better than R1234yf (of GWP=4) for higher temperature applications. The exergy destruction using R134a is higher than R152a. R1234yf refrigerant has (GWP = 4) can be used for high temperature applications which can replace R134a around 2030 and R152a, R600a, , R290, R600 are flammable in nature can be used by using safety measures. Therefore R134a recommended for all kind of applicationsbefore 2030.

Keywords: *Irreversibility; Exergetic Efficiency; Two Stage Vapour Compression Refrigeration Systems*.

1.0 Introduction

In past decades, refrigerants such as R12,R02,R22 etc. used in vapour compression refrigeration system responsible for increasing of global warming and ozone depletion potential. An international society named Montreal protocol discussed and signed on the refrigerants having higher global warming and ozone depletion potential values for all countries. In order to control the emission of green house gases one more committee was formed named as Kyto protocol [5].After 90's a program was ran to phase out the higher GWP and ODP refrigerants(CFC and HCFC) for the purpose of environmental problems.

To replace "old" refrigerants with "new" refrigerants lots of researches has been lots of researches has been carried out]. Coefficient of performance can be enhanced either by minimizing power consumption of compressor or increasing of refrigeration effect. Refrigeration effect can be increased by adoption of multi-stage throttling .On the other hand power consumption of compressor can be enhanced by incorporation of multi-stage compression and flash chamber. Collective effect of these two factors improves overall performance of vapour compression system as reported by several investigators [1-11].

2.0 Literature Review

Selladurai and Saravanakumar [12] evaluated performance parameters such as COP and exergetic efficiency with R290/R600 hydrocarbon mixture on a domestic refrigerator designed to work with R134a and observed that performance of same system is higher with R290/R600a hydrocarbon mixture compared to R134a. In their analysis condenser, expansion valve and evaporator showing lower exergy destruction compared to compressor. Reddy et al. presented theoretical analysis of R134a, R143a, R152a, R404A, R410A, R502 and R507A in vapour

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compression refrigeration system and effect on coefficient of performance and second law efficiency with variation of superheating of evaporator outlet, evaporator temperature and degree of subcooling at condenser outlet, vapour liquid heat exchanger effectiveness and degree of condenser temperature was discussed. They reported that COP and exergetic efficiency significantly affected with change of evaporator and condenser temperatures and also observed that R134a and R407C show highest and lowest performance in all respect. Kumar et al. they carried out energy and exergy analysis of single stage vapour compression refrigeration system using Rll and R12 as working fluids. Evaluation in terms of COP, exergetic efficiency and exergy losses in different components (compressor, evaporator, expansion valve and condenser) was done. Cornelissen proposed that non-renewable energy sources are useful for minimizing the irreversibility of the system for sustainable development of systems vapour compression refrigeration systems. Fatouh and Kafafy suggested to replace R134a with hydrocarbon mixtures such as propane, propane/isobutane/n-butane mixtures, butane, and various propane mass fractions in domestic refrigerator. Pure butane showed high operating pressures and low coefficient of performance among considered refrigerants. Wongwises et al. did experimental investigation on automotive air-conditioners with isobutene, propane, butane and suggested to replace R134a with these hydrocarbon mixtures.They observed that mixture of propane 50%, butane 40%, and isobutane 10% was best hydrocarbon mixture to replace Rl34a.Jung et al., Arcaklioglu, and Arcaklioglu et. al suggested to use of pure hydrocarbon instead of their mixtures due variation in condenser and evaporator temperature during phase changing at constant pressure. These Changes in condenser and evaporator temperature cause for problem in vapour compression refrigeration cycle. Liedenfrost et al. investigated freon as refrigerant on the performance of a refrigeration cycle Through above literature, it was found that energy, exergy and sustainable analysis of single stage vapour compression refrigeration systems have been done. But no literature contributed for energy and exergy analysis of two-stage vapour compression refrigeration system. Present works analyze the system in terms of energy and exergy efficiencies and explain the effect of exergy losses on two-stage vapour compression refrigeration system with hydrocarbons and R134a.

3.0 Methods for Improving Thermal Performances of Two Stages Refrigeration Systems

Refrigeration technology based on the principle of rejection of heat to the surrounding at higher temperature and absorption of heat at low temperature [1]l Evaporator, expansion valve, condenser and compressor are the main four components of single stage vapour compression system. Vapour compression refrigeration systems consume large amount of electricity. This difficulty can be removed by improve the performance parameters of system. Coefficient of performance and exergetic efficiency are main two parameters to calculate the performance of refrigeration systems. The irreversibility in system components take place due to large temperature difference between system and surrounding. In order to improve the system performance Irreversibility should be measured in the cycle because Exergy losses are responsible for degradation of system performance .Coefficient of performance is commonly used to calculate the performance of vapour compression system but COP provides no information regarding thermodynamic losses in the system components.

Using exergy analysis one can be quantify the exergy losses in vapour compression refrigeration systems. Exergy losses increase with increasing of temperature difference between systems and surrounding. Exergy is the available or useful energy and loss of energy means loss of exergy in the system. Exergy losses are useful to improve the performance of system and better utilization of energy input given to the system which is beneficial for environmental conditions and economics of energy technologies. Utilization of green energy can be increased by this method. [2,,4]

Two stage vapour compression refrigeration system consist of low and high pressure compressor, condenser, evaporator, expansion valves, water-intercooler and flash chamber. Energy and exergy efficiencies are different for different refrigerants for same systemTo analyzed the two-stage vapour compression refrigeration system based on energy and exergy method following assumptions are taken in the thermodynamic analysis:

1. Effect of temperature and pressure losses arenegligible.
2. All components of two stages vapour compression refrigeration system are working under steady state conditions.
3. Energy and exergy losses due to potential energyand kinetic energy are neglected.
4. Thermal efficiencies of low and high pressure compressors are assumed to be 80%.

Two stage vapour compression refrigeration system and its P-H plot shown in Figure 1 and Figure 2 respectively.

Fig 1: Schematic Diagram of Two-Stage Vapour Compression Refrigeration System

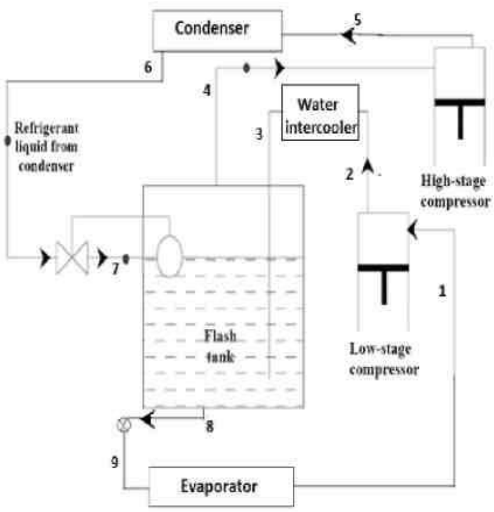
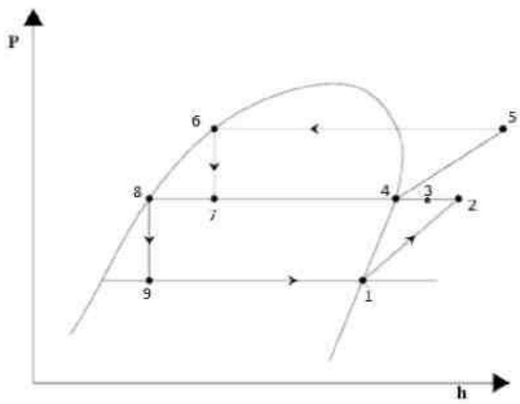


Fig 2: Pressure Enthalpy Diagram of Two-Stage Vapour Compression Refrigeration System



4.0 Irreversibility Evaluation Using Entropy Generation Principle

Exergy at any point, $EX = (h - h_{amb}) - T_{amb}(s - s_{amb})$ (1)

For high and low temperature compressors

$$\left(T_{amb}\dot{S}_{gen}\right)_{HP} = W_{HP}^{\cdot} + m_{HP}((h_1 - h_2) - T_{amb}(s_1 - s_2)) \quad (2)$$

$$\left(T_{amb}\dot{S}_{gen}\right)_{LP} = W_{LP}^{\cdot} + m_{LP}((h_4 - h_5) - T_{amb}(s_4 - s_5)) \quad (3)$$

For evaporator

$$\left(T_{amb}\dot{S}_{gen}\right)_{Evap} = \dot{m}_{LP}((h_9 - h_1) - T_{amb}(s_9 - s_1)) + Q\left(1 - \frac{T_{amb}}{T_L}\right) \quad (4)$$

For condenser

$$\left(T_{amb}\dot{S}_{gen}\right)_{Cond} = \dot{m}_{HP}((h_5 - h_6) - T_{amb}(s_5 - s_6)) - Q_{Cond}\left(1 - \frac{T_{amb}}{T_H}\right) \quad (5)$$

For expansion valves

$$\left(T_{amb}\dot{S}_{gen}\right)_{EV} = \dot{m}_{HP}((h_6 - h_7) - T_{amb}(s_6 - s_7)) + \dot{m}_{LP}((h_8 - h_9) - T_{amb}(s_8 - s_9)) \quad (6)$$

For water-intercooler

$$\left(T_{amb}\dot{S}_{gen}\right)_{WI} = \dot{m}_{LP}((h_2 - h_3) - T_{amb}(s_2 - s_3)) \quad (7)$$

For flash chamber

$$\left(T_{amb}\dot{S}_{gen}\right)_{FC} = \dot{m}_{LP}((h_3 - h_4) - T_{amb}(s_3 - s_4)) + (\dot{m}_{HP}h_7 - \dot{m}_{LP}h_8) - T_{amb}(\dot{m}_{HP}s_7 - \dot{m}_{LP}s_8) \quad (8)$$

Exergetic efficiency

$$\eta_{ex} = \frac{Q\left(1 - \frac{T_{amb}}{T_L}\right)}{W_{LP} + W_{HP}} \quad (9)$$

Coefficient of Performance (COP)

$$COP = \frac{\dot{m}_{LP}((h_1 - h_9)}{W_{LP} + W_{HP}} \quad (10)$$

Total entropy generation in the two stage vapour compression system is

$$\left(\dot{S}_{gen}\right)_{TOTAL} = \sum\left(\dot{S}_{gen}\right)_{HP} + \left(\dot{S}_{gen}\right)_{LP} + \left(\dot{S}_{gen}\right)_{Evap} + \left(\dot{S}_{gen}\right)_{Cond} + \left(\dot{S}_{gen}\right)_{EV} + \left(\dot{S}_{gen}\right)_{WI} + \left(\dot{S}_{gen}\right)_{FC}$$

Total exergy losses based on the entropy generation in the two stage vapour compression system is

$$\left(T_{amb}\dot{S}_{gen}\right)_{TOTAL} = \sum\left(T_0\dot{S}_{gen}\right)_{HP} + \left(T_0\dot{S}_{gen}\right)_{LP} + \left(T_0\dot{S}_{gen}\right)_{Evap} + \left(T_0\dot{S}_{gen}\right)_{Cond} + \left(T_0\dot{S}_{gen}\right)_{EV} + \left(T_0\dot{S}_{gen}\right)_{WI} + \left(T_0\dot{S}_{gen}\right)_{FC}$$

Exergy destruction in the two stage vapour compression refrigeration system based on the exergy input (i.e. total two compressor work in the system) is expressed as Rational exergy destruction ratio $EDR_{Rationa}i$ is a ratio of total exergy losses based on the entropy generation in the two stage vapour compression system to the exergy input.

$$EDR_{Rational} = \{(T_{amb}\dot{S}_{gen})_{TOTAL}/(W_{\_LP}+W_{\_HP})\}.$$

Similarly exergy destruction ratio in the two stage vapour compression refrigeration system is also based on exergy output can expressed as a ratio of total exergy losses based on the entropy generation in the two stage vapour compression system to the exergy of product can be expressed as

$$COPsystem = (T_{amb}\dot{S}_{gen})_{TOTAL}/(T_{amb}\dot{S}_{gen})_{TOTAL} =$$

$$\Sigma(T_0\dot{S}_{gen})_{HP}+(T_0\dot{S}_{gen})_{LP}+(T_0\dot{S}_{gen})_{Evap}+(T_0\dot{S}_{gen})_{Cond}+(T_0\dot{S}_{gen})_{EV}+(T_0\dot{S}_{gen})_{WI}+\frac{(T_0\dot{S}_{gen})_{FC}}{} /(\frac{Q_{evap}\left(1-\frac{T_{amb}}{T_L}\right)}{})$$

5.0 Results and Discussions

The effect of change of evaporator and condenser temperature on performance parameters like coefficient of performance, exergy loss in terms of Exergy destruction ratio based on input and exergy destruction ratio based on output exergy, exergetic efficiency was investigated as shown in Table-1 for for sixteen ecofriendly refrigerants.

As cleared from Table. 1 that highest coefficient of performance of R123is found and lowest COP is using R125. R717 is toxic in nature while R152a, R290 and R600a, R600 are found to be flammable nature. Although R134a consumes more electricity than R152a and R600. COP of vapour compression refrigeration system increase with increase in evaporator temperature and decrease with decrease in evaporator temperature in the considered system with R152a, R600, R134a, R600a, R290, R410a, R1234yf and R404a Ambient condition play an important role in electricity consumption of vapour compression refrigeration systems because higher the temperature difference between system and surrounding higher will be compressor work. For all considered refrigerants exergy destructions ratio is higher for R125 and lowest for R717 and next lowest is R134a. R1234yf has global warming potential of six can be used for high temperature circuit while exergy input in terms of total work of compressors is higher for using R404 than R717. From Table-2, 3 & 4 shows the variation of condenser temperature with performance parameters using R1234yf, R134a and R717 refrigerant. The purpose of condenser to take out the heat produced by compressor in discharge line and carried by refrigerant during cooling effect in evaporator. This heat in refrigerant removed by transferring heat to the wall of condenser tubes due to convection and then transfer of heat due to conduction from tubes wall to surrounding. From Table-2-4 , the EDR and exergy of fuel is also increases with increases with increasing condensing temperature. This is due to increase of temperature difference between condenser and surrounding and cop and exergetic efficiency is decreases with increases condenser temperature Table-5 to Table-7 is representing the variation of evaporator temperature with performance parameters using R1234yf, R134a and R717 refrigerants. .From Table-4-6, exergy destructions or exergy losses decreases with increase of evaporator temperature. This is because that if evaporating temperature decreases the heat exchange between working fluid entered into the evaporator tubes and space being cooled also decreases, which finally decrease the cooling effect and therefore exergy destruction increases. It was also observed that flash chamber, compressor, condenser, expansion valve, water-intercooler and evaporator are in increasing order of exergy loss for different refrigerants. Exergy losses decrease with increase of evaporating temperature for considered refrigerants. The R123 gives highest exergetic efficiency among selected refrigerants.

Table 1: Performance Evaluation of Sixteen Eco-Friendly of Two Stage Two Compressor Single Evaporator Vapour Compression Refrigeration System for Condenser Temperature =40°C And Evaporator Temperature of -40°C And Computed Exergy Output =9.764 "KJ/Kg) And Carnot Coefficient Of Performance. 3.585

Refrigerant	COP	EDR	ETA_{Second}	Exergy-input (Kj/Kg)	EDR_Rational
R1234yf	1.623	8.027	0.4529	21.56	0.5471
R134a	1.769	7.847	0.4934	19.79	0.5066
R717	1.988	7.626	0.5546	17.60	0.4454
R404a	1.537	8.149	0.4289	22.77	0.5711
R410a	1.743	7.876	0.4862	20.08	0.5138
R407c	1.607	8.045	0.4482	21.79	0.5518
R507a	1.552	8.127	0.4330	22.55	0.5670
R152a	1.894	7.714	0.5283	18.48	0.4717
R125	1.429	8.326	0.3986	24.50	0.6014
R123	1.931	7.68	0.5386	18.13	0.4614
R290	1.730	7.892	0.4826	20.23	0.5174
R600	1.843	7.766	0.5142	18.99	0.4858
R600a	1.760	7.857	0.4910	19.89	0.5090
R245fa	1.873	7.735	0.5226	18.68	0.4774
R235fa	1.696	7.933	0.4732	20.64	0.5268
R227ea	1.497	8.211	0.4177	23.37	0.5823

Table 2: Variation of Performance Parameters With Condenser Temperature Using R1234yf Eco-Friendly in the Two Stage Two Compressor Single Evaporator Vapour Compression Refrigeration System for Condenser Temperature =40°C And Evaporator Temperature Of -40°C, HP Compressor Efficiency=0.80, LP Compressor Efficiency=0.80

Condenser temperature (°C)	COP	COP_{carnot}	EDR	$Exergy_{product}$	$Exergy_{fuel}$	ETA_{Second}	$EDR_{Rational}$
30	2.006	3.589	7.607	9.764	17.45	0.5597	0.4403
35	1.804	3.589	7.804	9.764	19.40	0.50.32	0.49.68
40	1.623	3.589	8.027	9.764	21.57	0.4529	0.5471
45	1.461	3.589	8.272	9.764	23.96	0.4074	0.5926
50	1.312	3.589	8.548	9.764	26.68	0.366	0.6340
55	1.175	3.589	8.865	9.764	29.79	0.3278	0.6722
60	1.047	3.589	9.236	9.764	33.41	0.2922	0.7078

Table 3: Variation of Performance Parameters With Condenser Temperature Using R134a Eco-Friendly in the Two Stage Two Compressor Single Evaporator Vapour Compression Refrigeration System For Condenser Temperature =40°C and Evaporator Temperature Of -40°C, HP Compressor Efficiency=0.80, LP Compressor Efficiency=0.80

Condenser temperature (°C)	COP	COP_{carnot}	EDR	$Exergy_{product}$	$Exergy_{fuel}$	ETA_{Second}	$EDR_{Rational}$
30	2.142	3.585	7.495	9.764	16.34	0.5974	0.4026
35	1.944	3.585	7.664	9.764	18.0	0.5424	0.4576
40	1.769	3.585	7.847	9.764	19.79	0.4934	0.5066
45	1.611	3.585	8.044	9.764	21.73	0.4494	0.5506
50	1.468	3.585	8.261	9.764	23.85	0.4094	0.5906
55	1.336	3.585	8.50	9.764	26.19	0.3728	0.6272
60	1.275	3.585	8.776	9.764	28.82	0.3388	0.6612

Table 4: Variation of Performance Parameters With Condenser Temperature Using R717eco-Friendly in the Two Stage Two Compressor Single Evaporator Vapour Compression Refrigeration System For Condenser Temperature =40°C And Evaporator Temperature Of -40°C, HP Compressor Efficiency=0.80, LP Compressor Efficiency=0.80

Condenser temperature (°C)	COP	COP_{carnot}	EDR	$Exergy_{product}$	$Exergy_{fuel}$	ETA_{Second}	$EDR_{Rational}$
30	2.327	3.585	7.364	9.764	15.04	0.6493	0.3507
35	2.147	3.585	7.493	9.764	16.30	0.5989	0.4011
40	1.988	3.585	7.626	9.764	17.60	0.5546	0.4444
45	1.847	3.585	7.763	9.764	18.95	0.5153	0.4847
50	1.721	3.585	7.905	9.764	20.33	0.4802	0.5198
55	1.608	3.585	8.052	9.764	21.77	0.4485	0.5515
60	1.504	3.585	8.204	9.764	23.26	0.4197	0.5803

Table 5: Variation of Performance Parameters With Evaporator Temperature Using R1234yf Eco-Friendly in the Two Stage Two Compressor Single Evaporator Vapour Ompression Refrigeration System For Condenser Temperature =40°C And Evaporator Temperature Of -40°C HP Compressor Efficiency=0.80, LP Compressor Efficiency=0.80

Evaporator Temperature (°C)	COP	COP_{carnot}	EDR	$Exergy_{product}$	$Exergy_{fuel}$	ETA_{Second}	$EDR_{Rational}$
-30	2.015	4.418	10.29	7.9222	17.37	0.456	0.544
-35	1.805	3.967	8.991	8.824	19.39	0.455	0.545
-40	1.623	3.585	8.027	9.764	21.56	0.4529	0.5471
-45	1.465	3.257	7.283	10.75	23.89	0.4498	0.5502
-50	1.326	2.973	6.696	11.27	26.40	0.4459	0.5541
-55	1.203	2.725	6.222	12.84	29.10	0.4410	0.5590
-60	1.094	2.506	5.833	13.97	32.0	0.4364	0.5636

Table 6: Variation of Performance Parameters With Evaporator Temperature Using Rl 34a Eco-Friendly in the Two Stage Two Compressor Single Evaporator Vapour Compression Refrigeration System For Condenser Temperature =40°C and Evaporator Temperature Of -40°C, HP Compressor Efficiency=0.80, LP Compressor Efficiency=0.80

Evaporator temperature (°C)	COP	COP_{carnot}	EDR	$Exergy_{product}$	$Exergy_{fuel}$	ETA_{Second}	$EDR_{Rational}$
-30	2.171	4.418	10.13	7.922	16.12	0.4914	0.5086
-35	1.956	3.967	8.823	8.824	17.9	0.4930	0.5070
-40	1.769	3.585	7.847	9.764	19.79	0.4934	0.5066
-45	1.605	3.257	7.091	10.75	21.81	0.4928	0.5072
-50	1.461	2.973	6.483	11.77	23.95	0.4914	0.5086
-55	1.334	2.725	6.001	12.84	26.24	0.4894	0.5106
-60	1.220	2.506	5.598	13.97	28.68	0.4869	0.5131

Table 7: Variation of Performance Parameters with Condenser Temperature Using R717 Eco-Friendly in the Two Stage Two Compressor Single Evaporator Vapour Compression Refrigeration System For Condenser Temperature =40°C and Evaporator Temperature Of -40°C, HP Compressor Efficiency=0.80, LP Compressor Efficiency=0.80

Evaporator Temperature (°C)	COP	COP_{carnot}	EDR	$Exergy_{product}$	$Exergy_{fuel}$	ETA_{Second}	$EDR_{Rational}$
-30	2.421	4.418	9.923	7.922	14.46	0.5479	0.4521
-35	2..19	3.967	8.609	8.824	15.98	0.5521	0.4479
-40	1.988	3.585	7.626	9.764	17.60	0.5546	0.4454
-45	1.81	3.257	6.864	10.75	19.33	0.5558	0.4442
-50	1.653	2.973	6.257	11.77	21.18	0.5558	0.4442
-55	1.512	2.725	5.764	12.84	23.45	0.5549	0.4451
-60	1.386	2.506	5.356	13.97	25.26	0.5530	0.4470

6.0 Conclusions and Recommendations

Using first and second law analysis on two stage refrigeration system was carried out using sixteen ecofriendly refrigerants and following conclusions and recommendation are presented below:

(i) R123 shows best first law efficiency and R125 shows lowest first law performance among selected sixteen ecofriendly refrigerants refrigerants,

(ii) Exergy destruction for Rl 34a is higher than Rl 52a. R152a, R600a, R290, R600 are flammable in nature can be used by using safety measures. Therefore R134a recommended for all kind of applications,

(iv) R1234yf refrigerant has (GWP = 4) can be used for high temperature applications

(v) The first and second law performance of using R1234ze (of GWP =6) is better than R1234yf (of GWP=4) for higher temperature applications

(vi) Flash chamber responsible for highest exergy destruction for all refrigerants taken under consideration.

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Nomenclature

CFC	Chlorofluorocarbon
HCFC	Hydrochlorofluorocarbon
Q	rate of heat transfer (kW)
W	work (kW)
T	temperature (oC)
s	specific entropy (kJ/kgK)
h	specific enthalpy(kJ/kg)
$\dot{S}$	entropy (kJ/s.K)
ODP	ozone depletion potential
GWP	global warming potential
m	mass flow rate (kg/s)
η	efficiency (non-dimensional)

Subscripts

Evap	Evaporator
Cond	Condenser
amb	ambient conditions
WI	water intercooler
H	high temperature
L	low temperature
LP	low pressure
EV	expansion valve
gen	Generation
HP	high pressure
FC	flash chamber
ex	Exergetic