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Thermodynamic (energy-exergy) analysis to improve its efficiencies of multiple stage vapour compression refrigeration systems

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Abstract

The performance of refrigerator is evaluated in term of COP which is the ratio of refrigeration effect to the net work input given to the system. The COP of vapour compression refrigeration system can be improved either by increasing refrigeration effect or by reducing work input given to the system. A higher COP, indices the better performance of refrigeration system. COP of the system can be increased either by decreasing the work of compression by using multi stage compound compression or increasing the refrigerating effect or both. It is possible to reduce the compressor work to considerable extent by compressing the refrigerant very close to the saturated line. This can be accomplished by compressing the refrigerant in the more stages with intermediate intercoolers. The refrigerating effect can be increased by maintaining the condition of the refrigerant very close to the liquid line. The expansion can be brought close to the liquid line by sub cooling the refrigerant and refrigerant and by removing the flashed vapour. By incorporating the flash chamber in the working cycle, the evaporator size is reduced as unwanted vapour formed is removed before the liquid refrigerant enters the evaporator. It is well known that throttling process in VCR is an irreversible expansion process. Expansion process is one of the main factors responsible for exergy loss in cycle performance because of entering the portion of the refrigerant flashing to vapour in evaporator which will not only reduce the cooling capacity but also increase the size of evaporator. This problem can be eliminated by adopting multi-stage expansion where the flash vapours is removed after each stage of expansion as a consequence there will be increase in cooling capacity and reduce the size of the evaporator.

Keywords: VCRS, Energy-Exergy-analysis, Thermodynamic Performances, Irreversibility analysis

1. Introduction

In the vapour compression refrigeration systems, the major operating cost is the energy input to the system in the form of mechanical work (i.e. compressor work). Thus any method of increasing coefficient of performance is advantageous so long as it does not involve too heavy an increase in other operating expenses, as well as initial plant cost and consequent maintenance. Since the coefficient of performance of a vapour compression refrigeration system is the ratio of refrigerating effect to the compressor work, therefore the coefficient of performance can be increased either by increasing the refrigerating effect or by decreasing the compressor work.
Several methods are available for improving first law efficiency in the terms of coefficient of performance (COP) of vapour compression refrigeration systems as given below. By introducing the flash chamber between the expansion valve and the evaporator. However the refrigerating effect and coefficient of performance and the power required are similar as that of a simple vapour saturation cycle when the flash chamber is not used. Thus the use of flash chamber has no effect on the thermodynamic cycle. The only effect resulting from the use of flash chamber is the reduction in the mass of refrigerant flowing through the evaporator and hence the reduction in the size of evaporator. By using the accumulator or pre cooler. When the accumulator is used in the vapour compression refrigeration system, the refrigerating effect, coefficient of performance, and power required to run the compressor is same as the simple saturation cycle. The accumulator or pre cooler is used only to protect the liquid refrigerant to flow into the compressor and thus dry compression is always used. By subcooling the liquid refrigerant by the vapour refrigerant. We know that subcooling the liquid refrigerant by the vapour refrigerant, the coefficient

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of performance of cycle is reduced and by subcooling the liquid refrigerant leaving the condenser by liquid refrigerant from the expansion valve. In this process, the mass of refrigerant required in the heat exchanger is exactly equal as the mass of flash and that forms in the simple saturation cycle. Since the COP of this modified cycle and the power required to derive the compressor is same as that of simple saturation cycle. Therefore, this arrangement of subcooling the liquid refrigerant has no advantage because this method of subcooling of thermodynamically same as the simple saturation cycle. A liquid suction heat exchanger is used to sub-cool the liquid refrigerant from the condenser by exchanging heat with cold suction vapour. The subcooling would increase the refrigerating effect per kg of refrigerant. Also the suction vapour gets superheated, and it ensures that no liquid droplets should enter the compressor , thereby preventing any damage to the compressor valve. But at the same time, the compressor work would increase. However, there may be some improvement in COP of the cycle.

The performance of vapour compression refrigeration system, be improved by a little consideration in compression in refrigerant a reduction of compressor work very closed to saturated vapour line. This can be achieved by compressing the refrigerant in a more stages with intermediate intercooling. It is economically only where the pressure ratio is considerable as would be the case when very low evaporator are desired or when high condenser temperature may be required. Therefore compound compression is generally economical in the large refrigeration plants. The refrigerating effect can be increased by maintaining the condition of refrigerant in more liquid state at the entrance to the evaporator. This can be achieved by expanding the refrigerant very close to the saturated liquid line. It was observed that by subcooling the refrigerant and by removing the flashed vapour as they are during multi stage expansion, the expansion can be brought closed to the liquid line.

2. Improvements in Vapour Compression Refrigeration Systems

Refrigeration is a technology which absorbs heat at low temperature and provides temperature below the surrounding by rejecting heat to the surrounding at higher temperature. Simple vapour compression refrigeration system which consists of four major components compressor, expansion valve, condenser and evaporator in which total cooling load is carried at one temperature by single evaporator but in many applications like large hotels, food storage and food processing plants, food items are stored in different compartment and at different temperatures. Therefore there is need of multi evaporator vapour compression refrigeration system. The systems under vapour compression technology consume huge amount of electricity, this problem can be solved by improving performance of system. Performance of systems based on vapour compression refrigeration technology can be improved .The performance of refrigerator is evaluated in term of COP which is the ratio of refrigeration effect to the net work input given to the system. The COP of vapour compression refrigeration system can be improved either by increasing refrigeration effect or by reducing work input given to the system. It is well known that throttling process in VCR is an irreversible expansion process. Expansion process is one of the main factors responsible for exergy loss in cycle performance because of entering the portion of the refrigerant flashing to vapour in evaporator which will not only reduce the cooling capacity but also increase the size of evaporator. This problem can be eliminated by adopting multi-stage expansion where the flash vapours is removed after each stage of expansion as a consequence there will be increase in cooling capacity and reduce the size of the evaporator.

Kumar et al. [1] did energy and exergy analysis of vapour compression refrigeration system by the use of exergy-enthalpy diagram. They did first law analysis or energy analysis for calculating the coefficient of performance and exergy analysis for evaluation of various losses occurred in different components of vapour compression cycle using R11 and R12 as refrigerants.

Nikolaidis and Probert [2] studied analytically that change in evaporator and condenser temperatures of two stage vapour compression refrigeration plant using R22 add considerable effect on plant irreversibility. They suggested that there is need for optimizing the conditions imposed upon the condenser and evaporator.

Yumrutas et al [3] carried out exergy analysis based investigation of effect of condensing and evaporating temperature on vapour compression refrigeration cycle in terms of pressure losses, COP, second law efficiency and exergy losses. Variation in temperature of condenser as well as have negligible effect on exergy losses of compressor and expansion valve, also first law efficiency and exergy efficiency increase but total exergy losses of system decrease with increase in evaporator and condenser temperature.

Halimic et al. [4] compared performance of R401A, R290 and R134A with R12 by using in vapour compression refrigeration system, which is originally designed for R12.Due to similar performance of R134a in comparison with R12,R134A can be replaced in the same system without any medication in the system components. But in reference to greenhouse impact R290 presented best results. `

Xuan and Chen [5] presented in this manuscript about the replacement of R502 by mixture of HFC-161.Through experimental study it was found that mixture of HFC-161 gives same and higher performance than R404A at lower and higher evaporative temperature respectively on the vapour compression refrigeration system designed for R404A.

Cabello et al. [6] effect of condensing pressure, evaporating pressure and degree of superheating was experimentally investigated on single stage vapour compression refrigeration system using R22, R134a and R407C.It was observed that mass flow rate is greatly affected by change in suction conditions of compressor in results on refrigeration capacity because refrigeration capacity depended on mass flow rate through evaporator. It was also found that for higher compression ratio R22 gives lower COP than R407C.

Spatz and Motta [7] focused on replacement of R12 with R410a through experimental investigation of medium temperature vapour compression refrigeration cycles. In terms of thermodynamic analysis, comparison of heat transfer and pressure drop characteristics, R410a gives best performance among R12, R404a and R290a.

Han et al. [8] under different working conditions experimental results revealed that there could be replacement of R407C in vapour compression refrigeration system having rotor compressor with mixture of R32/R125/R161 showing higher COP, less pressure ratio and slightly high discharge compressor temperature without any modification in the same system.

Cabello et al. [9] had studied about the effect of operating parameters on COP, work input and cooling capacity of single-stage vapour compression refrigeration system. There is great influence on energetic parameters due change in suction pressure, condensing and evaporating temperatures.

Mohanraj et al. [10] through experimental investigation of domestic refrigerator they arrived on conclusions that under different environmental temperatures COP of system using mixture of R290 and R600a in the ratio of 45.2: 54.8 by weight showing up to 3.6% greater than same system using R134a, also discharge temperature of compressor with mixture of R290 and R600a is lower in the range of 8.5-13.4K than same compressor with R134a.

Getu and Bansal [11] had optimized the design and operating parameters of like condensing temperature, subcooling temperature, evaporating temperature, superheating temperature and temperature difference in cascade heat exchanger R744-R717 cascade refrigeration system. A regression analysis was also done to obtain optimum thermodynamic parameters of same system.

Padilla et al. [12] exergy analysis of domestic vapour compression refrigeration system with R12 and R413A was done. They concluded that performance in terms of power consumption, irreversibility and exergy efficiency of R413A is better than R12, so R12 can be replaced with R413A in domestic vapour compression refrigeration system.

Stanciu et al. [13] did numerical and graphical investigation on one stage vapour compression refrigeration system for studied refrigerants (R22, R134a, R717, R507a, R404a) in terms of COP, compressor work, exergy efficiency and refrigeration effect. Effect of subcooling, superheating and compression ratio was also studied on the same system using considered refrigerants and present system optimization when working with specific refrigerant.

Ahamed et al. [14] emphasized on use of hydrocarbons and mixture of hydrocarbons and R134a in vapour compression refrigeration system. By studying of various research papers they found that compressor shows much higher exergy destruction as compared to rest of components of vapour compression refrigeration system and this exergy destruction can be minimized by using of nanofluid and nanolubricants in compressor.

Bolaji et al. [15] had done experimentally comparative analysis of R32, R152a and R134a refrigerants in vapour compression refrigerator. They reached to the conclusions that R32 shows lowest performance whereas R134a and R152a showing nearly same performance but best performance was obtained of system using R152a.

Ahamed et al. [16] had performed experimental investigation of domestic refrigerator with hydrocarbons (isobutene and butane) by energy and exergy analysis. They reached to the results that energy efficiency ratio of hydrocarbons comparable with R134a but exergy efficiency and sustainability index of hydrocarbons much higher than that of R134a at considered evaporator temperature. It was also found that compressors shows highest system defect (69%) among components of considered system.

Reddy et al. [17] performed numerical analysis of vapour compression refrigeration system using R134a, R143a, R152a, R404A, R410A, R502 and R507A and discussed the effect of evaporator temperature, degree of subcooling at condenser outlet, superheating of evaporator outlet, vapour liquid heat exchanger effectiveness and degree of condenser temperature on COP and exergetic efficiency. They reported that evaporator and condenser temperature have significant effect on both COP and exergetic efficiency and also found that R134a has the better performance while R407C has poor performance in all respect

Mastani Joybari et al. [18] performed experimental investigation on a domestic refrigerator originally manufactured to use of 145g of R134a.They concluded that exergetic defect occurred in compressor was highest as compare to other components and through their analysis it has been found that instead of 145g of R134a if 60g of R600a is used in the considered system gave same performance which ultimately result into economic advantages and reduce the risk of flammability of hydrocarbon refrigerants.

Anand and Tyagi [19] did detailed exergy analysis of 2TR window air conditioning test rig with R22 as working fluid and reached to the conclusions that irreversibility in system components will be highest when the system is 100% charged and lowest when 25% charged and irreversibility in compressor is highest among system components.

Selladurai and Saravanakumar[20]compared the performance between R134a and R290/R600a mixture on a domestic refrigerator which is originally designed to work with R134a and found that R290/R600a hydrocarbon mixture showed higher COP and exergetic efficiency than R134a. In their analysis highest irreversibility obtained in the compressor compare to condenser, expansion valve and evaporator.

Arora and Kaushik [21] developed numerical model of actual vapour compression refrigeration system with liquid vapour heat exchanger and did energy and exergy analysis on the same in the specific temperature range of evaporator and condenser. They concluded that R502 is the best refrigerant compare to R404A and R507A, compressor is the worst and liquid vapour heat exchanger is best component of the system.

Mishra [22] carried out detailed energy and exergy analysis of multi-evaporators at different temperatures with multiple compressors and multiple expansion valves in parallel and series with intercooler and flash chambers in the six type vapour compression refrigeration systems in terms of performance parameter for R410a, R290, R600, R600a, R1234yf, R502, R404a and R152a refrigerants and numerically computed thermal performances in terms of COP, exergy Destruction Ratio and exergetic efficiency for six systems and found that the first law and second law efficiency improved by 22% and found that the thermal performance in terms of first law efficiency (i.e. coefficient of performance) and Second law efficiency (i.e. exergetic efficiency) of six systems using R600 and R152a nearly matching same values under the accuracy of 5%. The worst component from the viewpoint of irreversibility is expansion valve followed by condenser, compressor and evaporators, respectively. The most efficient component is sub-cooler. The R-152a has least effciency defects for 313K condenser temperature. Similarly the increase in dead state temperature has a positive effect on energetic effciency and Exergy destruction ratio (EDR). The Exergy destruction ratio (EDR) decreases and exergetic efficiency increases with increase in dead state temperature. Both R-152a and R-600 show the identical trends for exergetic efficiency are nearly overlapping. The exergetic efficiency for R-600 is 0.40.5% higher than that of R-152a for the range of dead state temperature considered [22].

The above investigators did not go through:

The detailed irreversibility analysis or second law analysis of multiple evaporators systems with multi-stage expansion in vapour compression refrigeration systems and component's irreversibility and second law analysis of single and multi-stage vapour compression refrigeration systems.

Detailed theoretical analysis in terms of first law efficiency, second law efficiency, and exergy destruction of single and multiple stages vapour compression refrigeration systems using ecofriendly refrigerants using ecofriendly HFO refrigerants.

3. Results and Discussion

Table-1.1 to Table 8.2 show, the effect of different ecofriendly refrigerants of three stage vapour compression refrigeration

Table-1.1:Thermal performance of Three stage vapour compression refrigeration system using multiple Evaporators at different temperatures with single compressor and individual expansion valves and back pressure valves (T_{R1}=263+5 (K),T_{R2}=278+5 (K), T_{R3}=283+5 (K), T_1=263K, , T_5=283K, T_5=278K,T_3=313K, $T_{Ambient}$= 298KQ_{Eva2}=105kW, Q_{Eva1}=70kW,,Q_{Eva3}=35kW, ETA_{Comp1}=0.8 , ETA_{Comp2}=0.8, ETA_{Comp3}=0.8)

Refrigerant	COP	EDR	EFF_{Second}	$EDR_{Rational}$	$Exergy_{Fuel}$ kW	$Exergy_{Product}$ kW	2nd Law Efficiency
R134a	3.582	1.84	0.2664	0.7336	39.8	10.41	0.3370
R1234yf	3.524	1.994	0.2536	0.7464	39.73	10.07	0.3227
R1234ze	3.616	2.02	0.2510	0.7490	38.72	9.717	0.3217
R227ea	3.448	2.246	0.2289	0.7711	40.6	9.293	0.2959
R236fa	3.606	2.335	0.2259	0.7741	38.82	8.768	0.2954
R245fa	3.742	2.102	0.2457	0.7543	37.45	9.201	0.3182

Table-1.2:Percentage Exergy Losses in the Components based on exergy of fuel of multiple Evaporators at different temperatures with single compressor and individual expansion valves and back pressure valves(T_{R1}=263+5 (K),T_{R2}=278+5 (K), T_{R3}=283+5 (K), T_1=263K, , T_5=283K, T_5=278K,T_3=313K, $T_{Ambient}$= 298KQ_{Eva2}=105kW, Q_{Eva1}=70kW,,Q_{Eva3}=35kW, ETA_{Comp1}=0.8 , ETA_{Comp2}=0.8, ETA_{Comp3}=0.8)

Refrigerant	% Exergy $Loss_{Comp}$	% Exergy $Loss_{Cond}$	% Exergy $Loss_{Eva}$	% Exergy $Loss_{Valve}$	% Exergy $Loss_{Total}$	Rational Efficiency (%)
R134a	17.93	22.34	5.286	3.459	49.02	0.5009
R1234yf	18.49	22.03	5.169	3.609	49.3	0.5070
R1234ze	18.36	21.36	6.997	3.54	50.26	0.4974
R227ea	18.95	19.61	8.457	4.392	51.41	0.4859
R236fa	18.64	20.7	9.896	3.485	52.73	0.4727
R245fa	18.25	22.21	8.523	2.661	51.64	0.4836

Table-1.3 :Percentage Exergy Losses in the Components of multiple Evaporators at different temperatures with single compressor and individual expansion valves and back pressure valves($T_{\_R1}$=263+5 (K),$T_{\_R2}$=278+5 (K), $T_{\_R3}$=283+5 (K), T_1=263K, , T_5=283K, T_5=278K,T_3=313K, $T_{\_Ambient}$= 298KQ_{Eva2}=105kW, Q_{Eva1}=70kW,,Q_{Eva3}=35kW, $ETA_{\_Comp1}$=0.8 , $ETA_{\_Comp2}$=0.8, $ETA_{\_Comp3}$=0.8)

Refrigerant	% Exergy $Loss_{\_Comp}$	% Exergy $Loss_{\_Cond}$	% Exergy $Loss_{\_Eva}$	% Exergy $Loss_{\_Valve}$	Second law Efficiency	Rational Efficiency (%)
R134a	36.58	45.58	10.78	7.056	0..5098	0.3370
R1234yf	37.5	44.69	10.58	7.32	0.507	0.3227
R1234ze	36.53	42.51	13.92	7.043	0.4974	0.3217
R227ea	36.86	38.15	16.45	8.544	0.4859	0.2959
R236fa	35.36	39.26	18.72	6.61	0.4727	0.2954
R245fa	35.34	43.0	16.5	5.154	0.4236	0.3182

System-2

Table-2.1: Thermal performance of Three stage vapour compression refrigeration system using multiple evaporators at different temperatures with compressor and individual expansion valves using $T_{\_R1}$=263+5 (K),$T_{\_R2}$=278+5 (K), $T_{\_R3}$=283+5 (K) T_1=263K, T_5=283K, T_5=278K,T_3=313K,$T_{\_Ambient}$= 298KQ_{Eva2}=105kW, Q_{Eva1}=70kW, Q_{Eva3}=35kW, $ETA_{\_Comp1}$=0.8, $ETA_{\_Comp2}$=0.8 $ETA_{\_Comp3}$=0.8

Refrigerant	COP	EDR	$EFF_{\_Second}$	$EDR_{\_Rational}$	$Exergy_{\_Fuel}$ kW	$Exergy_{\_Product}$ kW	2^{nd} Law Efficiency
R134a	4.033	1.13	0.3203	0.6797	52.07	16.68	0.5367
R1234yf	3.84	2.278	0.3051	0.6949	54.67	16.68	0.5112
R1234ze	4.009	2.14	0.3184	0.6816	52.38	16.68	0.5336
R227ea	3.657	2.443	0.2904	0.7096	51.43	16.68	0.4866
R236fa	3.956	2.183	0.3142	0.6858	53.03	16.68	0.5265
R245fa	4.233	1.973	0.336	0.664	49.61	16.68	0.5633

Table-2.2:Percentage Exergy Losses in the Components based on exergy of fuel of Three stage vapour compression refrigeration system using multiple evaporators at different temperatures with compressor and individual expansion valves $T_{\_R1}$=263+5 (K),$T_{\_R2}$=278+5 (K), $T_{\_R3}$=283+5 (K) T_1=263K, T_5=283K, T_5=278K,T_3=313K, $T_{\_Ambient}$= 298K, Q_{Eva2}=105kW,, Q_{Eva1}=70kW,, Q_{Eva3}=35kW, $ETA_{\_Comp1}$= $ETA_{\_Comp2}$= $ETA_{\_Comp3}$=0.8

Refrigerant	% Exergy $Loss_{\_Comp}$	% Exergy $Loss_{\_Cond}$	% Exergy $Loss_{\_Eva}$	% Exergy $Loss_{\_Valve}$	% Exergy $Loss_{\_Total}$	Rational Efficiency (%)
R134a	19.47	24.41	8.0	15.98	67.87	0.3213
R1234yf	19.71	25.81	6.428	18.17	69.49	0.3051
R1234ze	20.06	24.06	7.604	16.73	64.14	0.3186
R227ea	19.78	22.78	7.077	21.32	70.96	0.2904
R236fa	19.78	23.75	7.881	17.16	68.58	0.3142
R245fa	19.71	24.93	8.394	13.32	66.34	0.336

Table 2.3: Percentage Exergy Losses in the Components of Three stage vapour compression refrigeration system using multiple evaporators at different temperatures with compressor and individual expansion valves

Refrigerant	% Exergy $Loss_{\_Comp}$	% Exergy $Loss_{\_Cond}$	% Exergy $Loss_{\_Eva}$	% Exergy $Loss_{\_Valve}$	EDR	$EFF_{\_Second}$
R134a	28.69	35.97	11.8	23.95	1.13	0.3203
R1234yf	28.37	36.23	9.25	26.15	2.278	0.3051
R1234ze	28.97	35.31	11.8	23.95	2.14	0.3184
R227ea	27.88	32.1	9.973	30.04	2.443	0.2904
R236fa	28.84	34.64	11.49	25.03	2.183	0.3142
R245fa	29.7	37.51	12.65	20.07	1.973	0.336

Table-3.1:Thermal performance of Three stage vapour compression refrigeration system using multiple evaporators at different temperatures with single compressor and multiple expansion valves and back pressure valves for T_1=263K, T_5=283K, T_5=278K,T_3=313K, $T_{\_Ambient}$= 298K Q_{Eva1}=105kW,, Q_{Eva2}=70kW,, Q_{Eva3}=35kW, $ETA_{\_Comp}$=0.8

Refrigerant	COP	EDR	$EFF_{\_Second}$	$EDR_{\_Rational}$	$Exergy_{\_Fuel}$ kW	$Exergy_{\_Product}$ kW
R134a	3.579	1.747	0.2997	0.7003	58.68	17.59
R1234yf	3.509	1.842	0.2859	0.7141	59.85	17.11
R1234ze	3.603	1.846	0.2882	0.7118	58.28	16.8
R227ea	3.419	2.088	0.2618	0.7382	61.41	16.08
R236fa	3.582	2.074	0.2667	0.7333	58.62	15.64
R245fa	3.727	1.871	0.2890	0.711	56.35	16.28

Table-3.2:Percentage Exergy Losses in the Components based on exergy of fuel of Three stage vapour compression refrigeration system using multiple evaporators at different temperatures with single compressor and multiple expansion valves and back pressure valves for T_1=263K, T_5=283K, T_5=278K,T_3=313K, $T_{\_Ambient}$= 298K, Q_{Eva1}=105kW,, Q_{Eva2}=70kW,, Q_{Eva3}=35kW, $ETA_{\_Comp}$=0.8

Refrigerant	% Exergy $Loss_{\_Comp}$	% Exergy $Loss_{\_Cond}$	% Exergy $Loss_{\_Eva}$	% Exergy $Loss_{\_Valve}$	% Exergy $Loss_{\_Total}$
R134a	18.06	21.96	8.462	3.825	52.36
R1234yf	18.62	21.71	8.317	4.015	52.67
R1234ze	18.51	20.99	9.74	3.968	53,208
R227ea	19.03	19.35	11.37	4.915	54.66
R236fa	18.83	20.35	12.23	3.916	55.33
R245fa	18.42	21.81	10.84	3.00	54.07

Table-3.3: Percentage Exergy Losses in the Components of Three stage vapour compression refrigeration system using multiple evaporators at different temperatures with single compressor and multiple expansion valves and back pressure valves

Refrigerant	% Exergy $Loss_{\_Comp}$	% Exergy $Loss_{\_Cond}$	% Exergy $Loss_{\_Eva}$	% Exergy $Loss_{\_Valve}$
R134a	34.49	41.94	16.16	7.402
R1234yf	35.36	41.22	15.79	7.624
R1234ze	34.79	39.45	18.3	7.457
R227ea	34.81	35.4	20.79	8.991
R236fa	34.04	36.78	22.11	7.078
R245fa	*34.07*	*40.33*	*20.04*	*5.554*

Table-4.1: Thermal performance of three stage vapour compression refrigeration system using multiple evaporators at different temperatures individual compressors and individual expansion valves

Refrigerant	COP	EDR	$EFF_{\_Second}$	$EDR_{\_Rational}$	$Exergy_{\_Fuel}$ kW	$Exergy_{\_Product}$ kW
R134a	4.399	2.264	0.3062	0.6938	47.74	14.62
R1234yf	4.204	2.418	0.2926	0.7074	49.96	14.62
R1234ze	4.379	2.281	0.3038	0.6962	47.95	14.62
R227ea	4.018	2.575	0.2797	0.7203	52.26	14.62
R236fa	4,329	2.319	0.3013	0.6083	48.51	14.62
R245fa	4.612	2,114	0.3210	0.6790	45.53	14.62

Table-4.2:Percentage Exergy Losses in the Components based on exergy of fuel of Three stage vapour compression refrigeration system using multiple evaporators at different temperatures individual compressors and individual expansion valves

Refrigerant	% Exergy $Loss_{\_Comp}$	% Exergy $Loss_{\_Cond}$	% Exergy $Loss_{\_Eva}$	% Exergy $Loss_{\_Valve}$
R134a	19.35	26.18	8.572	15.2
R1234yf	19.59	27.06	6.854	17.24
R1234ze	19.63	25.84	8.178	17.24
R227ea	19.66	24.55	7.622	20.20
R236fa	19.65	25.54	8.465	16.21
R245fa	19.59	26.74	8.996	12.54

Table-4.3: Percentage Exergy Losses in the Components of Three stage vapour compression refrigeration system using multiple evaporators at different temperatures individual compressors and individual expansion valves

Refrigerant	% Exergy $Loss_{Comp}$	% Exergy $Loss_{Cond}$	% Exergy $Loss_{Eva}$	% Exergy $Loss_{Valve}$
R134a	27.92	37.78	12.37	21.93
R1234yf	27.69	38.25	9.69	24.36
R1234ze	28.23	37.17	11.76	22.83
R227ea	27.29	34.08	10.58	28.05
R236fa	28.13	36.55	12.12	23.2
R245fa	28.87	39.4	13.26	18.48

Table-4.4: Percentage Exergy Losses in the Compressors of Three stage vapour compression refrigeration system using multiple evaporators at different temperatures individual compressors and individual expansion valves

Refrigerant	Power (kW) $Required_{Comp1}$	Power (kW) $Required_{Comp2}$	Power (kW) $Required_{Comp3}$	Total Power Required/ $Exergy_{Fuel}$ kW	% Exergy $Loss_{comp}$
R134a	7.265	5.484	34.99	47.74	27.92
R1234yf	7.863	5.824	36.27	49.96	27.69
R1234ze	7.422	5.544	34.99	47.95	28.23
R227ea	8.571	6.182	37.51	52.26	27.29
R236fa	7.661	5.658	35.19	48.51	28.13
R245fa	5.213	6.905	33.41	45.53	28.87

Table-5.1:Thermal performance of Three stage vapour compression refrigeration system using multiple evaporators at different temperatures with individual compressors and multiple expansion valves

Refrigerant	COP	EDR	EFF_{Second}	$Exergy_{Fuel}$ kW	$Exergy_{Product}$ kW	2nd Law Efficiency
R134a	4.877	1.824	0.3674	42.81	15.82	0.5460
R1234yf	4.815	1.866	0.3627	43.71	15.82	0.539
R1234ze	4.908	1.816	0.3697	42.69	15.82	0.5403
R227ea	4.744	1.935	0.3574	44.77	15.82	0.5311
R236fa	4.895	1.837	0.3688	42.93	15.82	0.548
R245fa	5.023	1.749	0.3784	41.42	15.82	0.5623

Table-5.2:Percentage Exergy Losses in the Components based on exergy of fuel of Three stage vapour compression refrigeration system using multiple evaporators at different temperatures with individual compressors and multiple expansion valves

Refrigerant	% Exergy $Loss_{Comp}$	% Exergy $Loss_{Cond}$	% Exergy $Loss_{Eva}$	% Exergy $Loss_{Valve}$	% Exergy $Loss_{Total}$
R134a	18.59	26.57	15.47	6.386	67.01
R1234yf	18.97	27.36	14.46	6.892	67.68
R1234ze	19.0	26.04	15.51	6.599	67.15
R227ea	19.02	24.97	16.73	8.431	69.15
R236fa	19.04	25.76	16.33	6.624	67.75
R245fa	18.98	26.8	15.38	5.013	66.17

Table-5.3: Percentage Exergy Losses in the Components of three stage vapour compression refrigeration system using multiple evaporators at different temperatures with individual compressors and multiple expansion valves

Refrigerant	% Exergy $Loss_{Comp}$	% Exergy $Loss_{Cond}$	% Exergy $Loss_{Eva}$	% Exergy $Loss_{Valve}$
R134a	27.75	39.65	23.08	9.529
R1234yf	28.03	40.42	21.37	10.18
R1234ze	28.3	38.78	23.1	9.828
R227ea	27.51	36.11	24.2	12.19
R236fa	28.1	38.02	24.1	9.776
R245fa	28.68	40.5	23.24	9.577

Table-6.1: Thermal performance of three stage vapour compression refrigeration system using multiple evaporators at different temperatures individual compressors and multiple expansion valves

Refrigerant	COP	EDR	EFF_{Second}	$Exergy\_{Fuel}$ kW	$Exergy\_{Product}$ kW	2nd Law Efficiency
R134a	4.905	1.867	0.3414	42.81	14.62	0.3626
R1234yf	4.804	1.915	0.3344	43.71	14.62	0.3598
R1234ze	4.919	1.858	0.3424	42.69	14.62	0.3639
R227ea	4.69	1.98	0.3265	44.77	14.62	0.3536
R236fa	4.892	1.878	0.3405	42.93	14.62	0.3601
R245fa	5.070	1.791	0.3529	41.42	14.62	

Table-6.2:Percentage Exergy Losses in the Components based on exergy of fuel of Three stage vapour compression refrigeration system using multiple evaporators at different temperatures individual compressors and multiple expansion valves

Refrigerant	% Exergy $Loss\_{Comp}$	% Exergy $Loss\_{Cond}$	% Exergy $Loss\_{Eva}$	% Exergy $Loss\_{Valve}$	% Exergy $Loss\_{Total}$
R134a	18.57	26.73	8.881	9.559	63.86
R1234yf	18.97	27.31	7.834	9.914	64.02
R1234ze	18.99	26.10	9.186	9.33	63.61
R227ea	19.02	24.74	8.897	11.99	64.64
R236fa	19.04	25.75	9.56	9.533	63.93
R245fa	18.96	27.02	9.889	7.34	63.21

Table-6.3: Percentage Exergy Losses in the Components of Three stage vapour compression refrigeration system using multiple evaporators at different temperatures individual compressors and multiple expansion valves

Refrigerant	% Exergy $Loss\_{Comp}$	% Exergy $Loss\_{Cond}$	% Exergy $Loss\_{Eva}$	% Exergy $Loss\_{Valve}$
R134a	29.14	41.93	12.37	13.93
R1234yf	29.62	42.66	12.24	15.48
R1234ze	29.86	41.03	14.44	14.67
R227ea	29.43	38.27	13.74	18.54
R236fa	29.79	40.28	14.97	14.97
R245fa	30.0	42.74	15.64	11.61

Table-6.4: Percentage Exergy Losses in the Compressors of three stage vapour compression refrigeration system using multiple evaporators at different temperatures individual compressors and multiple expansion valves

Refrigerant	Power (kW) $Required\_{Comp1}$	Power (kW) $Required\_{Comp2}$	Power (kW) $Required\_{Comp3}$	Total Power Required/ $Exergy\_{Fuel}$ kW	% Exergy $Loss\_{comp}$
R134a	19.6	18.2	5.0	42.81	29.14
R1234yf	20.19	18.47	5.052	49.96	29.62
R1234ze	19.62	18.1	4.966	47.95	29.86
R227ea	20.92	18.75	5.102	52.26	29.43
R236fa	19.84	18.13	4.96	48.51	29.79
R245fa	18.92	17.64	4.855	41.42	30.0

Table-7.1:Thermal performance of Three stage vapour compression refrigeration system using multiple evaporators at different temperatures with individual compressors and multiple expansion valves

Refrigerant	COP	EDR	EFF_{Second}	$EDR\_{Rational}$	$Exergy\_{Fuel}$ kW	$Exergy\_{Product}$ kW	2nd Law Efficiency
R134a	5.173	1.825	0.3601	0.6399	40.59	14.62	0.6968
R1234yf	5.127	1.848	0.3589	0.6411	40.96	14.62	0.6824
R1234ze	5.213	1.81	0.3628	0.6372	40.29	14.62	0.6937
R227ea	5.072	1.898	0.3530	0.6470	41.4	14.62	0.6750
R236fa	5.207	1.824	0.3624	0.6376	40.33	14.62	0.693
R245fa	5.318	1.758	0.3702	0.6298	39.49	14.62	0.7078

Table-7.2:Percentage Exergy Losses in the Components based on exergy of fuel of Three stage vapour compression refrigeration system using multiple evaporators at different temperatures with individual compressorsand multiple expansion valves

Refrigerant	% Exergy $Loss_{\_Comp}$	% Exergy $Loss_{\_Cond}$	% Exergy $Loss_{\_Eva}$	% Exergy $Loss_{\_Valve}$	% Exergy $Loss_{\_Total}$	Rational Efficiency (%)
R134a	18.59	27.88	14.02	5.219	65.7	0.3430
R1234yf	18.97	28.83	12.69	8.301	65.96	0.3404
R1234ze	19.0	27.39	13.95	5.337	65.67	0.3433
R227ea	19.02	26.4	14.83	6.765	67.01	0.3299
R236fa	19.04	27.13	14.68	5,273	66.12	0.3388
R245fa	18.97	28.11	14.04	3.698	65.09	0.3491

Table-7.3: Percentage Exergy Losses in the Components of three stage vapour compression refrigeration system using multiple evaporators at different temperatures with individual compressors and multiple expansion valves

Refrigerant	% Exergy $Loss_{\_Comp}$	% Exergy $Loss_{\_Cond}$	% Exergy $Loss_{\_Eva}$	% Exergy $Loss_{\_Valve}$	Rational Efficiency (%)
R134a	28,3	42.23	21.33	7.943	0.3430
R1234yf	28.76	43.7	19.24	8.30	0.3404
R1234ze	28.93	41.7	22.24	8.127	0.3433
R227ea	28.38	39.4	22.12	6.765	0.3299
R236fa	28.8	41.03	22.2	7.976	0.3388
R245fa	29.15	43.19	21.57	6.096	0.3491

Table-7.4: Percentage Exergy Losses in the Compressors of Three stage vapour compression refrigeration system using multiple evaporators at different temperatures with individual compressors and multiple expansion valves

Refrigerant	Power (kW) $Required_{\_Comp1}$	Power (kW) $Required_{\_Comp2}$	Power (kW) $Required_{\_Comp3}$	Total Power Required/ $Exergy_{\_Fuel}$ kW	% Exergy $Loss_{\_comp}$
R134a	15.92	15.86	8.817	40.59	28.3
R1234yf	15.69	15.65	9.614	40.96	28.76
R1234ze	15.64	15.62	8.192	40.29	28.93
R227ea	15.51	15.49	10.4	41.4	28.38
R236fa	15.57	15.52	9.24	40.33	28.8
R245fa	15.68	15.61	8.192	39.49	29.15

Table-8.1:Thermal performance of three stage vapour compression refrigeration system using multiple evaporators at different temperatures with compound compression and multiple expansion valves and flash intercoolers (system-6)

Refrigerant	COP	EDR	$EFF_{\_Second}$	$EDR_{\_Rational}$	$Exergy_{\_Fuel}$ kW	$Exergy_{\_Product}$ kW	2nd Law Efficiency
R134a	4.465	1.82	0.3547	0.6453	47.03	16.68	0.5943
R1234yf	4.361	1.887	0.3464	0.6436	48.5	16.68	0.5804
R1234ze	4.473	1.815	0.3552	0.6548	46.95	16.68	0.5952
R227ea	4.248	1.964	0.3374	0.6426	49.44	16.68	0.5653
R236fa	4,443	1.834	0.3529	0.6471	47.27	16.68	0.5912
R245fa	4.620	1.725	0.3669	0.6331	45.46	16.68	0.6148

Table-8.2: Percentage Exergy Losses in the Components three stage vapour compression refrigeration system using multiple evaporators at different temperatures with compound compression and multiple expansion valves and flash intercoolers

Refrigerant	% Exergy $Loss_{\_Comp}$	% Exergy $Loss_{\_Cond}$	% Exergy $Loss_{\_Eva}$	% Exergy $Loss_{\_Valve}$	% Exergy $Loss_{_Sub}$cooler	% Exergy $Loss_{\_Total}$	Rational Efficiency (%)
R134a	19.41	24.41	8.121	10.47	1.994	64.53	35.47
R1234yf	19.71	25.20	6.456	11.66	2.36	65.36	34.64
R1234ze	19.74	24.08	7.696	10.96	2.0	64.48	35.52
R227ea	19.78	24.84	7.227	13.92	2.48	66.26	33.74
R236fa	19.78	24.79	8.030	8.03	1.87	64.71	35.29
R245fa	19.71	24.94	8.513	8.513	1.40	63.31	36.69

system using multiple evaporators at different temperatures with single compressor and individual expansion valves and back pressure valves and it was observed that first law performance in terms of coefficient of performance (COP) of HFO-1234ze is better than HFC -134a refrigerant but higher than another HFO-1234yf refrigerant. While COP of R236fa is slightly lower than R1234ze but higher than HFC-134a. However, the COP of R245fa is highest. Similarly second law efficiency of of Three stage vapour compression refrigeration system using multiple evaporators at different temperatures with single compressor and individual expansion valves and back pressure valves is highest by using HFC-134a which gives the exergy destruction ratio based on exergy of product is lowest in case of HFC-134a . However, the second law efficiency in terms of exergetic efficiency using HFO-1234yf refrigerant is slightly less than HFC 134a and higher than HFO-1234ze. The exergy destruction ratio (based on exergy of fuel which meant the total power required to run the system) is highest for R236fa because exergetic efficiency of system using R236fa is lowest. Similarly exergy of fuel in terms of the total power required to run the system is lowest by using HFC-134a. The power consumption using R227ea is higher and lower by using R245fa . The exergy of product is higher by using R134a and slight lower by using HFO-1234yf refrigerant. The percentage exergy losses using similar trens with minor variation nealy in the all components of vapour compression refrigeration systems. The exergy losses based on the total exergy destruction is computed Three stage vapour compression refrigeration system using multiple evaporators at different temperatures with single compressor and individual expansion valves and back pressure valves is shown in table-1(b) -1(c) respectively. It was found that percentage exergy losses in the compressor using ecofriendly R227ea refrigerant is more than while the using ecofriendly R245fa refrigerant. Similarly for low GWP and zero ODP HFO refrigerants using R 1234yf is 18.49% while using R1234ze is 18.36% as compared to HFC R134a is 17.93 %. The maximum exergy destruction is found in condenser is 22.34% by using HFC-134a refrigerant while by using R1234yf is 22.03% and slightly higher than HFO-1234yf. The percentage exergy losses in the various system are shown in Table-1(b)-1(c) respectively. Similar trend is found in Table-1(c) where % exergy destruction in the component based on total exergy destruction in all components of the system have been observed. Table- 9 shows the comparison between developed model and data [20] taken from reference for assuming 80% compressor efficiencies, . And it was found that thermal models developed gives similar results under the limits to validates our model as shown in Table-9

Table9: Comparison between developed model and data [22]

S.No.	Parameters	Ref [24].	(Developed Model)
1	COP	4.465	4.465
2	W_Comp	49.9 kW	47. 3kW

To improve thermal performance of vapour compression refrigeration systems (both single and multiple evaporator system) by improving:

First law efficiency

According to first law of thermodynamic energetic efficiency /COP is defined as the ratio of net refrigeration effect to the per unit power consumed. First law analysis restricted to calculate only coefficient of performance of the systems. Detailed theoretical analysis in terms of first law efficiency, second law efficiency, and exergy destruction of single and multiple stages vapour compression refrigeration systems using ecofriendly refrigerants.

Second law efficiency

The concept of exergy was given by second law of thermodynamics. Second law efficiency is the exergy of the heat abstracted in to the evaporators from the space to be cooled and exergy of fuel is actual compressor work input. Effect of subcooling on first law efficiency, second law efficiency and irreversibility of each component of both systems (single and multi-stage) vapour compression refrigeration systems.

4. Conclusion

The following conclusions were drawn

(i) The increase in COP decreases EDR and increases exergetic efficiency.
(ii) The subcooling increases refrigeration capacity.
(iii) The subcooling has no effect on compressor work.
(iv) COP and exergetic efficiency are almost same for considered eco-refrigerants as compared with R-12 refrigerant.
(v) Both COP and EDR will decrease with increase in condenser temperature.
(vi) EDR increase with increase in condenser temperature.

The exergetic (rational) efficiency increases with increase in condenser temperature for 273K temperature of all evaporators with 5K degree of subcooling**.**

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