Entropy generation and exergy destruction analyses for vapour compression refrigeration system with various refrigerants

Ankur Geete¹ · Mamta Sharma¹ · Pranjal Shrimali¹

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Abstract

In this experimental work, entropy generation minimization and exergy destruction minimization concepts have been applied on vapour compression refrigeration system. For that, entropy generations and exergy destructions have been found for each component of vapour compression refrigeration system; compressor, condenser, expansion device and evaporator, and also for whole system at different time intervals with various refrigerants. Refrigerants R134a, R600a, 95%R134a + 5%R290, 90%R134a + 10%R290, 85%R134a + 15%R290 and 85%R134a + 15%R152a blend refrigerants have been chosen for this experimental research work. Percentages increments/decrements for the entropy generations and exergy destructions have also been calculated to find best conditions and refrigerant, with developed computer software which eliminate hectic calculations and human mistakes. Minimum entropy generation (i.e. 533.64 J/kgK) and exergy destruction (i.e. 160090.8 J/kg) for the system have been found for R134a, and componentwise least entropy generations and exergy destructions have also been obtained with R134a but it affects environment. After this experimental work, 85%R134a + 15%R290 blend or R600a refrigerants have been recommended for refrigeration systems because of least percentage increments for entropy generation and exergy destruction. R134a as refrigerant is generally used in the refrigerating systems but it has high global warming potential (1430 GWP), so it should be replaced by alternative eco-friendly refrigerant and R600a is favourable which has zero ozone depletion potential and least global warming potential.

Keywords Exergy destruction · Entropy generation · Vapour compression refrigeration system · Blend refrigerants

List of symbols

C	Specific heat of refrigerant (J/kg K)
I	Exergy destruction (J/kg)
S	Entropy (J/kg K)
T	Temperature (K)
W	Work done (J/kg)

Subscripts

0	Ambient conditions
comp	Compressor
cond	Condenser
evp	Evaporator
exp	Expansion device
p	Constant pressure
t	Total

1 Introduction

To maintain the temperature of a body/substance below atmospheric temperature or removing heat from that body a thermodynamic process is required called refrigeration process, system which is used for it called refrigerating system and fluid which is flowing and absorbing heat called refrigerant. Schematic and p–h diagrams are shown in Figs. 1, 2 [1, 2]. Working procedure of vapour compression refrigeration system can be described to understand the system by the following stages; (1) compressor—process 1–2 is isentropic compression process where saturated vapour is compressed, and pressure and temperature increase isentropically. At the inlet of compressor, saturated vapour refrigerant is present whereas at

✉ Ankur Geete, ankur_geete@yahoo.co.in | ¹Mechanical Engineering Department, Sushila Devi Bansal College of Technology, Indore, Madhya Pradesh 453331, India.

Fig. 1 Schematic diagram

Fig. 2 p-h diagram for vapour compression refrigeration system

outlet superheated vapour, (2) condenser—process 2–3 is constant pressure heat rejection process where high pressure and temperature superheated vapour refrigerant is converted into liquid refrigerant by desuperheating and then by phase changing processes. This cooling is done by air or water and additional decrease in temperature occurs in the pipe and liquid receiver so the liquid refrigerant is sub-cooled. At the inlet of the condenser, superheated vapour refrigerant is present and at outlet sub-cooled liquid refrigerant, (3) throttle device—process 3–4 is isenthalpic process where high pressure and low temperature saturated liquid refrigerant is expanded and its pressure and temperature decrease, this throttling device also regulates the flow of refrigerant into the evaporator. At the inlet of the throttling device, sub-cooled liquid refrigerant is present whereas at outlet from the device mixture of liquid and vapour refrigerant, and (4) evaporator—4–1 is constant pressure heat addition process where low

pressure and temperature liquid refrigerant absorbs heat from substance/matter that is to be cooled. In this process, liquid refrigerant converts into low pressure/temperature saturated or superheated vapour refrigerant. At the inlet of the evaporator, mixture of liquid and vapour refrigerant is present and at outlet from the device saturated vapour refrigerant is present which will be entered again in the compressor [1, 2]. Experimental setup is shown in Fig. 3. Some researchers have done worked on vapour compression refrigeration system to improve the performance of the system [3–9] and also investigated alternative refrigerants [10–13] which should be environmental friendly in terms of ozone depletion potential and global warming potential [14–18]. Thermodynamic analyses on vapour compression refrigeration system by designed computer software have been done with consideration of internal irreversibility, and the performance analyses on the refrigeration system have also been done with alternative refrigerants and found COPs, work inputs, second law efficiencies at different operating conditions [19–21]. Most of the refrigerants which are utilized in refrigerating systems for the refrigeration process have unpleasant effects on the environment and these unpleasant effects on the environment are understood by two most important terms; ozone depletion potential and global warming potential. Ozone depletion potential (ODP) is the amount of degradation of ozone layer caused by the refrigerant and if the value of ODP is higher than that refrigerant is more harmful for ozone layer. Global warming potential (GWP) is the measurement of global warming caused by refrigerant and the value of GWP of the refrigerant should be less. In this experimental research work, entropy generations and exergy destructions have been found for vapour compression refrigeration system with pure refrigerants;

Fig. 3 Experimental setup for vapour compression refrigeration system

R134a and R600a, and with blend refrigerants; R134a with R290 and with R152a at different mass fractions to find that refrigerant which has less ozone depletion potential and global warming potential with minimum entropy generations and exergy destructions from the system. The mass fractions which have been taken for refrigerants in this research work are; 95% of R134a mixed with 5% of R290, 90% of R134a mixed with 10% of R290, 85% of R134a mixed with 15% of R290 and 85% of R134a mixed with 15% of R152a which mentioned as 95%R134a + 5%R290, 90%R134a + 10%R290, 85%R134a + 15%R290 and 85%R134a + 15%R152a respectively. These comparatively analyses (entropy and exergy) have been done for compressor, condenser, expansion device and evaporator at different time intervals with different refrigerants. Percentage increments and decrements have also been investigated to find best operating conditions with best alternative refrigerant for vapour compression refrigeration system.

2 Methodology

Entropy is the microscopic disorder of the system which is an extensive equilibrium property of the system introduced by Clausius, and he found that thermodynamic phenomenon can also be explained by term dQ/T which is also known as reduced heat. Entropy can be defined as; it is that amount of heat energy which is unavailable for the conversion into useful work energy, and it remains constant for a reversible process called isentropic process (ideal/hypothetical) but increases for irreversible process called actual process. Researchers have discussed that when temperature of a perfect crystal is absolute zero, the entropy is also zero and if temperature increases then entropy also increases but it increases abruptly when phase changing process occurs from solid to liquid or from liquid to gas. Change in entropy for different processes has been shown in Table 1 [22, 23]. Exergy also called as availability or available energy is the maximum useful work that can be achieved from the system at specified state in specific environment but exergy destruction is the dissipate work energy during a process as effect of irreversibility.

Table 1 Change in entropy for various processes

Sr. No.	Various processes	Change in entropy (J/kg K)
1	Constant volume process	$C_v \ln(T_2/T_1)$ or $C_v \ln(P_2/P_1)$
2	Constant pressure process	$C_p \ln(T_2/T_1)$ or $C_p \ln(V_2/V_1)$
3	Constant temperature process	$R \ln(V_2/V_1)$ or $R \ln(P_1/P_2)$
4	Isentropic process	0

Exergy can also be defined as the maximum useful work that can be obtained from a thermodynamic system when that system reaches to the thermodynamic equilibrium state with the surroundings, it means if the system is in equilibrium state with the surroundings then its temperature and pressure will be in equilibrium with surroundings i.e. T_0 and P_0 and there will be no chemical action/reaction takes place also. This state of the system is called dead state and when the system reaches to dead state condition its exergy becomes zero. For a heat engine, amount of work that can be obtained from the engine is known as available energy but some amount of heat energy will be rejected from system to surrounding is known as unavailable energy. It has been found that if a reversible heat engine operates between finite temperatures T_1 and T_0 (i.e. source and sink temperatures), exergy of the heat engine decreases when the source temperature decreases or heat rejection/unavailable energy increases which is known as exergy lost or destruction. Ideal or reversible work transfer is always more than actual work transfer and the difference between these work transfers is called irreversibility of the system or losses, and irreversibility can be found by *Gouy-Stodola* equation which is $T_0 S_{gen}$. This equation states that rate of entropy generation during a process for a thermodynamic system is proportional to the exergy destruction and the pressure drop for a flow process is also proportional to the exergy lost, so for better performance of the system entropy generation or exergy destruction should be as minimum as possible [22–29].

In this experimental research work, entropy generation and exergy destruction have been analysed for vapour compression refrigeration system with R134a, R600a, 95%R134a + 5%R290, 90%R134a + 10%R290, 85%R134a + 15%R290, and 85%R134a + 15%R152a as blend refrigerants at different time intervals; 15, 30, 45 and 60 min. And for that, following methodology has been applied on refrigeration system to optimize the performance and find better alternative refrigerant for the system. Exergy destructions for compressor have been calculated at different conditions by the following equation [22–30];

$$I_{comp} = [C_p(T_2 - T_1)] - [T_0 C_p \ln(T_2/T_1)] + W_{comp} \quad (1)$$

where I_{comp} is the exergy destruction for compressor in J/kg, C_p is specific heat of the flowing fluid called refrigerant in J/kgK, T_2 and T_1 are temperatures at outlet and inlet of the compressor in Kelvin, T_0 is environmental temperature which is taken 300 K for this experimental work and W_{comp} is compressor work or power which is given to the compressor in J/kg. Then, exergy destructions for the condenser have been found for different time intervals by the following equation [22–30];

$$I_{cond} = [C_p(T_3 - T_2)] - [T_0 C_p \ln(T_3/T_2)] + [C_p(T_3 - T_2)(1 - T_0/T_3)] \quad (2)$$

where I_{cond} is the exergy destruction for condenser in J/kg and T_3 is the outlet temperature of the condenser in Kelvin. Exergy destructions for expansion device have been evaluated by the following equation [22–30];

$$I_{exp} = [C_p(T_4 - T_3)] - [T_0 C_p \ln(T_4/T_3)] \quad (3)$$

where I_{exp} is the exergy destruction for expansion device in J/kg and T_4 is the inlet temperature for evaporator in Kelvin. Finally, at various time intervals exergy destructions have been estimated for evaporator by following equation [22–30];

$$I_{evp} = [C_p(T_1 - T_4)] - [T_0 C_p \ln(T_1/T_4)] + [C_p(T_1 - T_4)(1 - T_0/T_1)] \quad (4)$$

For this research work, total exergy destructions have also been calculated which show exergy destruction for the vapour compression refrigeration system [22–30];

$$I_t = I_{comp} + I_{cond} + I_{exp} + I_{evp} \quad (5)$$

Exergy destruction is also calculated by the entropy generation (S_{gen}) and ambient temperature (T_0) as shown in equation which has been given below [22–30].

$$I = T_0 S_{gen} \quad (6)$$

And entropy generations for vapour compression refrigeration system have been calculated by following equation [22–30].

$$S_{gen} = I / T_0 \quad (7)$$

3 Results and discussions

Entropy generations and exergy destructions have been found for compressor, condenser, expansion device and evaporator when R134a and R600a were used as pure refrigerants for refrigeration system and also when R290 and R152a were used as blend refrigerants with different mass fractions. Specific heats of refrigerants have been taken for this experimental work are; for R134a and its blends 1.34 and 0.9 kJ/kg K, and for R600a 2.31 and 1.64 kJ/kg K for liquid and vapour phase respectively. Total entropy generations and exergy destructions for vapour compression refrigeration system, and componentwise exergy dissipations and entropy generations at different time intervals for various refrigerants have been shown in Tables 2, 3. For better analyses of the results, percentage increments/decrements have also been calculated as; decrements in exergy destructions and entropy generations for compressor, increments in exergy destructions and entropy

generations for condenser, increments in exergy destructions and entropy generations for expansion device, increments in exergy destructions and entropy generations for evaporator with different refrigerants and increments in entropy generations and exergy destructions after 15, 30, 45 and 60 min time periods as shown in Figs. 4, 5, 6, 7, 8, 9, 10, 11 and 12 respectively. Results indicated that percentages of decrement in exergy destructions for R134a are 0.185, 0.252 and 0.345, for 95%R134a + 5%R290 are 0.03, 0.046 and 0.062, for 90%R134a + 10%R290 are 0.052, 0.059 and 0.058, for 85%R134a + 15%R290 are 0.0046, 0.0646 and 0.0836, for R600a are 0.0159, 0.0735 and 0.1616, for 85%R134a + 15%R152a are 0.0249, 0.0649 and 0.1729 at 100, 200 and 300% increments in time intervals respectively for compressor. Percentages of increment in exergy destructions for R134a are 69.39, 130.7 and 160.57, for 95%R134a + 5%R290 are 100.82, 288.4 and 308.41, for 90%R134a + 10%R290 are 90.84, 202.42 and 215.86, for 85%R134a + 15%R290 are 66.089, 135.157 and 168.043, for R600a are 3.004, 4.067 and 8.729, for 85%R134a + 15%R152a are 57.984, 177.226 and 201.8 at 100, 200 and 300% increments in time intervals respectively for condenser. Percentages of increment in exergy destructions for R134a are 296.021, 383.437 and 504.7, for 95%R134a + 5%R290 are 183.986, 196.092 and 247.222, for 90%R134a + 10%R290 are 255.131, 299.605 and 317.538, for 85%R134a + 15%R290 are 33.419, 70.979 and 102.121, for R600a are 7.267, 21.598 and 38.004, for 85%R134a + 15%R152a are 48.833, 86.848 and 120.567 at 100, 200 and 300% increments in time intervals respectively for expansion device. Percentages of increment in exergy destructions for R134a are 254.741, 316.493 and 401.887, for 95%R134a + 5%R290 are 240.077, 255.589 and 314.867, for 90%R134a + 10%R290 are 345.124, 417.415 and 449.052, for 85%R134a + 15%R290 are 41.886, 70.207 and 103.05, for 85%R134a + 15%R152a are 58.034, 99.687 and 113.8, but percentages of decrement for R600a are 2.252, 2.618 and 3.384 at 100, 200 and 300% increments in time intervals respectively for evaporation. EGED-VCRSBR software shown in Fig. 13, i.e. entropy generation and exergy destruction analyses for vapour compression refrigeration system with various blend refrigerants, has been designed on visual basic language to eliminate hectic calculations and human mistakes during research work [31, 32]. Theoretical/Carnot coefficient of performances of refrigerating system with R134a and R600a refrigerants have already been calculated as 2.638 at 4 and 120 psi, 2.807 at 5 and 120 psi and 2.963 at 6 and 120 psi suction and discharge pressures when R134a was used, similarly 3.966 at 12.9 and 99.7 psi, 3.903 at 11.7 and 94.7 psi, 3.807 at 10.5 and 91.2 psi, and 3.632 at 8.9 and 87.2 psi suction and discharge pressures when R600a was used as

Table 2 Total entropy and exergy analyses of vapour compression refrigeration system with different blend refrigerants

Experi- ment no.	T1 (°C)	T2 (°C)	T3 (°C)	T4 (°C)	P1 (psi)	P2 (psi)	Total entropy generation (J/ kg K)	Total exergy destruction (J/ kg)
<i>R134a refrigerant</i>								
1	19.0	25.1	19.3	2.8	5	120	533.64	160090.8
2	11.2	28.3	20.7	− 18	5	120	550.55	165165.3
3	9.0	30.2	21.3	− 22.3	6	120	555.26	166579.8
4	6.3	31.9	22.4	− 27.6	4	120	561.70	168510.5
<i>R134a + 05% R290 blend refrigerant</i>								
5	18.1	23.4	18.3	− 4.2	8	120	538.62	161588
6	16.6	23.7	16.5	− 23.4	8	130	561.83	168550.2
7	16.2	25.2	15.2	− 24.6	10	125	563.52	169057.2
8	15.6	26.7	16.4	− 28.2	6	125	569.61	170884
<i>R134a + 10% R290 blend refrigerant</i>								
9	17.3	23.6	17.3	− 2.2	15	140	536.49	160948.4
10	15.2	25.1	16.4	− 24.6	15	150	562.84	168851.2
11	14.9	25.2	14.3	− 27.8	17	150	568.04	170406.6
12	14.8	24.3	13.2	− 29.1	18	150	570.15	171044.7
<i>R134a + 15% R290 blend refrigerant</i>								
13	18	24.6	18.2	− 14.1	6	170	549.37	164811.5
14	17.6	24.1	15.9	− 20.3	6	180	557.61	167283.5
15	14.6	23.4	13.7	− 26.3	5	175	564.92	169476.2
16	14.2	25.1	14.7	− 30.2	6	180	571.91	171574.7
<i>R600a refrigerant</i>								
17	21.3	34.2	23.2	− 13.5	12.9	99.7	569.25	170776.6
18	19.4	35.3	24.1	− 14.8	11.70	94.7	570.48	171143.7
19	16.5	36.5	25.2	− 17.3	10.5	91.2	573.41	172024.3
20	13.3	38.0	26.4	− 20	8.9	87.2	576.63	172990.7
<i>R134a + 15% R152a blend refrigerant</i>								
21	16	23.8	17.1	− 16.5	8	140	551.17	165351.5
22	15	24.2	15.8	− 25.3	6	130	563.76	169127.7
23	13.6	25.3	14.2	− 31.2	5	120	573.30	171990.4
24	10.1	26.1	14.5	− 35.6	8	120	579.10	173729.5

refrigerant in the system, and better theoretical coefficient of performance was found with R600a refrigerant.

4 Conclusion

In this work, total entropy generations and exergy destructions for vapour compression refrigeration system have been found at different operating conditions, the conditions are; different time intervals and different refrigerants/blend refrigerants. Percentages increments or decrements have also been investigated at same conditions. The main aim of this experimental work was to find best conditions (in terms of refrigerant) which will give best and environmental friendly performance from the refrigeration system. Total and componentwise minimum entropy generations and exergy destructions have been analysed and minimum

increments in entropy generation and exergy destruction have also been found. It has been observed that when time interval increases then total entropy generation and exergy destruction increase. Maximum total entropy generation (i.e. 579.10 J/kg-K) and exergy destruction (i.e. 173729.5 J/kg) were found when 85% of R134a and 15% of R152a was used as blend refrigerant for refrigeration system if 10.1 °C and 26.1 °C were inlet and outlet temperatures of the compressor, whereas minimum total entropy generation (i.e. 533.64 J/kg-K) and exergy destruction (i.e. 160090.8 J/kg) were achieved with pure R134a but it has high global warming potential (i.e. 1430 GWP). It has also been found that exergy destruction and entropy generation increased with time interval for condenser, expansion device and evaporator but decreased for compressor. Least decrements in exergy destructions and entropy generations were found for compressor with 85% of R134a and 15%

Table 3 Componentwise exergy dissipations and entropy generations at different time intervals for various refrigerants

Refrigerants	Time intervals (min)	Exergy dissipation (J/kg)				Entropy generation (J/kg K)			
		Compressor	Condenser	Expansion device	Evaporator	Compressor	Condenser	Expansion device	Evaporator
R134a	15	158147.696	52.461	1248.092	642.550	527.159	0.175	4.160	2.141
	30	157854.377	88.867	4942.707	2279.390	526.181	0.296	16.475	7.597
	45	157748.892	121.028	6033.745	2676.177	525.829	0.403	20.112	8.920
	60	157601.707	136.700	7547.216	3224.874	525.339	0.455	25.157	10.749
R134a + 5% R290 blend refrigerant	15	158138.378	40.903	2165.194	1243.492	527.127	0.136	7.217	4.144
	30	158090.365	82.143	6148.855	4228.829	526.967	0.273	20.496	14.096
	45	158065.603	158.870	6410.962	4421.719	526.885	0.529	21.369	14.739
	60	158040.111	167.053	7518.041	5158.843	526.800	0.556	25.060	17.196
R134a + 10% R290 blend refrigerant	15	158113.219	62.674	1822.800	949.700	527.044	0.208	6.076	3.165
	30	158030.934	119.613	6473.324	4227.347	526.769	0.398	21.577	14.091
	45	158019.174	189.539	7284.010	4913.889	526.750	0.631	24.280	16.379
	60	158021.497	197.965	7610.889	5214.344	526.738	0.659	25.369	17.381
R134a + 15% R290 blend refrigerant	15	158124.700	64.269	3980.508	2641.985	527.082	0.214	13.268	8.806
	30	158117.321	106.744	5310.792	3748.616	527.057	0.355	17.702	12.495
	45	158022.397	151.133	6805.866	4496.851	526.741	0.503	22.686	14.989
	60	157992.455	172.269	8045.444	5364.560	526.641	0.574	26.818	17.881
R600a	15	158289.521	331.101	6891.792	5264.212	527.631	1.103	22.972	17.547
	30	158264.301	341.050	7392.672	5145.653	527.547	1.136	24.642	17.152
	45	158173.024	344.567	8380.347	5126.392	527.243	1.148	27.934	17.087
	60	158033.671	360.003	9510.951	5086.039	526.778	1.200	31.703	16.953
R134a + 15% R152a blend refrigerant	15	158069.407	70.919	4461.004	2750.192	526.898	0.236	14.870	9.167
	30	158029.895	112.041	6639.460	4346.258	526.766	0.373	22.131	14.487
	45	157966.712	196.606	8335.295	5491.784	526.555	0.655	27.784	18.305
	60	157796.001	214.034	9839.503	5879.914	525.986	0.713	32.798	19.599

Fig. 4 Decrement in exergy destructions for compressor with different refrigerants

Fig. 5 Increment in exergy destructions for condenser with different refrigerants

Fig. 6 Increment in exergy destructions for expansion device with different refrigerants

of R290 blend refrigerant and maximum decrements in losses were attained with pure R134a, but least increments in exergy destructions and entropy generations

were achieved for condenser, expansion device and evaporator with R600a, and maximum increments in the losses were found with pure R134a and blend with

Fig. 7 Increment in exergy destructions for evaporator with different refrigerants

Fig. 8 Decrement in entropy generations for compressor with different refrigerants

R290/R152a refrigerants. After analyses, 85% of R134a and 15% of R290 blend refrigerant or R600a refrigerant has been recommended for vapour compression refrigeration systems but due to high global warming

potential of R134a, R600a is preferable which has zero ozone depletion potential and 3 global warming potential.

Fig. 9 Increment in entropy generations for condenser with different refrigerants

Fig. 10 Increment in entropy generations for expansion device with different refrigerants

Fig. 11 Increment in entropy generations for evaporator with different refrigerants

Fig. 12 Increments in entropy generations and exergy destructions after 15, 30, 45 and 60 min of experiments

Fig. 13 Designed EGEDVCRSBR software for entropy and exergy analyses at different conditions

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Compliance with ethical standards

Conflict of interest There is no conflict of interest between authors.

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