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EXERGY ANALYSIS ON A VAPOR COMPRESSION REFRIGERATING SYSTEM USING R12, R134A AND R290 AS REFRIGERANTS

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ABSTRACT

This paper describes an exergetic analysis on a vapor compression refrigerating system. The exergetic relations have been defined. A mathematical model for carrying out exergy analysis by computer has been developed. An experiment and an exergy analysis on 3 refrigerators/freezers using R12, R134a and R290 have been carried out to illustrate the various exergy losses occurring in the different components, and to display the potential improvements.

NOMENCLATURE

COP	*coefficient of performance*
e	*specific exergy (kJ kg^{-1})*
E	*exergy (kJ)*
h	*specific enthalpy (kJ kg^{-1})*
$\dot{m}$	*mass flow (kg sec^{-1})*
Q	*heat (kJ)*
s	*specific entropy (kJ kg^{-1} K^{-1})*
T	*temperature (K)*
w	*work (kJ kg^{-1})*
W	*work (kJ)*

Greek

Δ	*exergy loss*
η_{ex}	*exergy efficiency*

Subscripts

a	*air or surrounding*
c	*condenser*
$comp$	*compressor*
e	*evaporator*
h	*lubricant oil*
i	*defrosting*
l	*capillary*
ls	*liquid in subcooler*
m	*motor*
n	*connecting pipe*
p	*compression*
r	*heat emission in air*
s	*subcooler*
v	*superheating in suction pipe*
vs	*vapor in subcooler*
x	*desuperheating in discharge*
0	*reference state*
$1...10$	*state points*

INTRODUCTION

According to the MONTREAL PROTOCOL, the refrigerant R12 will be abandoned by 1995, due to its high ODP and GWP level. For domestic refrigeration, R134a and R290 are possible substitutes known. Their interest is that they can be applied by some simple alterations of materials since they have near thermodynamic properties with R12. Therefore, a comparison of performance within R12, R134a and R290 has been carried out with the help of exergetic analysis method in this paper.

Exergetic analysis has showed a great interest in recent years due to the fact that it combines the application of the first and the second law of thermodynamic. This analysis helps to understand clearly irreversibility influences in thermodynamic process. It permits to identify and calculate the various exergy losses in different components, and hence leads to improve thermodynamic efficiency.

The aim of this paper is to introduce an exergetic analysis method on vapor compression refrigerating system in order to compare the performance between 3 refrigerators/freezers using R12, R134a and R290 as the refrigerants, hence to find an appropriate substitute of R12. In this paper, an exergetic analysis model by micro-computer has been developed. Experiment with 3 refrigerators/freezers has been carried out. The exergy analysis resultats are reported. The means for reducing the various exergy losses in different components are also discussed.

REVIEW OF EXERGY CONCEPTS

Exergy definition

Exergy at a given state is equal to the maximum work that can be obtained when operating reversibly between the given state and the reference state:

$$e=(h-h_0)-T_0(s-s_0) \tag{1}$$

For a heat Q at a constant temperature T, exergy can be also calculated by

$$E=(1-\frac{T_0}{T})Q \tag{2}$$

The reference state is often the surrounding of system.

Exergy loss and exergy efficiency

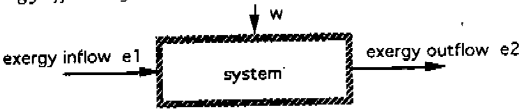

Figure 1 Exergy balance

According to the second law of thermodynamic, irreversibilities in process cause always some thermodynamic losses. Therefore, for a steady process with a mechanical input w (Figure 1), the exergy input flow is always greater than the exergy outflow. The exergy loss of this process can be calculated by exergy balance:

$$\Delta e=w+e_1-e_2 \tag{3}$$

In particular, for a reversible process

$$\Delta e=w_r+e_1-e_2=0 \tag{4}$$

Since $w>w_r$, the irreversibilities absorbe a portion of mechanical energy input for compensating the exergy losses. For appreciating the perfection degree of an irreversible process in comparing its correspondent reversible process, we introduce an exergy efficiency:

$$\text{Exergy efficiency}=\frac{\text{work requested by correspondent reversible process}}{\text{work consummated by irreversible process}}$$

$$\eta_{ex}=\frac{w_r}{w}=1-\frac{\Delta e}{w} \tag{5}$$

The exergy efficiency is equal to 1 when process is reversible, and is less than 1 in else case.

EXERGY ANALYSIS OF VAPOR COMPRESSION SYSTEM

The refrigerator system consists of a compressor, a condenser, a subcooler, a capillary and an evaporator (Figure 2). For the freezer system, after compression the refrigerant encircles the joint of freezer door for defrosting (Figure 3).

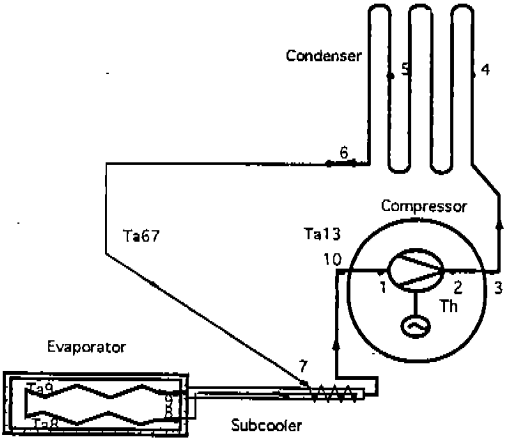

Figure 2 Refrigerator circuit

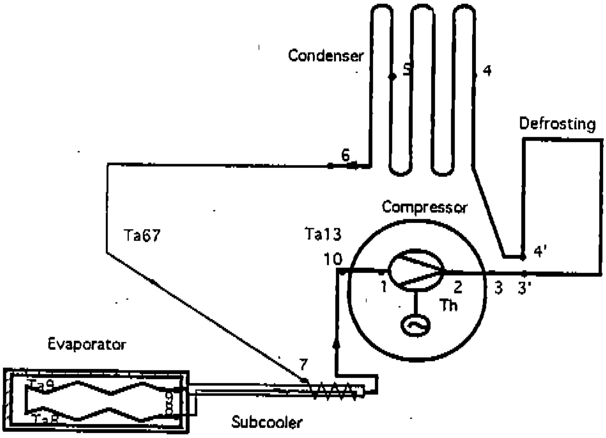

Figure 3 Freezer circuit

1 Exergetic analysis of components

In condenser and in subcooler, exergy losses are caused by heat transfer between different temperature levels.

Condenser

$$\Delta E_c=E_c-E_{ac}=(e_3-e_6)\dot{m}-(1-\frac{T_0}{T_{ac}})(h_3-h_6)\dot{m} \tag{6}$$

Subcooler

$$\Delta E_s=E_{ls}-E_{vs}=(e_7-e_8)\dot{m} - (e_{10}-e_9)\dot{m} \tag{7}$$

Evaporator

In evaporator, exergy loss is caused by different temperature levels and pressure loss

$$\Delta E_e=E_{ae}-E_e=(1-\frac{T_0}{T_{ae}})(h_9-h_8)\dot{m}-(e_9-e_8)\dot{m} \tag{8}$$

Capillary

In capillary, exergy loss is caused by irreversible expansion.

$$\Delta E_l=(s_7-s_6)\dot{m} \tag{9}$$

Compressor

The exergy analysis of motor-compressor is complex. Taking electric efficiency of motor (60%-80%) into account, a considerable part of electric power is transformed into heat flow absorbed by lubricant oil. A part of this heat flow is used to superheat refrigerant vapor between the compressor inlet and the suction of compressor piston. The rest is get free in the surrounding. For reason of simplification, the compression is assumed adiabatic. Between piston discharge and compressor outlet, refrigerant is desuperheated by yielding heat flow into lubricant oil, finally into the surrounding. By the same ways above, we carry out an exergy analysis in compressor.

Loss of motor

In the motor, a part of electric power is transformed into heat flow by magnetic and mechanical losses. According to the second law of thermodynamic, the quality of electric energy and of heat is different. Hence, the exergy loss can be calculated by

$$\Delta E_m=W_m-E_m=W_m-(1-\frac{T_0}{T_h})W_m=\frac{T_0}{T_h}W_m \tag{10}$$

With heat flow $W_m=W-W_p$

Superheating in suction pipe

$$\Delta E_v=E_{hv}-E_v=(1-\frac{T_0}{T_h})W_v-(e_1-e_{10})\dot{m} \tag{11}$$

With superheating flow $W_v=(h_1-h_{10})\dot{m}$

Heat emission in surrounding

$$W_r=W_m-W_v$$

$$\Delta E_r=E_{hr}-E_{ar}=(1-\frac{T_0}{T_h})W_r-(1-\frac{T_0}{T_{a13}})W_r \qquad (12)$$

Compression

The irreversibility of compression causes an increase of entropy, hence an exergy loss:

$$\Delta E_p=(s_2-s_1)\dot{m} \qquad (13)$$

superheating in discharge pipe

$$\Delta E_x=E_x-E_{ax}=\dot{m}(e_2-e_3)-(1-\frac{T_0}{T_{a13}})\dot{m}(h_2-h_3) \qquad (14)$$

The total exergy loss of compressor is

$$\Delta E_{comp}=\Delta E_m+\Delta E_v+\Delta E_r+\Delta E_p+\Delta E_x \qquad (15)$$

For freezer system, we have to take into account the exergy losses in desuperheating and in defrosting upstream from condenser.

Desuperheating in connecting pipe

$$\Delta E_n=E_n-E_{an}=\dot{m}(e_3-e_{3'})-(1-\frac{T_0}{T_{ac}})\dot{m}(h_3-h_{3'}) \qquad (16)$$

Defrosting

$$\Delta E_i=E_i-E_{ai}=\dot{m}(e_3-e_{4'})-(1-\frac{T_0}{T_{ac}})\dot{m}(h_{3'}-h_{4'}) \qquad (17)$$

2 Exergy balance of system

After exergy analysis of each component, we can make an exergy balance of this refrigeration system. For a close system, the exergy gains are egal to the sum of exergy losses:

$$E_v+W_p+E_e+E_{vs}=\Delta E_p+E_x+E_n+E_i+E_c+\Delta E_l+E_{ls} \qquad (18)$$

Considering the above exergy equations of each component, we can finally obtain the exergy balance of this refrigeration system:

$$\begin{aligned}W=(&\Delta E_m+\Delta E_v+\Delta E_r+\Delta E_p+\Delta E_x+\Delta E_n+\Delta E_i+\Delta E_c+\Delta E_l+\Delta E_s+\Delta E_e)\\&+((E_{ar}+E_{ax}+E_{an}+E_{ai}+E_{ac})-E_{ac})\end{aligned} \qquad (19)$$

We remark that electric comsumption of compressor is used to:

(i) Raise the exergy of system from the system source at a low temperature (cold room) to the system sink at a high temperature (surrounding).

$$E_{sy}=(E_{ar}+E_{ax}+E_{an}+E_{ai}+E_{ac})-E_{ac} \tag{20}$$

(ii) Compensate total exergy losses due to irreversibilities in system.

$$\Delta E_{sy}=\Delta E_m+\Delta E_v+\Delta E_r+\Delta E_p+\Delta E_x+\Delta E_n+\Delta E_i+\Delta E_c+\Delta E_l+\Delta E_s+\Delta E_e \tag{21}$$

3 COP and exergy efficiency

The coefficient of performance is calculated by

$$COP=\frac{P_f}{W} \tag{22}$$

Where P_f is the refrigerating capacity of system.

In order to calculate the exergy efficiency given by equation (5), we have to calculate at first the reversible power of system. Therefore, we determine an equivalent average temperature for the source ($\overline{T_s}$) and for the sink ($\overline{T_k}$) from their exergy. Here $\overline{T_s}$ is the average air temperature in cold room and $\overline{T_k}$ is the average air temperature of system surrounding. In this way, the COP of CARNOT and the reversible power of system can be calculated :

$$COP_{carnot}=\frac{\overline{T_s}}{\overline{T_k}-\overline{T_s}} \tag{23}$$

$$W_r=\frac{P_f}{COP_{carnot}} \tag{24}$$

the exergy coefficient is

$$\eta_{ex}=\frac{W_r}{W}=\frac{COP}{COP_{carnot}} \tag{25}$$

The exergy efficiency shows clearly thermodynamic perfection degree of refrigeration system.

In this paper, a model of vapor compression system for carrying out exergy analysis by computer has been developed.

EXPERIMENTS

In an air-conditioned cabinet, 3 refrigerators/freezers each using one fluide of R12, R134a and R290 have been tested at a surrounding temperature of 32 °C according to ISO 8187. The circuit is the same. But ester oil is used for R134a compressor lubrication. For R290 refrigerator, the volume of compressor is a little reduced because of its too high compressor load and greater volumetric refrigerating capacity. In this test, temperature regulation is canceled in system and refrigerating capacity of system is controled constant by an electric resistance for achieving steady operating state. 27 temperatures, 2 pressures and 2 electric power have been measured at steady state on each cycle for carrying out carefully an exergy analysis.

Parameters		R12	R134A	R290
T cond	°C	57.4	54.1	48.3
P cond	bar	14.4	14.6	16.5
Tin evap	°C	-21.3	-17.7	-17.8
Pin evap	bar	1.43	1.46	2.62
Tout evap	°C	-19.6	-17.1	-14.9
Pout evap	bar	1.42	1.35	2.43

Table 1 Operating parameters of 3 refrigerators

	R12		R134a		R290	
	exergy loss [W]	%	exergy loss [W]	%	exergy loss [W]	%
Condenser	4.60	6.57	3.67	5.62	2.76	3.78
Subcooler	2.75	3.92	2.08	2.97	2.30	3.28
Capillary	0.06	0.08	0.03	0.04	0.05	0.07
Evaporator	6.67	9.52	5.37	7.70	5.43	7.43
Compression	55.98	79.90	58.65	84.03	62.44	85.43
Total	70.05	100	69.79	100	73.08	100

Table 2 Exergy losses in refrigerator components

		R12	R134a	R290
$\overline{T}_s$	°C	3.1	1.3	3.85
$\overline{T}_k$	°C	38.6	39.1	38.7
Pf	W	61.59	57.30	51.27
W	W	79.50	79.30	81.13
Wr	W	7.93	7.89	6.45
COP		0.775	0.721	0.63
COPcarnot		7.771	7.253	7.952
η_{ex}		0.0997	0.0995	0.0795

Table 3 COP and exergy efficiency of 3 refrigerators

	R12		R134a		R290	
	exergy loss [W]	%	exergy loss [W]	%	exergy loss [W]	%
Compression	0.16	0.3	4.77	8.1	4.68	7.49
motor	42.77	76.4	40.79	69.6	44.70	71.6
Superheating	0.89	1.6	0.82	1.4	0.98	1.6
Heat emission	5.82	10.4	5.43	9.3	5.37	8.6
Desuperheating	6.33	11.3	6.84	11.7	6.71	10.7
Total	55.98	100	58.65	100	62.44	100

Table 4 Exergy losses in refrigerator compressors

Parameters		R12	R134A	R290
T.cond	°C	44.5	46.6	46.4
P cond	bar	10.7	12.1	15.8
Tin evap	°C	-30	-25.7	-30.7
Pin evap	bar	1.00	1.03	1.62
Tout evap	°C	-22.6	-18.4	-20.1
Pout evap	bar	0.9	0.8	1.24

Table 5 Operating parameters of 3 freezers

	R12		R134a		R290	
	exergy loss [W]	%	exergy loss [W]	%	exergy loss [W]	%
Condenser	1:33	1.59	1.82	2.30	1.53	1.46
Subcooler	2.83	3.39	2.35	2.97	4.68	4.48
Capillary	0.02	0.02	0.03	0.04	0.09	0.08
Evaporator	2.89	3.46	3.41	4.31	6.42	6.14
Compression	73.92	88.42	69.07	87.27	84.12	80.46
Desuperheating	0.53	0.63	0.38	0.49	0.9	0.86
Defrosting	2.08	2.48	2.08	2.63	6.80	6.51
Total	83.59	100	79.14	100	104.55	100

Table 6 Exergy losses in freezer components

		R12	R134a	R290
$\bar{T}$s	°C	-23.9	-20.9	-22.3
$\bar{T}$k	°C	35.6	34.9	31.4
Pf	W	62.45	59.26	75.36
W	W	99.50	93.00	120.50
Wr	W	14.91	13.11	16.15
COP		0.628	0.637	0.625
COPcarnot		4.187	4.521	4.67
ηex		0.150	0.141	0.134

Table 7 COP and exergy efficiency of 3 freezers

	R12		R134a		R290	
	exergy loss [W]	%	exergy loss [W]	%	exergy loss [W]	%
Compression	0.23	0.3	3.66	5.3	0.48	0.6
motor	59.30	80.2	51.38	74.4	63.95	76.0
Superheating	0.85	1.2	0.88	1.3	1.77	2.1
Heat emission	7.37	10.0	6.05	8.76	9.28	11.0
Desuperheating	6.17	8.4	7.09	10.3	8.63	10.3
Total	73.92	100	69.07	100	84.12	100

Table 8 Exergy losses in freezer compressors

RESULTATS AND DISCUSSION

Table 1 and Table 5 give the main operating parameters of 3 refrigerators and of 3 freezers.

Table 2 and Table 6 show exergy losses in each component of 3 refrigerators and of 3 freezers.

Table 3 and Table 7 report temperature levels, coefficient of performance and exergy efficiency of 3 refrigerators and of 3 freezers.

Table 4 and Table 8 show the various exergy losses in each compressor.

On comparing 3 refrigerators, the exergy efficiency for R12 and for R134a is almost egal. We see that COP for R12 is a little higher than for R134a. But we can't compare directly them in this case, because they have not exactly the same temperature levels. According to thermodynamic properties of refrigerants, R134a always works with a greater pressure ratio than R12 for given temperatures. It's usually a disadvantage about the volumetric efficiency of compressor and so that the cycle for R134a is somewhat less efficient than for R12. This test indicates that this difference of performance is very small between R12 and R134a refrigerators. The cycle with R290 is less efficient than with R12 and with R134a. In this test, we noticed that R290 has the best volumetric refrigerating capacity in these 3 refrigerants. But it increases dramatically compressor load. Therefore, in this test we reduced the piston for R290 compressor, hence compressor load. Table 2 shows that the most exergy loss (about 80%) is occurred in compressors, especially in motors (Table 4). Therefore a careful study for improving electric efficiency of motor should be made in future. The exergy loss in evaporator is also important. It can be explained by its great different temperature levels. This exergy loss can be reduced by increasing evaporator surface.

As can be seen in Table 4 and Table 5, freezer with R12 is more efficient than with R134a and with R290. Exergy efficiency of R134a is only lightly less than R12. But we noticed in this test, evaporation temperature of R134a is limited at -25 °C in this circuit. This can be explained by the saturation curves of R134a. For achieving a lower temperature (-30 °C), R134a has to be expanded to a lower pressure (0.85 bar) at the end of capillary. If we prolong capillary for R134a freezer, it will increase inevitably the pressure ratio of compressor, hence compressor load, and will cause also some problem for circuit airtightess. However, the freezer of R134a can maintain steadily a low temperature less than -18 °C in this test. The freezer for R290 has a higher volumetric refrigerating capacity, but its compressor load is too great. Therefor, the freezer of R290 is globally less efficient. In order to improve the performance of R290 freezer, it's necessary to redesign compressor. As in refrigerators, exergy analysis of 3 freezers indicates that, the main exergy loss sources are always Compressor and evaporator. Hence, it's necessary to improve compressor and to increase evaporator surface in future research, however, it increases inevitably the cost of installation.

CONCLUSION

The exergy analysis method helps to localize exergy losses in refrigerating system, and to devise means to reduce them. This test indicates that, the great part of exergy loses is occurred in compressor and in evaporator for this vapor compression system. The refrigerator of R134a is almost efficient than for R12. But freezers for R134a and for R290 are less efficient than R12 freezer. Each has some difficulties to achieve the same performance of R12. To replace R12 in freezer, a careful study should be made in future.

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