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Research Article

Exergy Analysis of Vapour Compression Refrigeration System

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Abstract

Energy consists of two parts, one is available energy and other is unavailable energy. The available energy is useful part of energy from which maximum useful work is obtained which is known as exergy. Unavailable energy accounts for the losses and irreversibility's occurring in the system.Exergy analysis is an assessment technique for systems and processes that is based on the second law of thermodynamics. It has been increasingly applied over the last several decades largely because of its advantages over energy analysis. With exergy analysis, more meaningful efficiencies are evaluated, because they give a measure of the approach to the ideal and inefficiencies in a process. It also quantifies the types, causes, and locations of losses. Improvement in exergy efficiency will results in saving of electricity required to operate the system by minimizing the exergy loses. In this article, the role of exergy analysis in assessing and improving energy systems like vapour compression refrigeration system is examined. System taken under consideration is refrigeration tutor. Also, exergy and its use as an analysis technique are briefly described.

Keywords: *Energy, Available energy, Unavailable energy, Exergy, Exergy efficiency, Exergy analysis.*

1. Introduction

In thermodynamics, the term exergy of a system is the maximum useful work which is possible during a process that brings the system into equilibrium with a heat reservoir.When the surroundings are the reservoir, exergy is the potential of a system to cause a change as it achieves equilibrium with its environment. After the system and surroundings reach equilibrium, the exergy of a system is zero. Exergy is a property and is associated with the state of the system and the environment. A system that is in equilibrium with its surroundings has zero exergy and is said to be at the dead state. As engineers, we know that energy is already conserved. What is not conserved is exergy. Once the exergy is wasted, it can never be recovered. Exergy analysis involves the application of exergy concepts, balances, and efficiencies to evaluate and improve energy and other systems. A main aim of exergy analysis is to identify the meaningful (exergy) efficiencies and the causes and true magnitudes of exergy losses. Improvement in exergy efficiency will lead to reduction in irreversibilities and losses occurring in the system. This will lead to improve the performance of system, thereby causing saving in electricity, which ultimately justifies cost for their operation. Also, it is important to note that, basic purpose of analyzing vapour compression refrigeration system, that means, refrigeration tutor, is because refrigeration tutor is simplest of all vapour compression refrigeration system. It's just like a domestic refrigerator, which is so common and runs continuously everywhere.

2. Exergy Analysis

It includes exergy analysis of refrigeration tutor. A refrigeration tutor is mainly use for academic purpose because of its simplicity in operation. In this case study, experimental readings are taken on refrigeration tutor of 0.2 TR capacities using R12 as refrigerant. A constant loading in evaporator is done with the help of a heater provided inside the evaporator. Results are shown in tabular form along with respective graphs.

2.1 System configuration

System specifications of refrigeration tutor with individual components in brief are listed in table 1 as shown below.

Table 1 Specifications of experimental setup

S. No	Parameters	Description
1	Type	Refrigeration Tutor
2	Refrigerant	R12
3	Capacity	0.2 TR
4	Compressor	Hermetically sealed, Reciprocating type
5	Condenser	Finned coils, Air cooled
6	Expansion device	Thermostatic expansion valve
7	Evaporator	Finned coils

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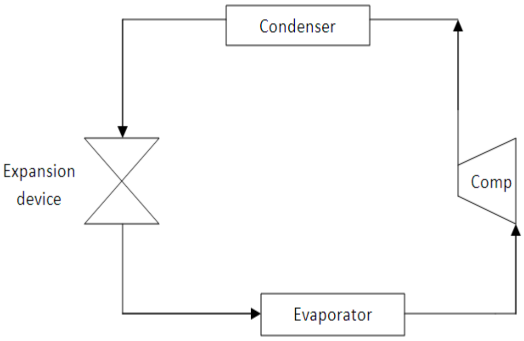

Fig.1 Refrigeration tutor schematic diagram

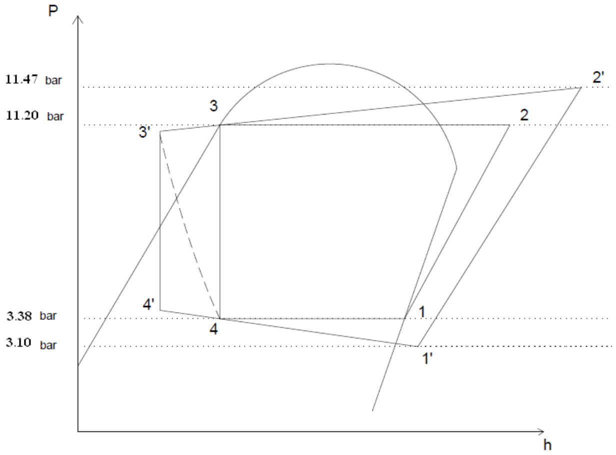

Fig.2 P–h chart representations

2.2 Operating parameters

Fig 2 shows system representations on P-h chart for ideal and actual vapour compression refrigeration cycle. There occurs pressure losses on both evaporator and condenser side. Thus, experimental readings are taken on refrigeration tutor for actual cycle considering pressure losses and observations are tabulated as shown below in table 2.

Table 2 Refrigeration tutor observations

S. No	Parameters	Values
1	Condenser pressure in	11.47 bar
2	Condenser pressure out	11.20 bar
3	Evaporator pressure in	3.38 bar
4	Evaporator pressure in	3.10 bar
5	Refrigerant flow rate	16 lph
6	Condenser inlet temperature	60^0C
7	Condenser outlet temperature	35^0C
8	Evaporator inlet temperature	-1^0C
9	Evaporator outlet temperature	15^0C

2.3 Formulae used

$$(\eta_{ex})_{comp} = \frac{W_{rev}}{W_{comp,ip}} = \frac{m_r\,[(h_2{}' - h_1{}') - T_0\,(s_2{}' - s_1{}')]}{\frac{N_C \times 3600}{t_C \times 1200}} \quad (1)$$

$$(\eta_{ex})_{cond} = \frac{E_{x,qh}}{E_{x,2} - E_{x,3}} = \frac{Q_H\left(1 - \frac{T_O}{T_H}\right)}{m_r\,[(h_2{}' - h_3{}') - T_0\,(s_2{}' - s_3{}')]} \quad (2)$$

$$(\eta_{ex})_{exp\ valve} = 1 - \frac{E_{x,dest,3-4}}{E_{x,3} - E_{x,4}} = 1 - \frac{m_r\,[(h_4{}' - h_3{}') - T_0\,(s_4{}' - s_3{}')]}{m_r\,[T_0\,(s_4{}' - s_3{}')]} \quad (3)$$

$$(\eta_{ex})_{evap} = 1 - \frac{E_{x,dest,4-1}}{E_{x,1} - E_{x,4}} = \frac{-Q_L\left(1 - \frac{T_O}{T_L}\right)}{m_r\,[(h_1{}' - h_4{}') - T_0\,(s_1{}' - s_4{}')]} \quad (4)$$

$$(COP)_{car} = \frac{T_L}{T_H - T_L} \quad (5)$$

$$(COP)_{theo} = \frac{RE}{W_C} \quad (6)$$

$$(COP)_{act} = \frac{W_{heater,ip}}{W_{comp,ip}} \quad (7)$$

$$(\eta_{ex})_{II} = \frac{COP_{act}}{COP_{carnot}} \quad (8)$$

Where,
h – enthalpy
s – entropy
m_r– refrigerant mass flow rate
T_0 – ambient temperature
T_H – highest temperature in system
T_L –lowest temperature in system
N_c– no. of revolutions by compressor energy meter
t_c– time taken for 10 revolutions of compressor meter
Q_H –heat energy rejected by condenser
Q_L – heat energy absorbed by evaporator
RE – refrigerating effect
W_c– work done by compressor
η –efficiency
rev– reversible
x, ex –exergy
c, comp – compressor
cond– condenser
exp valve – expansion device
car–carnot
evap– evaporator
theo– theoretical
act– actual
ip– input
dest– destruction
0 – ambient conditions
1’,2’,3’,4’– end points in system
II – second law efficiency

2.4 Results and discussions

Initially, exergy analysis of individual component of refrigeration tutor is done by applying various formulae. Then exergy analysis of complete system as a whole is done and results are tabulated in table 3.

Fig. 3 shows component wise exergy efficiency values of individual components which varies from 34 % to 92 % among themselves. Highest exergy efficiency value is obtained for evaporator, lowest for compressor. However, overall exergy efficiency for the system is found to be 58 %.

It is found analytically that, exergy efficiency increases linearly with the increase in condenser temperature as shown in fig 4. This is because enthalpy of refrigerant increases with the corresponding increase in condenser temperature. However, it imposes limitation on use of higher condenser inlet temperatures from compressor capacity and metallurgical considerations.

Table 3 Refrigeration tutor results

S. No	Parameters	Description
1	Compressor reversible work	0.14 kW
2	Compressor input	0.40 kW
3	Compressor exergy efficiency	34.60 %
4	Exergy in to condenser	0.09 kW
5	Exergy destruction in condenser	0.11 kW
6	Condenser exergy efficiency	75.45 %
7	Exergy in to capillary	0.06 kW
8	Exergy out from capillary	0.09 kW
9	Capillary exergy efficiency	67 %
10	Exergy in to evaporator	0.06 kW
11	Exergy destruction from evaporator	0.065 kW
12	Evaporator exergy efficiency	92 %
13	Carnot COP	4.459
14	Theoretical COP	3.933
15	Actual COP	2.576
16	Second law efficiency of system	57.79 %

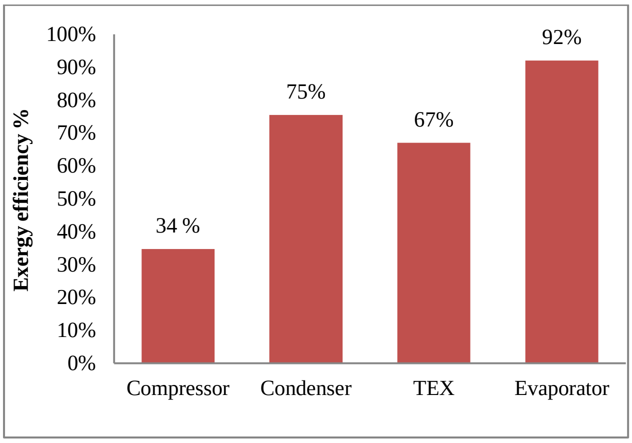

Fig.3 Component wise exergy efficiency values

2.5 Graphs

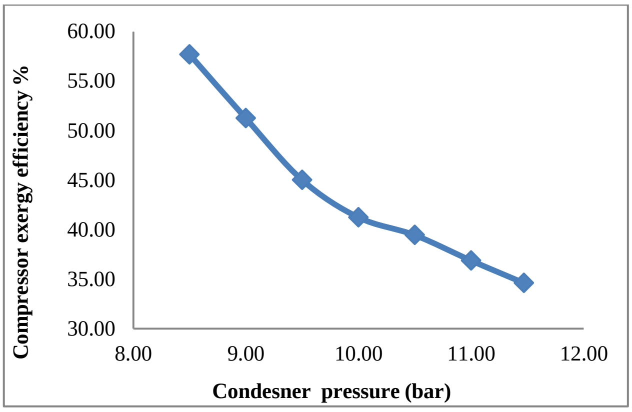

Fig.4 Variation of compressor exergy efficiency with condenser pressure

Fig 4 shows that, compressor exergy efficiency decreases with increase in condenser pressure and temperature. It means that compressor works more effectively at lower condenser pressure, because at higher pressure, it has to deal with highly superheated refrigerant which needs more volume to be handle and correspondingly to do more work.

Fig 5 shows that, condenser exergy efficiency increases with increase in its temperature. COP of the system also increases with increase in condenser temperature. However, it imposes limitation on use of higher condenser inlet temperatures from compressor capacity and metallurgical considerations.

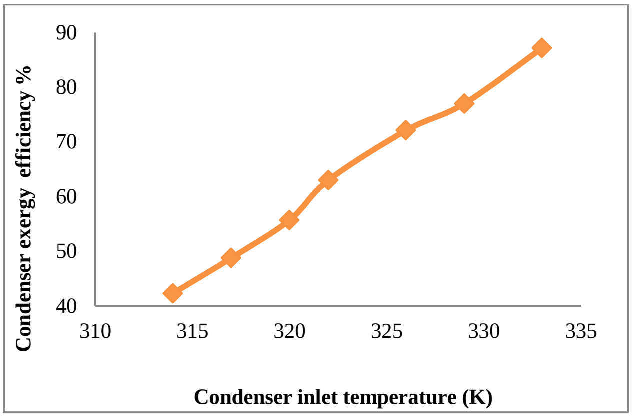

Fig.5 Variation of condenser exergy efficiency with condenser inlet temperature

Fig. 6 shows that, second law efficiency decreases linearly with the increase in evaporator temperature. Increase in evaporator temperature results in increase in exergy cooling load, while mass flow rate remains constant. At lower temperatures, exergy losses in are less, thus evaporator works effectively.

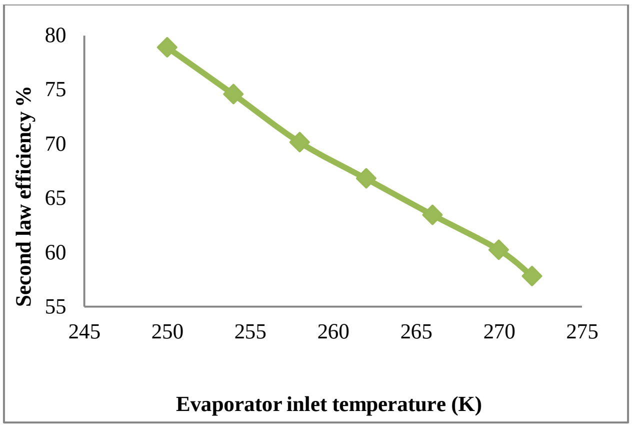

Fig.6 Variation of second law efficiency with evaporator inlet temperature

Fig 7 shows that, second law efficiency decreases linearly with the increase in condenser temperature. This is because enthalpy of refrigerant increases with the corresponding increase in condenser temperature. This trend is almost similar to that shown in fig 5.

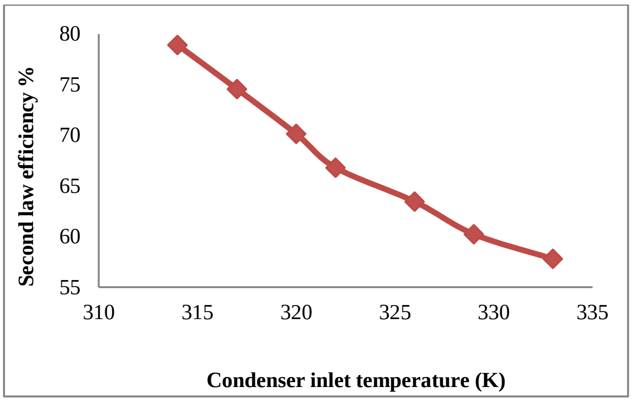

Fig.7 Variation of second law efficiency with condenser inlet temperature

Conclusions

Exergy analysis of refrigeration tutor is done and graphs are plotted as shown earlier. The results show that performance of system and hence exergy efficiency are affected due to change in evaporator and condenser temperature. Following conclusions have been made.

1) It is found that second law efficiency of the system is 58% which is low and shows that system is not performing effectively. This is because of may be gas leakages, internal irreversibility's present in the system and component wise exergy losses.
2) Second law efficiency increases with the decrease in evaporator as shown in fig 6. Reason for above is that, at lower evaporator pressures and temperatures, load on evaporator is more, thus it has to absorbs more heat, more refrigerating effect is obtained, COP increases. Moreover, exergy loses as we know reduces at lower pressures and temperatures. Thus, it got highest component wise exergy efficiency value.
3) Lowest value of exergy efficiency value is found for compressor as it follows non isentropic compression. Also, at higher condenser pressure, specific volume of superheated refrigerant increases and thus has to do more work, consequently results in decrease in its efficiency value.
4) One of the other reasons for failure of hermetically sealed compressors may be that burnt out of motor windings which run the compressor can contaminate whole systems requiring the system to be completely pumped down and the gas replaced.
5) Throttling process in capillary from state 3 to 4 is considered to be a straight line in theoretical case. However, in actual cycle, it is not a straight line, i.e., not an isenthalpic expansion as always enthalpy drops takes place in reality.
6) Unlike energy efficiencies, exergy efficiencies always provide a measure of how closely the operation of system approaches the ideal. By focusing research on plant sections or processes with the lowest exergy efficiencies, like compressors in this case, effort is directed to those areas that inherently have the largest margins for exergy efficiency improvement.
7) Major contributors to exergy losses include loss due to entropy generation, leakages in the piping of the system, system irreversibilities and so on, which should be minimized in order to increase performance of the system, to increase life of components and ultimately their operational cost.

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