Exergetic Investigations of a Multistage Multi-evaporator Vapour Compression Refrigeration System

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Abstract Energy is the ability to cause a change in a system. It is usually available as exergy and anergy. Exergy is a useful part of energy, also known as available energy. Anergy is the counterpart of exergy, also known as unavailable energy. Thermodynamics is the science associated with energy and exergy, thereby ensuring both laws of thermodynamics—the first and the second by incorporating energy and exergy efficiencies. Refrigeration is a technology to preserve commodities at lower temperatures than their surroundings. One of the most widely used refrigeration systems is a vapour compression refrigeration system whose basic objective is to produce a refrigerating effect at the desired location. Commercial large capacity plants consist of the preservation of a different variety of food items requiring different preservation temperatures. It needs to maintain the evaporators correspondingly at different required temperatures. It requires multi-staging in compressors to save the compressor energy consumption. Exergy efficiency governs the actual performance of the system by knowing its deviation from the ideal one, and thus, is a true measure of any system performance. In this paper, an exergetic investigation of a multistage multi-evaporator vapour compression refrigeration system with individual expansion valves using R22 refrigerant is carried out. A shell and helical type

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heat exchanger is inbuilt as an intercooler between two compression stages comprises of refrigerant on both—shell and tube side. The two evaporators are maintained at −10 °C and 10 °C. Various parameters like exergy destruction and exergy efficiency are computed. Compressor consumes the maximum exergy destruction among all the components. Variation of exergy efficiency with different parameters is represented in graphical forms. Exergy analysis is a well-known technique and proved to be an alone tool for evaluating and comparing systems more meaningfully. It also helps to improve and optimize the design and analysis of a system.

Keywords Energy · Thermodynamics · Refrigeration · Exergy efficiency · Exergy destruction

Nomenclature

W	Work input
m	Mass flow rate
h	Enthalpy
Q	Heat load
V	Voltage
I	Current
COP	Coefficient of performance
T	Temperature
RE	Refrigerating effect
N	Number of revolutions
t	Time
EX	Exergy
S	Entropy
EP	Exergy of the product
EDR	Exergy destruction ratio

Greek Letters

η	Efficiency

Subscripts

LP	Low-pressure compressor
HP	High-pressure compressor
e1	Evaporator 1

e2	Evaporator 2
r	Refrigerant
carnot	Carnot
theo	Theoretical
act	Actual
L	Low-temperature side
H	High-temperature side
Heater,ip	Input to the heater
comp,ip	Input to the compressor
h	Heater
c	Compressor
D	Destruction
0	Dead state condition
cond	Condenser
cap	Capillary tube
tex	Thermostatic expansion valve
ex	Exergy

1 Introduction

The energy crisis is the most critical issue in today's era. The first law of thermodynamics indicates the analysis, design, and evaluation of a given system, and it governs the quantity of energy only and not the quality. It is insufficient and incapable of dealing with practicalities associated with any system. As a corollary to this, the second law of thermodynamics is introduced which makes accountability for losses, irreversibilities, and exergy destructions in any system. Entropy generation creates disturbances within the system making it inefficient. Therefore, exergy is a tool in second law analysis. System exergy is the most attainable work to be pulled out from a system at a specified state under a given environment. Thus, it is a property of both: the system as well as the surroundings. 'Exergy' term is derived from Greek words: 'ex' means 'form' and 'ergon' means 'work'. Unlike conserved energy, exergy is always destroyed in all irreversible processes and is a boundary phenomenon. A dead state (normally referred to as environment) is a condition of complete equilibrium of both system and surroundings, and exergy at a dead state is always zero.

Exergy analysis overcomes the inadequacies that remain with energy analysis. It shows that degradation of exergy occurs when a system reaches a complete equilibrium state with surroundings; thereby no further work can be performed at all. Exergy analysis has the following characteristics: It quantifies true locations, the magnitude of losses, irreversibilities, and destructions along with inefficiencies. It also enables to have maximum availability or usefulness of a system to become more efficient. Exergy efficiency is a tool to measure the approach to idealness, which is not the case with often misleading energy efficiencies. Recently, exergy is used in conjunction with exergoeconomic terms wherein cost calculations, environmental impacts, and sustainability assessment are incorporated.

2 Literature Survey

Dincer [1] suggested different methods to perform an exergy analysis of some thermal systems. It focuses on various features of refrigeration, power production, and cryogenic intentions, etc. Exergy analysis case studies of various thermal systems are done involving their basic concepts. It is a research-oriented textbook that covers almost all features including theory and practice in an easily understandable format. It enlightens various latest techniques for viewing the exergy analysis all along together with their applications and recent information. It incorporates basic information to conduct an exergy analysis of any particular thermodynamic system like the principle of entropy generation, various practical case studies of energy, and exergy analysis, etc. It is the most widely referred book for exergy analysis of any particular system [1]. It also explained the basics of thermodynamic concepts for the analysis purpose. Moreover, examples of exergy concepts are illustrated with simple concepts [2]. A study includes the method to enhance the thermal functioning of the refrigeration system by using analysis tools like energy and exergy. The system considered is multiple evaporators with multistage compressors and multiple expansion valves including flash chambers. R134a finds its suitability for various commercial and practical applications. After going through numerical computations, an increase of 22% is obtained in both—the first and second law efficiencies. Among all the components, the worst thermal performance is shown by the expansion valve followed by the condenser, evaporator, and compressor. With the increase in ambient temperature, the corresponding decrease in exergy destruction ratio takes place with an increase in exergy efficiency [3].

A cascade (ammonia/carbon dioxide) vapour compression refrigeration system is simulated using the Energy Equation Solver tool. Exergy analysis provides a good look for system design, its analysis, and its exergy assessment. The overall plant exergy efficiency of 42.13% is suggesting scope for improvement from an energy point [4]. An EES tool is used for COP maximization with consideration of different variables and parameters. Interpretation predicts that with an increase in the subcooling phenomenon, COP increases. Also, R717 gives the best outcomes among all other refrigerants selected [5].

A simulation of high temperature and multistage compression using R1234ze(Z) as refrigerant of a heat pump including exergy analysis is done with hot water as supply from waste heat recovery. Exergy destruction for the compressor is higher in comparison with the evaporator and condenser of a single-stage system. The multistage system shows an increase of 9.1% and 14.6% in COP for two- and three-stage vapour compression refrigeration systems, respectively. COP increases proportionately with an increase in temperature of the source of waste heat. Among all the combinations, three-stage refrigeration systems offer various thermal performance advantages over others [6].

A thermodynamic analysis of waste heat extraction using ammonia as a refrigerant using an intercooler of a multistage refrigeration system is performed [7]. Heat recovery can be boosted by ensuring optimum operating conditions like water flow rate, water temperatures, use of suitable working fluid, etc. A 20 kW of waste heat recovery is achieved which thereby causes a 4–5% increase in COP value. Maximum COP of 3.087 for − 40 °C evaporator temperature is obtained. However, COP decreases with an increase in the condenser and a decrease in evaporator temperatures.

The thermal performance analysis of a multi-evaporator and multi-compressor refrigeration system using eco-friendly refrigerants is presented [8]. It includes both combinations of individual and multi-expansion valves by using different low GWP refrigerants. Mathematical formulae and expressions to interpret component-wise exergy destructions, etc., are presented. Results reveal that for the same operating conditions, multiple evaporator systems with multiple expansion valves give better performance than that with individual expansion valves. The highest exergy destruction is found for condenser and lowest for throttling valves. Experimental investigation of dual evaporator vapour compression refrigeration system shows there is an increase in COP, exergy efficiency, and exergetic performance coefficient with a drop in condenser temperature and an increase in evaporator temperature. Also, it summarizes a systematic procedure regarding designing a refrigeration system [9].

A systematic first and second law evaluation of a refrigeration system using a liquid vapour heat exchanger along with various low GWP refrigerants is carried out [10]. Results show that up to a 20% increase in exergy efficiency is achieved by adding a liquid vapour heat exchanger. Among all refrigerants used, R717 gives a better experimental performance with 5% accuracy for the same values. Due to practical difficulties and flammable properties of R600, R152A, R600A. R290 finds limitations in its applications from a safety point of view. An exergy assessment of a refrigeration system is involving mixtures of different refrigerants of hydrocarbons [11]. Exergy depends upon temperatures and pressures of condenser and evaporator, environmental conditions, etc. Among all components, the compressor has the largest exergy destructions. An exergy method using exergy—enthalpy charts with R11, R12 as refrigerants for analysing a vapour compression refrigeration system is used. System conditions include cold room maintained at − 15 °C and heat rejection at 30 °C. Exergy efficiencies of 49 and 50% are obtained for R11 and R12, respectively. Improvements in exergy efficiency may be possible by having a brief study of economic considerations [12, 13]. The waste heat rejected from the condenser of a refrigeration system can be used to drive an Organic Rankine Cycle to have energy conservation [14, 15]. Phase change materials are used nowadays to store/tap the waste heat energy [16]. Exergy analysis is a very powerful tool to examine the analysis of various thermal systems like single stage refrigeration systems [17, 18], multi-stage refrigeration systems [19], internal combustion engines [20], cryocoolers [21–24], etc. Nowadays, recent advancements in the exergy analysis domain involves the use of statistical approach [25], artificial intelligence [26], latent heat storage systems [27], materials characterizations [28], etc.

3 Exergy Analysis Methodology

It includes everything like the impact of environmental conditions, needs and procedure to carry out exergy analysis, the principle of increase of entropy, the exergy of system, mathematical expressions for exergy change, exergy balance, etc. Exergy analysis involves the use and concepts of energy and exergy balances, enthalpy, entropy, and exergy calculations at various stages in the system. To perform an exergetic investigation of any thermal system, certain specific assumptions are required to be made by considering practical difficulties which may be encountered during the actual analysis. Given this, it requires subdividing a given system into multiple subsystems. Exergy destruction is examined for the individual component. The outcome of this gives the area of major exergy destruction among all components, which can further be subjected to its minimizations. During exergy analysis of a system, certain things like having standard dead state conditions, negligible pressure drops in pipes, negligible potential, and kinetic energy changes, etc., associated with the system are assumed.

4 Experimental Facility

It consists of a two-stage open type reciprocating compressor with a shell and helical coil type intercooler, two evaporators each of 1.2 and 0.8 TR capacities are maintained at −10 and 10 °C with individual expansion valves as shown in Fig. 1. Loading on evaporators is done by heating elements placed inside them. Refrigerant from

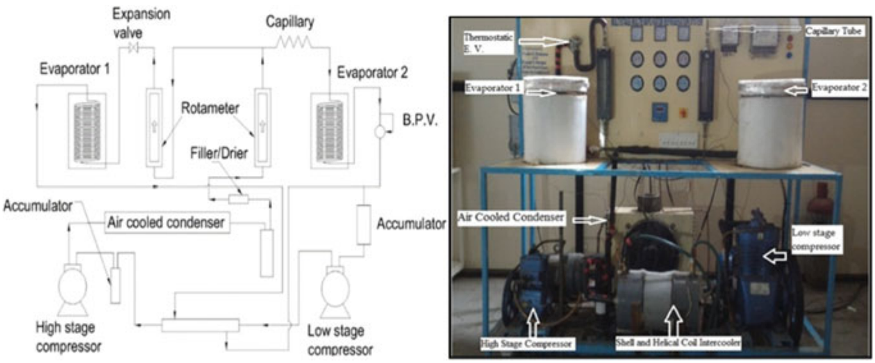

Fig. 1 Diagrammatic demonstration and real picture of the experimental setup

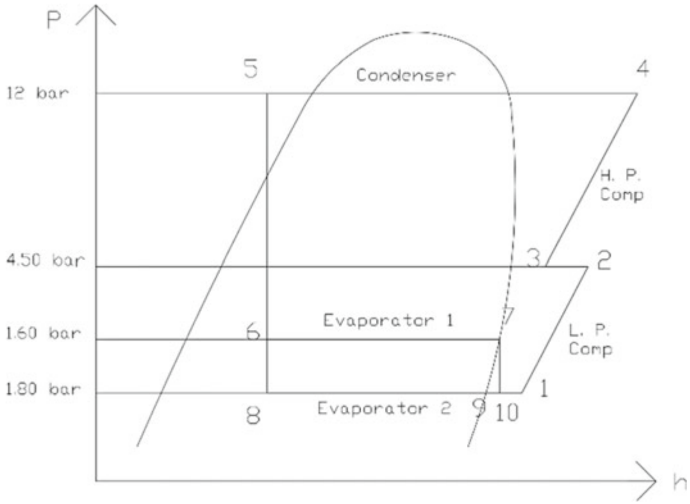

Fig. 2 Representation of system on P–h chart

evaporator 1 enters on the shell side of the intercooler to cool the refrigerant coming from the LP compressor. It is then clubbed with return line refrigerant coming from evaporator 2, to feed the mixture to LP compressor to repeat the cycle.

4.1 Measurements

As explained earlier, this refrigeration system works at 12 bar condenser pressure with 1.6 and 1.8 bar pressures of evaporator 1 and 2, respectively, as shown in Fig. 2.

The system is allowed to come under steady-state conditions after which corresponding readings were taken as shown in Table 1.

4.2 Calculations

The following formulae are used for performing energy and exergy analysis of the system:

Power input to LP compressor (kW)

$$W_{LP} = m_r \times (h_2 - h_1) \tag{1}$$

Power input to HP compressor (kW)

$$W_{HP} = m_r \times (h_4 - h_3) \tag{2}$$

Table 1 Experimental readings of setup at steady-state condition

Parameter	Unit	Value
Inlet pressure of LP compressor	bar	1.80
Intercooler pressure	bar	4.50
Condenser pressure	bar	12
Evaporator 1 pressure	bar	1.60
LP compressor—inlet temperature	°C	18
LP compressor—outlet temperature	°C	58
HP compressor—inlet temperature	°C	45
Condenser inlet temperature	°C	80
Condenser outlet temperature	°C	38
Evaporator 1 inlet temperature	°C	−12
Outlet temperature—evaporator 1	°C	−06
Inlet temperature—evaporator 2	°C	05
Evaporator 2 outlet temperature	°C	11

Load on evaporator—1 and 2 (kW)

$$Q_{e1} = V \times I_1 \text{ and } Q_{e2} = V \times I_2 \tag{3}$$

Carnot COP

$$(COP)_{carnot} = \frac{T_L}{T_H - T_L} \tag{4}$$

Theoretical COP

$$(COP)_{theo} = \frac{RE}{W_{c1} + W_{c2}} \tag{5}$$

Actual COP

$$(COP)_{act} = \frac{W_{heater,ip}}{W_{comp,ip}} = \left(\frac{N_h \times 3600}{t_h \times 1200}\right) / \left(\frac{N_c \times 3600}{t_c \times 3200}\right) \tag{6}$$

Exergy destruction in LP compressor (kW)

$$EX_{D\_LP} = m_r \times T_0(S_2 - S_1) \tag{7}$$

Exergy destruction in HP compressor (kW)

$$EX_{D\_HP} = m_r \times T_0(S_4 - S_3) \tag{8}$$

Exergy destruction in condenser (kW)

$$EX_{D\_cond} = m_r \times [(h_4 - h_5) - T_0(S_4 - S_5)] \quad (9)$$

Exergy destruction in the capillary tube (kW)

$$EX_{D\_cap} = m_r \times T_0(S_6 - S_5) \quad (10)$$

Exergy destruction in TEX (kW)

$$EX_{D\_tex} = m_{r2} \times T_0(S_8 - S_5) \quad (11)$$

Exergy destruction in evaporator—1 (kW)

$$EX_{D\_e1} = m_{r1}[(h_6 - h_7) - T_0(S_6 - S_7)] - \left[-Q_{e1}\left(1 - \frac{T_O}{T_{L1}}\right)\right] \quad (12)$$

Exergy destruction in evaporator—2 (kW)

$$EX_{D\_e2} = m_{r2}[(h_8 - h_9) - T_0(S_8 - S_9)] - \left[-Q_{e2}\left(1 - \frac{T_O}{T_{L2}}\right)\right] \quad (13)$$

Exergy of the product (kW)

$$EP = \left[-Q_{e1}\left(1 - \frac{T_O}{T_{L1}}\right)\right] + \left[-Q_{e2}\left(1 - \frac{T_O}{T_{L2}}\right)\right] \quad (14)$$

Exergy efficiency of the system (%)

$$\eta_{ex} = \frac{EP}{W_{c1} + W_{c2}} \quad (15)$$

Exergy destruction ratio

$$EDR = \left(\frac{1}{\eta_{ex}} - 1\right) \quad (16)$$

5 Results and Discussion

The outcomes of the analysis are tabulated in Tables 2 and 3 as shown.

From Fig. 3a, due to an increase in evaporator temperature, exergy efficiency decreases because of an increase in exergy of cooling load. Also, at lower temperatures, exergy losses are less, thus the evaporator works effectively. As condenser temperature increases, the enthalpy of refrigerant increases while exergy efficiency

Table 2 Energy analysis of system

Parameter	Unit	Value
Power input to LP compressor	kW	0.433
Power input to HP compressor	kW	0.692
Load on evaporator—1	kW	1.225
Load on evaporator—2	kW	0.245
Carnot COP	–	5.25
Theoretical COP	–	3.068
Actual COP	–	1.053

Table 3 Exergy analysis of system

Parameter	Unit	Value
Exergy destruction of LP compressor	kW	0.052
Exergy destruction of HP compressor	kW	0.051
Exergy destruction of the condenser	kW	0.493
Exergy destruction of the capillary tube	kW	0.156
Exergy destruction of TEX	kW	0.182
Exergy destruction of evaporator—1	kW	0.134
Exergy destruction of evaporator—2	kW	0.124
Exergy of product	kW	0.226
Exergy efficiency of the system	%	20.06
Exergy destruction ratio	–	3.985

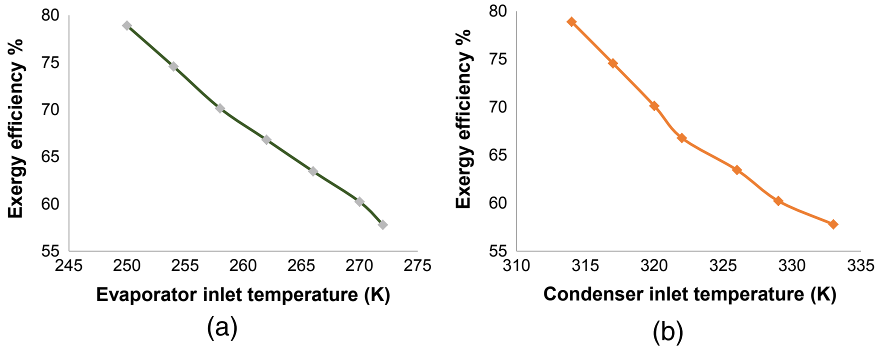

Fig. 3 Behaviour of exergy efficiency with **a** the evaporator inlet temperature and **b** the condenser inlet temperature

decreases as shown in Fig. 3b. The compressor works more effectively at lower condenser pressure; because at higher pressure, it has to deal with highly superheated refrigerant; needs to handle more volume and correspondingly require more work.

6 Conclusion

Exergy efficiency always gives a true representation of the index of system performance with the ideal one. A 20% overall system exergy efficiency is obtained for the system considered. The highest exergy efficiency is found for the evaporator and the lowest for the compressor. Major contributors to exergy losses include loss due to entropy generation, refrigeration piping leaks, systems irreversibility, and so on. These exergy destructions should be reduced to enhance the system performance and to boost the life of components; which ultimately reduces the operational and running cost. A lot of heat is wasted from the condenser which can be effectively utilized as waste heat recovery for certain applications. An effort is going on these areas that inherently have the highest margins for exergy efficiency improvement.

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