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Exergetic Investigations of a Multistage Multi Evaporator Vapour Compression Refrigeration System

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Energy is the ability to cause change in a system. It is usually available as exergy and anergy. Exergy is the useful part of energy, also known as available energy. Anergy is the counter part of exergy, also known as unavailable energy. Thermodynamics is the science associated with energy and exergy thereby ensuring both – the first and the second law of thermodynamics by incorporating energy and exergy efficiencies. Refrigeration is a technology to preserve commodities at lower temperatures than surroundings. One of the most widely used refrigeration system is a vapor compression refrigeration system whose basic objective is to produce refrigerating effect at a desired location. Commercial large capacity plants consists of preservation of 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 have saving in compressor energy consumption. Exergy efficiency governs the actual performance of system by knowing its deviation from the ideal one, and thus, is a true measure of any system performance. In this paper, an exergetic investigations of a multistage multi evaporator vapour compression refrigeration system with individual expansion valves using R22 refrigerant is carried out. A shell and helical type 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 ^{0}C and 10 ^{0}C. Various parameters like exergy destruction, exergy destruction ratio and exergy efficiency are calculated. Compressor has highest exergy destruction among all 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 design and analysis of a system.

Keywords**:** Energy, thermodynamics, refrigeration, exergy efficiency

1. Introduction

Energy crisis is the most critical issue in today's era. First law of thermodynamics which is law of conservation of energy signifies with design, analysis, evaluation of a given system and it governs quantity of energy only, and not quality. It is insufficient and incapable of dealing practicalities associated with any system. As a consequence to this, second law of thermodynamics is introduced which makes accountability for losses, irreversibility's and energy destructions in any system. Entropy generation creates disturbances within the system making it inefficient. Therefore, exergy is a tool in second law analysis. Exergy of a system is the maximum obtainable work that can be achieved from a system at a specified state and in a given environment. Thus, it's a property of combination of both: system as well as surroundings. 'Exergy' term is derived from two Greek words: 'ex' means 'form' and 'ergon' means 'work'. Unlike energy which is conserved, exergy is always destroyed in all reversible processes and is a boundary phenomenon. A dead state (normally referred 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 remain with energy analysis. It shows that degradation of exergy occurs when system reaches in complete equilibrium state with surroundings; thereby any further work cant be performed at all. Exergy analysis have following characteristics: It quantifies true locations, magnitude of losses, irreversibility's 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 approach to idealness, which is not the case with often misleading energy efficiencies. Recently, exergy is used in conjunction with exergoeconomic term wherein cost calculations, environmental impacts, and sustainability assessment are incorporated.

2. Literature Review

A method to improve the thermal performance of refrigeration system by using energy and exergy analysis is elaborated. System considered is multiple evaporators with multi stage compressors and multiple expansion valves including flash chambers. R134a find its suitability for various commercial and practical applications. After going through numerical computations, increase of 22% in both first and second law of efficiency is observed. Among all the components worst thermal performance is shown by expansion valve followed by condenser, evaporator and compressor. As dead state temperature increases, exergy destruction ratio decreases with increase in exergy efficiency [1]. A cascade (NH_3 / CO_2) vapour compression refrigeration system is evaluated using Energy Equation Solver tool for simulation. Exergy analysis provides a good look for system design, their analysis and its exergy assessment. Overall plant exergy efficiency of 42.13 % suggesting a scope for improvement from energy point of view [2]. A theoretical investigation of a multistage vapour compression refrigeration system using energy, exergy analysis and EES as a tool is performed. COP maximization with consideration of different variables and parameters is the objective function. Interpretation predicts that with increase in sub cooling phenomenon, COP increases. Also, R717 gives best outcomes among all other refrigerants selected [3].

Simulation including exergy analysis of high temperature and multi stage compression of heat pump using R1234ze(Z) as refrigerant is done with hot water as a supply from waste heat recovery. Exergy destruction for compressor is higher than that for evaporator and condenser in single stage system. Multistage system shows an increase of 9.1% and 14.6% in COP for a two and three stage vapour compression refrigeration systems respectively. COP increases proportionately with increase in temperature of source of waste heat. Among all the combinations, three stage vapour compression refrigeration systems offers various thermal performance advantages over others [4]. An energy and exergy analysis of waste heat extraction using ammonia refrigerant from intercooler of a multi stage vapour compression refrigeration system is performed. Heat recovery can be maximized by ensuring optimum operating conditions like water flow rate, water temperatures and use of suitable working fluid, etc. A 20 kW of waste heat recovery is achieved which thereby causes 4 % to 5 % increase in COP value. Maximum COP of 3.087 for - 40 ^{0}C evaporator temperature is obtained. However, COP decreases with increase in condenser and decrease in evaporator temperatures [5].

The thermal performance analysis of a multi-evaporator and multi compressor Vapour Compression Refrigeration system with use of eco-friendly refrigerants is done. It includes both combinations of individual and multi expansion valves by using different low GWP refrigerants is done. Mathematical formulae and expressions to interpret component wise exergy destructions, exergy destruction ratio are also presented. Results reveal that for same operating conditions, multiple evaporator system with multiple expansion valves gives better performance than that with individual expansion valves. Highest exergy destruction is found for condenser and lowest for throttling valves [6]. Experimental investigation of dual evaporator vapour compression refrigeration system shows COP, exergy efficiency and Exergetic Performance Coefficient (EPC) increases with decrease in condenser temperature and increase in evaporator temperature. This paper summarizes a systematic procedure including selection of design parameters for a refrigeration system [7].

A systematic energy and exergy analysis of a vapour compression refrigeration system with use of liquid vapour heat exchanger along with various low GWP refrigerants is carried out. Results show that up to 20 % increase in energy and exergy efficiency is achieved by adding a of liquid vapour heat exchanger. Among all refrigerants used, R717 gives better experimental performance with 5 % accuracy for same values. Also, due to practical difficulties and flammable properties of R600, R152A, R600A and R290, finds limitations in their applications from safety point of view [8]. A review of exergy analysis for vapour compression refrigeration system for mixtures of different refrigerants of hydrocarbons is presented. Exergy depends upon temperatures and pressures of condenser and evaporator, environmental conditions, etc. Among all components, compressor has largest exergy destructions. However, addition of Nano lubricants and nanofluids may help to reduce these exergy losses [9]. A valuable tool in quantifying various exergy flows of a process is exergy analysis. In this article, an exergy method for analysing a vapour compression refrigeration system with R11, R12 as refrigerants with use of exergy – enthalpy charts is shown. System conditions includes cold room maintained at -15 ^{0}C and heat rejection at 30 ^{0}C. Exergy efficiency value of 49 % and 50 % is obtained for R11 and R12 respectively. Improvements in exergy among different components may be possible against an ‘optimal exergy loss’ which requires a brief study of economic considerations [10].

3. Exergy Analysis Methodology

Exergy analysis involves the use and concepts of energy and exergy balances, enthalpy, entropy and exergy calculations at various states in system. To carry out exergy analysis of a system, in general, certain specific assumptions are required to be made by considering practical difficulties which may encountered during the actual analysis. Subdivide a given system into multiple sub systems. Exergy destruction is calculated across each component. Outcome of this gives area of major exergy destruction among all components, which can further be subjected to its minimizations.

4. Experimental Setup

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 ^{0}C and 10 ^{0}C with individual expansion valves as shown in Fig. 1 and Fig. 2. Loading on evaporators is done by heating elements placed inside them. Refrigerant from evaporator 1 enters on shell side of intercooler to cool warm refrigerant coming from LP compressor. It is then mixed with return line refrigerant from evaporator 2, where the mixture is then fed to LP compressor from where cycle gets repeated.

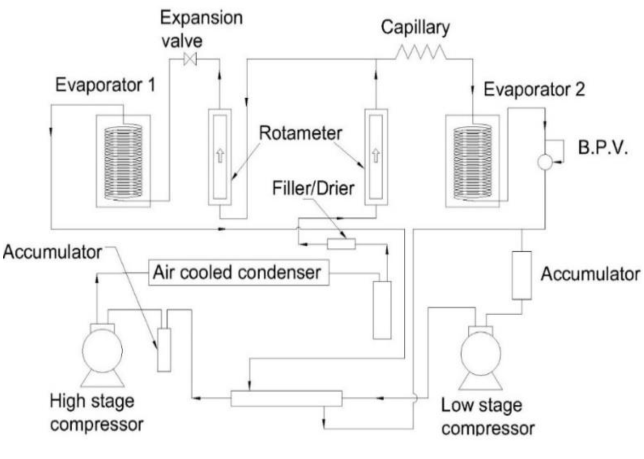

Fig. 1. Schematic diagram of experimental setup

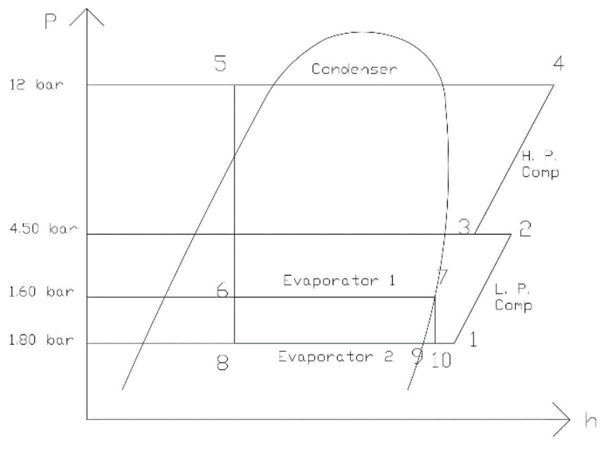

Fig. 2. A representation on P – h chart

Table. 1. Experimental readings of setup at steady state condition

Parameter	Unit	Value
Suction pressure at LP compressor	bar	1.80
Intercooler pressure	bar	4.50
Condenser pressure	bar	12
Evaporator 1 pressure	bar	1.60
Suction temperature of LP compressor	^{0}C	18
Discharge temperature of LP compressor	^{0}C	58
Suction temperature of HP compressor	^{0}C	45
Condenser inlet temperature	^{0}C	80
Condenser outlet temperature	^{0}C	38
Evaporator 1 inlet temperature	^{0}C	-12
Evaporator 1 outlet temperature	^{0}C	-06
Evaporator 2 inlet temperature	^{0}C	05
Evaporator 2 outlet temperature	^{0}C	11

5. Results and Discussions

Table. 2. Energy and exergy calculations of system

Parameter	Symbol	Formula	Value
LP compressor input (kW)	W_{c1}	$m_r \times (h_2 - h_1)$	0.433
HP compressor input (kW)	W_{c2}	$m_r \times (h_4 - h_3)$	0.692
Evaporator – 1 load (kW)	Q_{e1}	$V \times I_1$	1.225
Evaporator – 2 load (kW)	Q_{e2}	$V \times I_2$	0.245
Carnot COP	$(COP)_{carnot}$	$\frac{T_L}{T_H - T_L}$	5.25
Theoretical COP	$(COP)_{theo}$	$\frac{RE}{W_{c1} + W_{c2}}$	3.068
Actual COP	$(COP)_{actual}$	$\frac{W_{heater,ip}}{W_{comp,ip}} = \left(\frac{N_h \times 3600}{t_h \times 1200}\right) / \left(\frac{N_c \times 3600}{t_c \times 3200}\right)$	1.053
Component wise exergy destructions (kW):			
LP compressor	EX_{D_LP}	$m_r \times T_0 (S_2 - S_1)$	0.052
HP compressor	EX_{D_HP}	$m_r \times T_0 (S_4 - S_3)$	0.051
Condenser	EX_{D_cond}	$m_r \times [(h_4 - h_5) - T_0 (S_4 - S_5)]$	0.493
Capillary tube	EX_{D_cap}	$m_r \times T_0 (S_6 - S_5)$	0.156
Thermostatic valve	EX_{D_tex}	$m_{r2} \times T_0 (S_8 - S_5)$	0.182
Evaporator - 1	EX_{D_EP1}	$m_{r1}[(h_6 - h_7) - T_0(S_6 - S_7)] - \left[-Q_{e1}\left(1 - \frac{T_O}{T_{L1}}\right)\right]$	0.134
Evaporator – 2	EX_{D_EP2}	$m_{r2}[(h_8 - h_9) - T_0 (S_8 - S_9)] - \left[-Q_{e2}\left(1 - \frac{T_O}{T_{L2}}\right)\right]$	0.124
Exergy of product (kW)	EP	$\left[-Q_{e1}\left(1 - \frac{T_O}{T_{L1}}\right)\right] + \left[-Q_{e2}\left(1 - \frac{T_O}{T_{L2}}\right)\right]$	0.226
Exergy efficiency of system (%)	η_{ex}	$\frac{EP}{W_{c1} + W_{c2}}$	20.06
Exergy destruction ratio	EDR	$\left(\frac{1}{\eta_{ex}} - 1\right)$	3.985

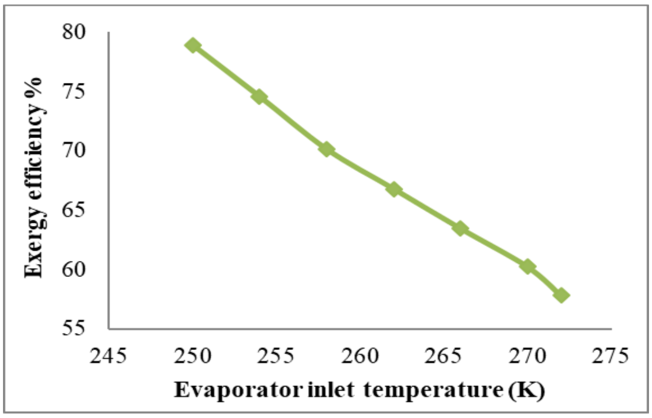

Fig. 3. Variation of exergy efficiency with evaporator inlet temperature

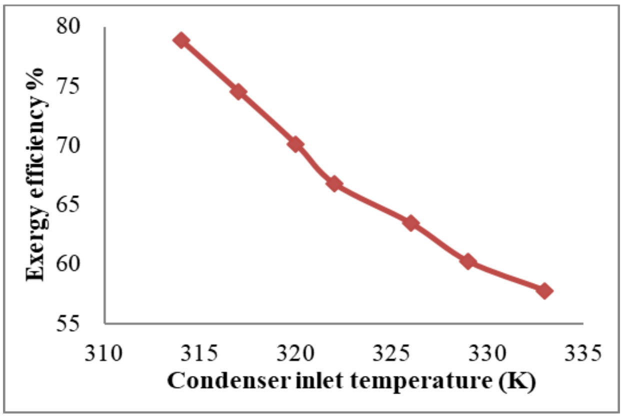

Fig. 4. Variation of exergy efficiency with condenser inlet temperature

From Fig. 3., with increase in evaporator temperature, second law efficiency decreases because of increase in exergy of cooling load. Also, at lower temperatures, exergy losses in are less, thus evaporator works effectively. With a corresponding increase in condenser temperature, enthalpy of refrigerant increases while second law efficiency decreases as shown in Fig. 4. Compressor works more effectively at lower condenser pressure; because at higher pressure, it has to deal with highly superheated refrigerant which needs to handle more volume and correspondingly requires more work.

6. Conclusion

Exergy efficiency always gives a true representation of index of system performance with the ideal one. Overall exergy efficiency of system is found to be around 20 %. Highest exergy efficiency is found for evaporator and lowest for compressor. Major contributors to exergy losses include loss due to entropy generation, leakages in the piping of the system, systems irreversibility and so on, which should be minimized in order to increase performance and life of components and ultimately reducing their operational cost. A lot of heat is wasted from 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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