Performance Analysis of Air-Cooled Compact Screw Refrigerant (R-134a) based Industrial Chiller System for Improving its Effectiveness by VCRS Cycle on the P-H Diagram

Jitendra Kirar[1], Alka Bani Agrawal[2]

[1]Student, Department of Mechanical Engineering, Rajiv Gandhi Proudyogiki Vishwavidyalaya, Bhopal, India
[2]Professor, Department of Mechanical Engineering, Rajiv Gandhi Proudyogiki Vishwavidyalaya, Bhopal, India

---***---

Abstract – *A Refrigeration system is an important unit and plays a pivotal role in the industrial, commercial, and residential sector refrigeration systems. Varieties of refrigeration units are available in the industry having capacities of 1 tonne to hundreds of tonnes and may construct or design as per the demand to perform specific tasks. Industrial chillers are generally used for controlled cooling of products, machinery, assemblies unit, etc. as per demand. The refrigerant is the hard key for the refrigeration or cooling process. As the chiller units are meant for high COP and manufactured to perform on high accuracy. In this study, it shows the system performance of industrial chiller unit while considering "R-134a" to improve its effectiveness by the VCRS Cycle on the p-h diagram. This analysis is done on the account to show the best performance and its effectiveness and would suggest the best troubleshooting.*

Key Words**: *Performance analysis, industrial chiller, VCRS cycle, p-h diagram, COP, EER, thermodynamic calculations, R-134a, troubleshooting.***

1. INTRODUCTION

This chronicle contains the performance analysis of an air-cooled compact screw chiller unit which is generally termed as 'chiller system' throughout the whole document. This chiller system is based on a vapour-compression refrigeration system (VCRS) having R-134a refrigerant fluid as the heat transfer medium. It has a cooling capacity of 134 TR and it has 130kg of refrigerant mass. This chiller system is very complex to understand and congested to explore physically. As we know, not any machine is complete and fully efficient in this world. That means this chiller system also has some problems. To observe those problems and fix them, it is needed to analyse the chiller system materially, numerically, and graphically as well.

This research work also includes the finding out the unknown or hidden parameters which are necessary for essential calculations. During the data collection from the HMI panel of the chiller system, it has been noticed that the present data is insufficient to complete the analysis. As the manufacturer has not provided the technical data and other thermodynamically calculated data. In reaching out to the final results, various processes have been done in a constructive sequence, starting from data collection, making a p-h graph to final calculations. The high weightage of this research work has consisted of data mining, which was much important to make this research possible.To do a complete analysis of the chiller system, every device and component of its, which is engaged in thermodynamic operations analysed successfully as far as possible. It was not always been possible to try hit and trial methods with this chiller system which is engaged in 24*7 operations to maintain the various working machines at a precise temperature for their life long and efficient working.

2. Context and Perspective

During the long term and efficient working period, the chiller maintains its operating life because they are programmed to save themselves from misconfigurations by tripping off themselves at a setpoint before any problem occurs. But that doesn't support them fully, as the need for cooling reaches out and the temperature goes down below a setpoint, the chiller switches itself off and after some time the heat load begins to rise and crosses set point, the chiller switches itself on. This on-off condition of the chiller system termed as 'cut-off' cycle, which in the long term makes chiller components or devices to start misbehaving and malfunctioning the refrigeration cycle. To correct this malfunctioning of the chiller system, the owner needs to call the supplier's technicians for troubleshooting. The technician connects the HMI panel with their confidential software on the encrypted system and just matches the currently running data with their database which helps him to get the problem and then the technician corrects the malfunctioning of the device(s) in which the problem was occurring. To save the waste of money and time too, the processes in this research paper can be followed up to do the same as mentioned above. The only thing that is needed is patience, hard work, and knowledge of refrigeration systems, these all can be find out easily in the same institution. Although the researcher will get all the necessary data for futuristic uses as well.

3. Current Scenario

During full heat load conditions, the heated water at 10°C-14°C enters the evaporator unit of the chiller system and the chiller runs at its full capacity to provide the outlet water at a temperature ranging from 9°C-6°C. But whenever the machines are not in working mode then the heat load will be negligible. In this condition, the heat load fluctuates up and down which makes the chiller unit operate in cut-off cycles. In cut-off cycles, the time taken to maintain the input temperature by this chiller system and decreasing it to get output temperature becomes less and when the output temperature decreases below its set point, then the chiller trips off itself, it keeps itself off until the inlet water temperature rises beyond its setpoint. All these cut-off cycles create issues in the chiller system which can be noticed when it is running at full load conditions.

4. System Design

This immense chiller unit works on vapour compression refrigeration cycle and it is meant for precision cooling. It has a huge capacity of 134 TR and it is using 130kg of R-134a refrigerant fluid as a cooling medium in its refrigeration circuit. A compact screw compressor, air-cooled condenser units, a BPHE type economizer to boost it, an electronic expansion valve, and a shell & tube type evaporator completes the chiller system by connecting themselves in the respected sequence.

This chiller system operates 24*7 to provide precision cooling and maintain the temperature of the huge machines and their components so that they can work efficiently in long terms. The chiller system keeps itself safe with the help of various inbuilt or programmed set points which helps the chiller system in tripping off itself before anything goes wrong. These setpoints help the chiller system to operate in safe mode. The inlet temperature of water at evaporator inlet ranges from 14°C-10°C and the outlet temperature of water at the evaporator outlet ranges from 9°C to 6°C along with precise temperature setpoint of 70C. The chiller system does not have any refrigerant leakage during the analysis.

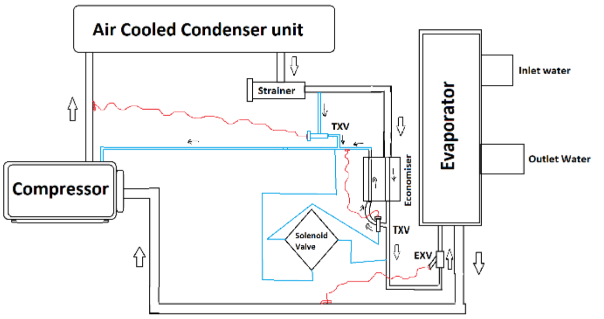

Fig - 1 Chiller System

Table - 1 Properties of Refrigerant

Refrigerant	R-134a
Molecular Weight	102.03 gm/mol
ODP	0
GWP	1300
Critical Temperature	101.06 °C
Critical Pressure	40.59 bar
Boiling Point	-26.3 °C
Refrigerant	R-134a
Molecular Weight	102.03 gm/mol

The economiser circuit is a bit tricky to understand. Referring figure 1 & 4, the refrigerant from the condenser unit passes through its primary side, and after that, the main flow of refrigerant mass divides into a major flow that forwards toward the EXV and minor flow which has less refrigerant mass moves through TXV & secondary side of the economizer. This minor flow further provides liquid injection cooling to the compressor and then gets mixed with the main flow of refrigerant in the screw compressor.

The economiser circuit only works when the motor running percentage is above 75% and if required cooling has not achieved. Also, the secondary side flow and pipelines contain very less amount of refrigerant and this section has no devices attached in it, so the secondary side of the economiser and after TXV portion the calculations and their conditions are neglected.

5. An introduction to the ideal working (VCRS) refrigeration cycle of this chiller system

The below diagram is showing the ideal working VCRS cycle of the chiller system with the economiser. It termed as an actual working cycle because of the deviations. It is hard to know in real refrigeration systems. The processes in this actual working VCRS cycle are:

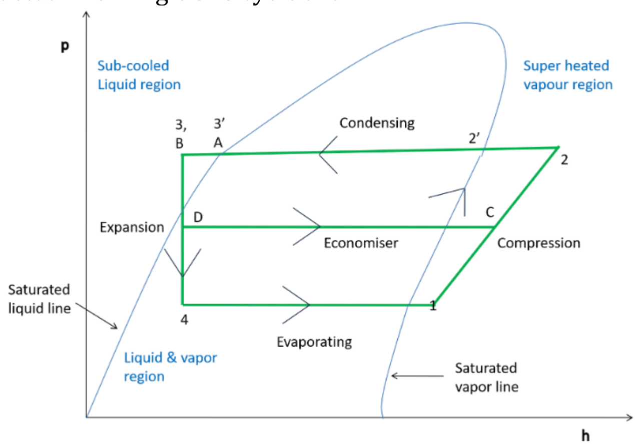

Fig - 2 Ideal Working VCRS cycle along with an Economiser on the p-h diagram for the chiller system

[1]: - Superheated Vapour from the Evaporator.
[1-2]: - The compression process is polytropic. Because of friction & heat loss.
[2-2']: - Discharge superheating and heat loss of vapour in the discharge line.
[2'-3']: - Refrigerant liquid condensation in the condenser.
[(3', A) - (3, B)]: - Subcooling in the Economiser and liquid line.
[B-4]: - Expansion of refrigerant in the EXV of the Evaporator.
[B-D]: - Expansion in the TXV of the Economiser.
[D-C]: - Heat Exchange with primary side fluid in Economiser.
[4-1]: - Heat Exchange with secondary side fluid in the Evaporator.
It is difficult but necessary to draw this cycle on the p-h diagram to find out some unknown parameters like pressure drops, and perfect temperature drops in the mechanical components of the discussed refrigerating circuit of the chiller system.So, only it is possible to draw the actual working VCRS cycle for the analysis purpose of the refrigeration system by assuming some assumptions.

6. Methodology

While investigating the chiller system & its data for proper analysis, it has been noted that the HMI panel contains insufficient data. Various necessary input data like pressure & temperature at some locations were not available so, a self-made small experimental setup which has 8 RTDs and a data logger, has been used for taking temperature readings from these necessary locations of the chiller system. Saturated & superheated properties and p-h graphs for refrigerant R-134a has been selected using Ref-prop V.10 software. The VCRS cycle for refrigerant R-134a has been drawn manually on its p-h chart for proper performance analysis of the chiller system. Then all the outcomes from the experiment and drawn p-h charts for refrigerant R-134a have been used as inputs for the final essential calculations. Various formulae have been used to reach out to the final results. The final results have been described as well for the better understanding of the analysis.

7. Experimental setup for data acquisition

For the analysis of the chiller system, the numerical approach is needed so that the best results can be achieved. The data which is required for the calculations is not sufficient. Data available is taken from the HMI panel of the chiller system and is insufficient. Moreover, for the calculations of the economiser and EXV, the temperature across them is needed, although the temperatures across the condenser unit are also needed. For the same purpose for taking these temperatures, a setup consisting of several RTDs have been made. In Fig. 3, the setup has a data logger to which all the 6 RTDs are connected correctly. The data logger automatically saves the data every 2 seconds. Moreover, the data from the data logger can be taken out in computer as excel sheets.

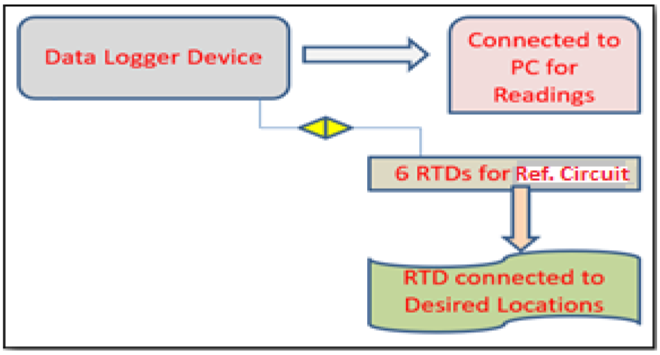

Fig - 3 Flow diagram of Data Acquisition Setup

For recording the data, all the RTDs are placed and thermally sealed on the desired locations on pipelines. While noticing the data at HMI panel, data from the data logger has been taken out at the same time. Before placing RTDs on locations, the error values of them at room temperature has been taken out so that they will be subtracted from the data for finding out the accurate data.

Table - 2 Temperature Data Taken with the help of Setup which further used as input data.

S No	Location of RTD	Temperature (˚C)
1	Economiser Inlet (Condenser Outlet)	50.2
2	EXV Inlet & TXV Inlet	40.9
3	TXV outlet (Economiser Inlet secondary side)	37.3
4	Economiser Outlet to Liquid Injection Line	45.7
5	Condenser Inlet	67.9
6	Ambient Air Temperature	36.8
7	EXV Outlet to Evaporator Inlet	8.7- 5- 2

8. Assumptions for the calculations

1. Pressure drop in the primary side between point A & B of economiser is taken as negligible.
2. Cooling length of tubes covered by baffles taken as 100mm.
3. Fouling factor of the evaporator is taken as 0.000018 m^2/˚C-watt. [2]
4. Scaling heat transfer coefficient is neglected for heat exchanger calculations.
5. The working of EXV has assumed as ideal.
6. Each refrigerating circuit of the chiller system practically contains 130 kg of R-134a Refrigerant, but the calculations have been done for the unit mass of refrigerant in the refrigerating circuits.
7. Refrigerant mass and its flow rate are taken negligible in the secondary side of the economiser including its TXV.

9. Input Parameters

The input data have been taken out from the HMI panel and the setup is given below in the form of tables. The data has been recorded as the average of values taken for two to five-minute duration. The average values have been selected for just getting the stability of the chiller system with values. Each value is taken at the same time.

Table - 3 Data from the HMI Panel of the Chiller System

Concerned Content	Data
The number of condenser fan stages running.	All three stages
Measured pressure drop in the condenser	3 PSI
The flow rate of water in the evaporator (m)	174 m3/hr, 48.33 LPS
The pressure of water at the inlet of the evaporator	21 PSI or 1.45 kg/cm2
The pressure of water at the outlet of the evaporator	14 PSI or 1 kg/cm2
Specific heat of water at	4.186 kJ/kg ˚C

constant volume	
Total heat transfer area of evaporator tubes	448620.28 cm2

Table - 4 Other technical data of the chiller system

SP	DP	ST	DT	OPD	M%	EXV%
31.5 PSI	208 PSI	5.44 °C	68 °C	175.6	91.3	49
SST	**SSH**	**SCT**	**DSH**	**WIT**	**WOT**	**ΔT**
2.6 °C	2.8 °C	56.14 °C	12.1 °C	10.7 °C	8.4 °C	2.3 °C

The thermodynamic properties of refrigerant R-134a have been evaluated by using Refprop software V.10.0. These properties at suction pressure, discharge pressure and condenser outlet pressure are given below in the tables.

Table - 5 Thermodynamic properties of R-134a at suction pressure & temperature (using Refprop Software V. 10.0) [3]

T	P	v	h	s	Cp	Cp/Cv
5.62 °C	31.5 PSI	0.102 m^3/kg	405.9kJ/kg	1.778 kJ/kg K	0.858 kJ/kg °C	1.1487
	217.18 kPa					
	2.1718 bar					

Table - 6 Thermodynamic properties of R-134a at discharge pressure & temperature (using Refprop Software V. 10.0) [3]

T	P	v	h	s	Cp	Cp/Cv
68.125 °C	208 PSI	0.01574 m3/kg	442 kJ/kg	1.7594 kJ/kg K	1.152 kJ/kg °C	1.2676
	1434.11 kPa					
	14.3411 bar					

Table - 7 Thermodynamic properties of R-134a at condenser pressure and temperature. [3]

T	**P**	**v**		**h**			**s**	
		Vf	**Vg**	**hf**	**hfg**	**hg**	**Sf**	**Sg**
50.25 °C	205 PSI	0.0009 m^3/kg	0.0150 m^3/kg	272.3 kJ/kg	151.6 kJ/kg	423.9 kJ/kg	1.2396 kJ/kgK	1.7085 kJ/kgK
	1327.36 kPA							
	13.273 bar							

Table - 8 The values of Enthalpies at defined locations

Point 1 at Suction Pressure	h_1	406 kJ/kg
Point 2 at Discharge Pressure	h_2	442 kJ/kg
Point 3 at Condenser Pressure	h_3	272.3 kJ/kg
Point 4 at EXV outlet	h_4	272.3 kJ/kg (h_3 - h_4)
Enthalpy at the outlet of the evaporator (before superheating)	$h_{1'}$	370.0 kJ/kg

(used for drawing the refrigeration cycle on the p-h chart.

10. Formula used

Table - 9 Formula used

Sr. No.	Particulars	Formula
1	Refrigeration Effect (qe):	qe= h1 - h4
2	Heat of Compression (qw)	qw = h2 - h1
3	Heat Rejected at Condenser (qc):	qc = h3 – h2
4	Refrigeration Capacity (Qe):	Qe = mCΔT
5	Refrigeration Capacity (Qe):	Qe = mCΔT TR = Qe/3.5168
6	COP of Cooling	$COP(C) = \frac{h_1 - h_4}{h_2 - h_1}$
7	COP of Heating:	$COP_{(H)} = \frac{h_2 - h_3}{h_2 - h_1}$
8	Refrigerant Circulation Rate or Mass Flow Rate:	$\dot{m} = \frac{Refrigeration\ Capacity\ in\ kw}{Refrigeration\ Effect}$
9	The volume of Suction vapour ($\dot{v}$):	$\dot{v} = \dot{m}v$ v = Specific volume = 0.1020
10	Work done by the compressor	$Q_w = \dot{m}qw$ $Q_w = \dot{m}\ (h_2 - h_1)$
11	Work done by Condenser:	$Q_c = \dot{m}q_c = \dot{m}\ (h_3 - h_2)$
12	Percentage of each kg of refrigerant that vaporises in the refrigerant control system (EXV):	$\frac{h_4}{h_{1'}} \times 100$
13	Energy Efficient Ratio (EER):	EER = 3.5 × COP
14	Compressor horsepower:	$Comp.\ HP = \frac{Q \times q_w}{q_e \times 42.41}$
15	HP per ton:	$\frac{Comp\ HP}{TR}$
16	Compressor Power in	1.2697 HP/ton ×

	watts/ton:	745.7 watt/HP
17	Compressor Screw Displacement:	$\dot{m} \times v$
18	Heat Exchanger Calculations for EVAPORATOR UNIT of the chiller system	Listed down
19	Log Mean Temperature Difference (LMTD) approach for Evaporator [6]	$\Delta T_m = \frac{(t_2-T_1)-(t_1-T_2)}{\ln\frac{(t_2-T_1)}{(t_1-T_2)}}$
20	Overall Heat Transfer Coefficient for Evaporator	$Q = U\,A\,\Delta T_m$
21	Pressure Drop-in the EVAPORATOR	$\Delta P = P_5 - P_1$
22	ε – NTU calculation for the EVAPORATOR [7]	• $C_{min} = \dot{m} \times C_v$ for refrigerant • $C_{max} = \dot{m}_w \times C_v$ for water, $NTU = \frac{U \times A}{C_{min}}$ • Capacity Ratio = $C_r = \frac{C_{min}}{C_{max}}$ • $\varepsilon = \frac{1-Exp[-NTU(1-Cr)]}{1-(Cr)Exp[-NTU(1-Cr)]}$
23	Pressure drop in the Expansion Valve.	$\Delta P = P_c - P_l - P_e$

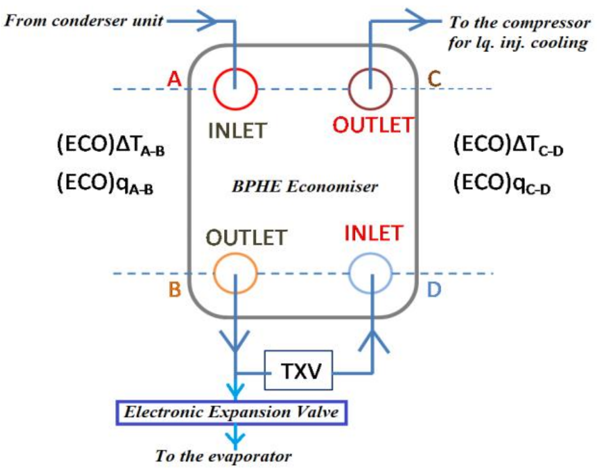

Fig - 4 Economiser and refrigerant circuits

11. Calculations

Calculations for BPHE ECONOMISER of the chiller system

Referring figure-4

- Temperature drop at the primary side of economiser (ECO) $\Delta T_{A\text{-}B} = T_A - T_B$
- Log Mean Temperature Difference (LMTD) approach of Economiser [6]
  $\Delta T_m = \frac{(T_B-T_D)-(T_A-T_C)}{\ln\frac{(T_B-T_D)}{(T_A-T_D)}}$
- Pressure and Temperature drop in TXV (TXV)$\Delta P = P_B - P_D$

12. Results and Discussion

Results and discussion based on the common data calculated for the chiller system:

In this section of the results, the discussion is based on the data calculated from all input data. As it has been concluded before that this chiller system has 134 TR capacity which also has been proved here by calculations. Referring table 9, it can be seen that the refrigerating capacity which is calculated during analysis is 132.31 TR which means it is very close to the rated capacity of chiller system and it shows that chiller is working in good conditions. The refrigeration effect '133.7 kJ/kg' shows that the heat transfer rate between the refrigerant and water inside the evaporator is also good. Work of compression shows, for reaching the rated capacity, the compressor has to do less work and the condenser units are also working too well. Heat rejected in condensers "-169.7 kJ/kg" shows that the condensers are free of any scaling, their fans are also working well. COP of this chiller system is impressive & it is also in the rated range. EER which is energy efficient ratio "12.98" gives the healthy signs of the chiller system. All other factors are showing the all-over good functioning of the chiller system.

Table - 10 Comparison based on Calculated Data from the Raw Data of HMI Panel

Sr. No.	Content	Calculated Data	Units
1	Refrigeration Effect	133.7	kJ/kg
2	Work of Compression	36	kJ/kg
3	Heat Rejected in Condenser	-169.7	kJ/kg
4	Refrigeration Capacity	132.31	TR
5	COP of Cooling	3.71	-
6	COP of Heating	4.714	-
7	Refrigerant Circulation Rate	3.48	Kg/sec
8	The volume of Suction Vapour	0.355	m3/kg
9	Work Done by Compressor	125.3	kJ/kg
10	Work Done by Condensers	590.56	kJ/sec

11	EER	12.98	-
12	Compressor Horsepower	168	HP
13	Horsepower per TR	1.27	HP/Ton
14	Compressor Power in Watt/Ton	946.81	Watt/ton
15	Compressor Screw Displacement	0.355	m3/sec

Table - 11 Thermodynamic Properties of R-134a at various stages

Thermodynamic Properties at each Specific State of R-134a					
State Points on p-h chart	Thermodynamic Properties				
	H kJ/kg	T ˚C	P PSI	S kJ/kgK	V m^3/kg
1	406	5.44	31.5	1.765	0.1020
C	431.5	45.7	108.77	1.77	0.035
2	442	68	208	1.7594	0.01574
2'	433.5	56.5	208	1.71	0.0165
3', A	272.3	50.2	205	1.2396	0.0009
3, B	258	40.9	205	1.184	-
D	258	37.3	136.335	1.187	-
4	258	5, 2	49.96	1.2	0.018
1'	392	2.2	31.5	1.735	0.0989

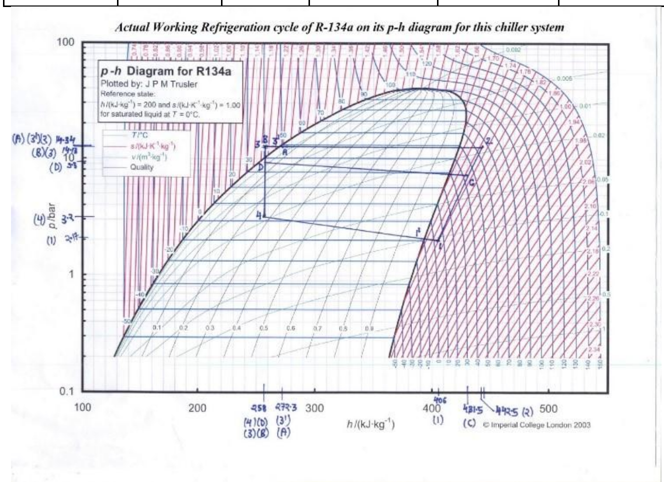

Fig - 5 Hand-drawn actual working refrigeration cycle of R-134a on the p-h diagram for this chiller system (only blank p-h graph [8])

It can be noticed in the graph that the evaporation process in the actual cycle somewhat deviates from its constant pressure path which is shown in the ideal cycle. Many of the results from this graph further help to analyse the evaporator, EXV and economiser.

Performance Analysis and comparison of Evaporator and EXV of the Chiller System at full load conditions

The following parameters are the values that were not available, but these are calculated by numerical and graphical method. In table 11, the area of heat transfer, the LMTD pressure drop in the evaporator are shown. The most critical factors are effectiveness and NTU values. The LMTD of the evaporator is 5.95°C which is very good to have.

Table - 12 Unknown (not readily available) Parameters of the evaporator

Unknown (not readily available) Parameters Name	Evaporator
A (m2)	44.862
ΔTm (˚C)	5.95
U (watt/m2K)	0.0372
ΔPevap (PSI)	18.46
Ɛ	0.472
NTU	0.642

Table - 13 Unknown (not readily available) Parameters of the electronic expansion valve

Unknown Parameter Name	**EXV**
EXV opening %	49
Refrigerant Unit Mass % that vaporizes in the EXV	67%
Pressure Drop in EXV (PSI)	155.04
Temperature Drop (˚C)	42.2

From table: 12, the plunger of the EXV is 49% opened which enables 67% refrigerant mass to vaporise in EXV. The 49% opening helps the evaporator to get low temperatures by dropping the refrigerant's pressure by 155 PSI along with a temperature drop of 42.2°C.

Performance Analysis of the Economiser of the Chiller System at full load Conditions

From table 13, it can be seen that the economiser's TXV has a temperature drop of 3.6°C with the pressure drop of 68.67 PSI which is quietly good. The LMTD of economiser is 4.03°C which is a good sign of its efficient working.

Table - 14 Unknown (not readily available) Parameters of the Economiser

Unknown Parameters Name	**Economizer**
ΔT_m (˚C)	4.03
Primary Side ΔT (˚C)	9.3
Secondary Side ΔT (˚C)	8.4
TXV ΔT (˚C)	3.6
TXV ΔP PSI	68.67

13. Conclusion

The research work of analysing the industrial chiller system has been done successfully with great outcomes or results. It has been analysed numerically as well as graphically that the chiller system and its components are working finely. The components are operating at their efficient stage during the full heat load. Since this analysis work has been done for full heat load conditions and it is successful in all aspects of research. The actual working of the chiller system somewhat deviates from the ideal cycle but it is providing almost complete refrigerating effect with a whopping amount of refrigeration capacity, which shows efficient operation.

The COP & EER further proves that all over the performance of the chiller system is very good. So, what makes the chiller unit to operate in cut-off cycles? Yes, that is the partial or no heat load conditions. Because in that condition also, the machines need cooling so the chiller cannot be stopped from working. So, how to overcome the cut-off cycle problem. The only way to operate the chiller in cut-off cycles within the safe mode is one any only the "hot gas bypass system". Hence this analysis to trap the problem helped us in this way. It can be recommended to model & install a hot gas bypass system in this chiller system.

14. Future Scope

This work directs and helps to understand the industrial chiller system and how to analyse it for checking whether it is malfunctioning or not. This research provides the sequence of tasks to reach out to the final results and can trap or solve the problem on its own. It can be learned how to draw the actual refrigeration cycle on the p-h diagram which helps to understand the cyclic behaviour of the chiller system. Further, this work would be used for the hot gas bypass system calculations for capacity control of the described chiller system. The obtained VCRS cycles on the p-h diagram of R-134a for this refrigerating circuit can be used as reference cycles.

ACKNOWLEDGEMENT

I would like to express my sincere gratitude towards my guide, Professor Alka Bani Agarwal for her constant guidance, suggestions and support. It would be incomplete acknowledgement if I would forget to thank Mr. Ashutosh Tripathi, his constant support, guidance and dedication to work helped me in every aspect on writing this journal paper to getting it published. There has never been any combination of words possible when it comes to thanking my family and a few friends for their constant, unconditional support and invaluable love.

REFERENCES

[1] D. Suva, "Thermodynamic properties of R-134a," DU Pont Suva.

[2] Voltas, "Energy-efficient air-cooled screw chillers," TUV India Pvt. Ltd.

[3] NIST, Refprop Software V.10.

[4] C. P. Arora, Refrigeration & air conditioning, 3rd ed., New Delhi, Delhi: Tata MacGraw Hill, 2009.

[5] R. J. Dossat, in Principles of Refrigeration, 4th ed., Wiley, Toppan, 1961, pp. 71-120.

[6] D. T. Jarullah, "Heat Exchanger Effectiveness (NTU method)," Tikrit University, Tikrit.

[7] U. o. lab, "Heat Exchanger," HERBERT WERTHEIM COLLEGE OF ENGINEERING.

[8] J. P. M. Trusler, "p -h Diagram for R134a," Imperial college , London, 2003.

BIOGRAPHIES

Jitendra Kirar is a student and pursuing Dual Degree Integrated Post Graduate Programme (B.E. + M. Tech) in Mechanical Engineering from University Institute of Technology, Rajiv Gandhi Proudyogiki Vishwavidyalaya Bhopal. (M.P.)

Alka Bani Agarwal, Professor, Department of Mechanical Engineering, University Institute of Technology, Rajiv Gandhi Proudyogiki Vishwavidyalaya. (M.P.)