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ENERGY OPTIMIZATION OF NATURAL REFRIGERANT-BASED AIR CONDITIONING SYSTEM FOR A SUSTAINABLE ENVIRONMENT ON THE BASIS OF THE MAJOR FIVE CLIMATIC ZONES IN INDIA

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Abstract

It envisages a serious problem of global warming effect and in consequence of the impact of ozone depletion, such refrigerants should be replaced by effective natural refrigerants due to their least global warming potential (GWP) &zero ozone depletion potential (ODP). The present analysis is carried out by using Cool Pack software (Version 1.50) and cross-verified by EES Software Professional V9.478(Version 11.319) as well as a practical environmental database, presenting a comprehensive assessment of different operating temperature conditions as per different climatic zones in India. Here, refrigerant operating temperatures are considered according to the climatic zones to have the optimum performance of the air conditioning system. This work emphasizes on application of R290 and operating parameters are optimized to have higher COP based on the different climatic zones of India. From the analysis, it is revealed that if the operating parameters specially evaporator temperatures and condenser temperatures changed compared to the standard system, based on climatic conditions yields huge power savings in the compressor i.e., 12.99 % in Hot and Dry Climate Zone; 41.73% in Warm and Humid Climate Zone; 44.36% in Temperate Climate Zone; 54.41% in Cold (Sunny/ Cloudy) Climate Zone; 19.17% in Composite Climate Zone.

Keywords: Indian climatic zone, Natural Refrigerants, Low power rated compressor, solar photovoltaic.

I. Introduction

Refrigeration is a system that has to deal with the production and control of temperature below that of the surrounding. Herein, heat must be removed from the system and transferred to another body whose temperature is below that of the refrigerated body, or the space needs to be cooled. Mainly, the heat source is the supply of sunshine and the need for refrigeration to reach maximum levels for the same reason. Over the coming two decades, according to the IPCC Report 2019, Asian countries account for 50% of national greenhouse gas emissions due to air conditioner use, which has increased significantly in recent decades. The cost of conventional electricity is increasing at an exponential rate, and domestic applications of air conditioners are expected to increase rapidly by three times by 2050. To realize the goal of climate change by focusing on the sub-tropical area it tried to investigate various optimization techniques and shows the directions toward an ultra-efficient air conditioner with extremely low operating energy consumption. Further, the limitation of temperature rise & Energy conservation is correlated by author Prasanta Kumar Bal [1]. This is a major concern in India and stated that one of the major concerns is domestic Electric power consumption by using only for the Air conditioner. A techno-economic assessment framework for life cycle analysis is proposed by Yanjie Li [2]. The authors show a case study of alternative air-conditioning technologies for the residential sector and evaluated the costs and environmental benefits. They develop a modeling framework that is capable of deriving reliable and intuitive results with a systemic and systematic assessment approach. Overall assessment in this study shows that R32 is the best candidate for achieving both greenhouse gas emission reductions with lower life cycle costs. But the ODP aspect of Natural Refrigerants should be preferred for future analysis and it is not natural refrigerants.

Integration of PV systems with air-conditioning can encourage not only solar energy developers but also focuses on the integration of PV systems into buildings. The integrated system could be improved in the future with the use of real HVAC data from a building with its energy being generated by a PV solar plant by Gustavo de et.al.[3]. The design and construction of a direct current (DC) air conditioning system integrated with a photovoltaic (PV) system which includes components like PV panels, solar chargers, inverters, and batteries is reported by I. Daut et.al. [4]. A typical meteorological year (TMY) was created and the hourly, monthly, and annual values of solar radiation are calculated. Cooling load calculation was performed to determine the kind of cooling and how much cooling was needed. F.J. Aguilar. al. [5] reported various possibilities and the viability of photovoltaic systems to supply energy without batteries or regulators to air conditioning equipment. In this case, the solar contribution obtained in cooling mode from May to October was 64.5%, and the production factor was 65.1%. Solar radiation estimation for the site is one of the major aspects of the proper design of the solar-powered air-conditioning system. Saurav Dubey et.al.[6] considered the solar radiation models that mainly focused on monthly or daily values. They have developed two kinds of hourly solar radiation datasets (frequency levels of 95% and 97.5%) for 17 locations for air-conditioning design. Zixu Yang et. al. [7] proposed an ultra-efficient air conditioner with smart evaporative cooling ventilation and a photovoltaic system. Natural refrigerant and natural sub-cooling are used to reduce cooling load through the roof envelope, with a similar improvement in COP compared to a mechanical sub-cooler. The simulation result with a dedicated mechanical sub-cooler was explained by Jay Prakash Bijarniya, et.al.[8]. Global electricity consumption is increasing rapidly, leading to the need for energy efficiency measures and renewable energy. Photovoltaics have received considerable attention, and HOMER software was used to optimize a solar PV-powered air conditioner system for an office building shown by Aziz Haffafa et.al. [9]. A significant amount of energy and emissions savings can be achieved by introducing improved and energy-efficient air conditioners (RACs), particularly in emerging economies. Nihar Shah et.al.[10] have studied and identified 'best-in-class' RAC components and RAC designs that are readily available or standardized to their production in the context of synthetic refrigerants. In this Last decade, considerable attention has been given to refrigeration systems in order to decrease their energy consumption. Various control methods for refrigeration systems were developed. Depending on system operating conditions, these methods differ in their theoretical basis and performance analysis directed by B. Saleh et.al.[11]. Researchers have developed various passive cooling technologies such as evaporative cooling, nocturnal radiative cooling, and phase change material (PCM) to reduce energy demands in India-based free cooling by considering solar thermal technology. Equations and correlations have been developed to determine various critical design parameters. [12].

The present analysis is carried out by using Cool Pack 1.50 software as well as a practical environmental database, which presents a comprehensive assessment of different operating temperature conditions per different climatic zones in India. Here, refrigerant operating temperatures are considered according to the climatic zones to have the optimum performance of the air conditioning system. Refrigeration or air-conditioning units are mainly required during the summer season. Tropical countries like India have an abundant source of solar radiation which is very much suitable to utilize solar power. Considering India is divided into five major climatic zones. This paper emphasizes on application of R290 as the natural refrigerant and the operating parameters are optimized to have higher COP based on the different climatic zones of India. Also, the present work argues sustainable and low power consumption to provide higher COP if the same capacity with the same refrigerant operates at different working temperatures as per different climatic zone. Here, an air conditioning system with 1 Ton capacity is considered for design purposes, and its compressor capacity is optimized based on the different climatic zone. Further, the results obtained are compared with the results from EES software.

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NOMENCLATURE

Roman	CR: compression ratio
c_p: Specific heat at constant pressure, (J kg^{-1} K^{-1})	HVAC heating, ventilation, and air-conditioning
c_v: Specific heat at constant volume, (J kg^{-1} K^{-1})	DA Dry Air
h: Specific enthalpy, (J kg^{-1})	Solar PV Solar photo voltaic
v: Specific volume, (m^3 kg^{-1})	η_v: volumetric efficiency
ṁ: mass flow rate (kg s^{-1})	Te Evaporator Temperature
P pressure (MPa)	Tc Condenser Temperature
q_{ev}: volumetric refrigeration capacity (kJ m^{-3})	Qc: heating capacity per unit of mass (kJ kg^{-1}
Wc: specific work of compressor (kJ kg^{-1})	Qe: refrigerating capacity per unit of mass (kJ kg^{-1}
AC Air-conditioner	CFC Cholofluoro carbon
ODP Ozone depletion potential	COP Co-efficient of performance
R12 Dichloro-difluoro-methane	R-11 Trichloro-fluoro-methane
GHG Greenhouse Gas	R-22 Freon
GWP Global warming potential	R-134a Tetra-fluoroetane
HC Hydrocarbon	R-600a Isobutane
HFC Hydro-fluoro carbon	R-290 Propane
IPCC International Panel of climate change	KW Kilo-watt

2. Methodology

In the present work, the authors considered a different climatic zone of India for designing the purpose of vapor compression cycle Air Conditioning Systems of Capacity of 1 ton with natural refrigerants (R 290) and compared the compressor capacity and its full load power consumption based on different condenser temperature in the different climatic zone with respect to the available standard system for all location. While comparing the system performance the evaporator temperature is kept at 10°C and condenser temperature and humidity are varied as per the available maximum temperature and humidity of that zone. A generalized flow chart is provided in Figure 1. For a better understanding of the methodologies. Here only compressor power consumption is estimated as it is the major power-consuming unit of the system. For analysis purposes, Cool Pack (Version 1.50) Software [13] is used. The details of the Indian climatic zone are discussed in subsequent sections.

2.1 Indian Climatic Zone

The whole of India is classified into five major climatic zones with consideration of the temporal and spatial distributions of temperature and rainfall patterns. India can be divided into **five climatic zones** i.e., hot and dry, warm and humid, Temperate, Cold (Sunny/ Cloudy), and composite, where most of the Indian states belong to more than one climatic zone with few states lying in the single climatic zone. This division of climatic zones is based on **temperature and humidity [1].** For estimation of maximum air conditioning power consumption with respect to standard 1-ton capacity air conditioning, system the properties of air in the different zone are considered and given in the tabular form in Table. 2. Also it is shown the amount of moisture and heat needs to be removed to maintain the comfort condition (25°C & RH 50%) of the room.

Table 1. Climatic zones based on temperature and humidity in India
[Ref.: https://www.firstgreen.co/climate-zone-map-of-india/]

CLIMATE ZONE	SUMMER MIDDAY (HIGH)	MEAN RELATIVE HUMIDITY	HIGHEST VALUE CONSIDERATION	REMARKS
HOT AND DRY	40 to 45	Very Low 25-40%	45°C & RH 40%	Main aim 25°C at RH 50%
WARM AND HUMID	30 to 35	High 70 to 90%	35°C & RH 90%	Main aim 25°C at RH 50%
TEMPERATE	30 to 34	High 60 to 85%	34°C & RH 85%	Main aim 25°C at RH 50%

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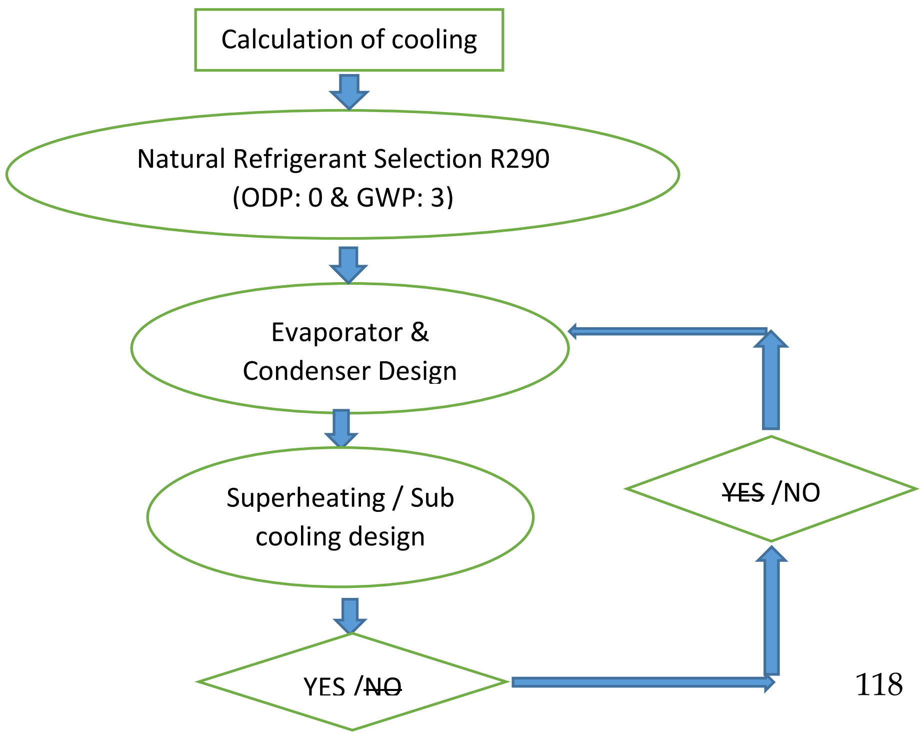
COLD (SUNNY/CLOUDY)	17 to 24 /20 to 30	Low:10-50% /High: 70-80%	30^{0}C & RH 80%	Main aim 25^{0}C at RH 50%
COMPOSITE	32 to 43	Variable Dry Periods=20-50% Wet Periods= 50-95%	43^{0}C & RH 95%	Main aim 25^{0}C at RH 50%

Table. 2 Air properties based on Maximum Temperature and Humidity of different climatic zone:

Highest temperature and humidity Consider (each zone)	Hot and dry zone 45^{0}C & RH 40%	Warm and humid zone 35^{0}C & RH 90%	Temperate zone 34^{0}C & RH 85%	Cold (Sunny/ Cloudy) 30^{0}C & RH 80%	Composite zone 43^{0}C & RH 95%	**25^{0}C & RH 50%**	Remarks
property	value	value	value	value	value	**value**	Air Properties in Each Zone are Separately shown to make it a comfort zone by proper design of the air conditioning unit.
Dry-bulb temperature in °C	45.0000	35.0000	34.3000	30.0000	43.2000	**25.0000**	
The wet-bulb temperature in °C	32.0710	33.5280	32.0350	27.1310	42.4540	**17.8900**	
Dew point temperature in °C	28.6820	33.1930	31.4770	26.2190	42.3430	**13.8900**	
Relative humidity in%	40.9000	90.4000	85.3000	80.2000	95.6000	**50.0000**	
moisture content in kg H_2O / kg DA	0.0243	0.0316	0.0286	0.0210	0.0526	**0.0099**	
Comfort moisture in kg H2O / kg DA	0.0099	0.0099	0.0099	0.0099	0.0099	**0.0099**	
Moisture removal in kg H2O / kg DA	0.0144	0.0217	0.0187	0.0111	0.0427	**0**	
humid volume in m^3 / kg DA	0.9355	0.9162	0.9100	0.8869	0.9704	**0.8580**	
specific enthalpy in kJ/kg DA	108.0200	116.1800	107.8300	83.8030	179.1100	**50.3200**	
Comfort-specific enthalpy in kJ/kg DA	50.3200	50.3200	50.3200	50.3200	50.3200	**50.3200**	
Heat removal from the room in kJ/kg DA	57.7000	65.8600	57.5100	33.4830	128.7900	**0.0000**	

The natural Refrigerant base solar air conditioner working principle is shown by an algorithm as follows;



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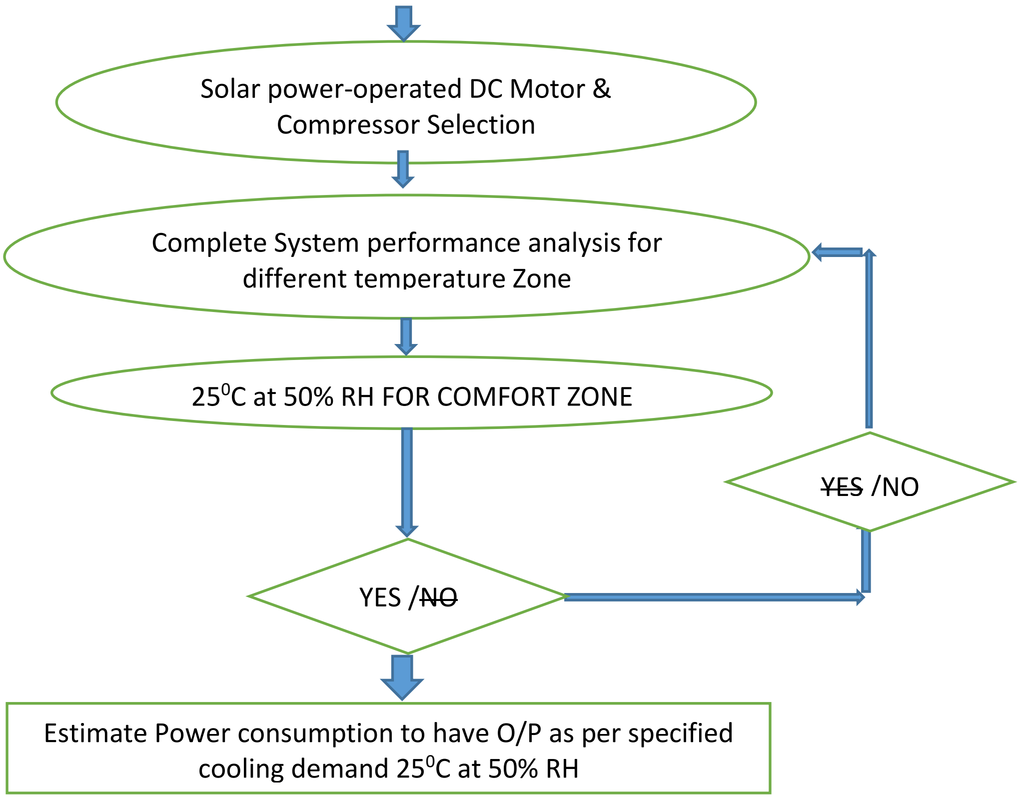

Figure 1. Methods of Air-conditioning process for estimating power consumption for different climate zone as shown by a flow chart

2.2. Natural Refrigerant

Very effective natural refrigerant liquid Propane (R- 290) is taken as a sample test for consideration of next-generation refrigerant for promising cooling capacity in spite of its inflammability (consideration of dilution effect with respect to ignition point). The R290 refrigerant has zero ozone depletion potential (ODP) and the lowest global warming potential (GWP) of only ‘3’ whereas other available refrigerants have a GWP of 675+. R290 has a high-temperature range and with a critical point above 96°C can easily be used with seawater condensers. The triple point lies at -188°C, making it suitable for both chilled water and provision cooling purposes. The pressure range is comparable with that of ammonia. At an evaporating temperature of -10°C, the absolute pressure is around 3,4 bar; at a condensation temperature of 25°C, the absolute pressure is around 10 bar. Latent heat values are quite decent. The enthalpy at the -10°C lines will be around 380 kJ/kg. Propane is a multi-functional substance that is used for many different applications, like fuel and it also is an excellent refrigerant. With thermodynamic properties that are comparable to that of synthetics like R-22 and R134a. The only downside is its moderate flammability [14].

3. Results

The present work emphasizes on application of Air-conditioning systems considering various climatic zone in India and it is shown as major 5 different categories as per the P-H diagram. Initially, an attempt has been made to understand the effect of variation of condenser temperature (Tc) keeping evaporator temperature (Te) constant. In that regards temperature of the evaporator (Te) is kept at 10^0C and the temperature of the condenser (Tc) is varied from 35^0C to 50^0C based on the different zone. The condenser temperature for each zone is kept at 5^0C more than the maximum temperature for that said zone. The output as evaporator heat removal, Qe [kW], condenser heat removal, Qc [kW], Compressor work, W [kW], and Co-efficient of Performance (COP) is estimated. Also, the variation

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of compressor work (W [kW]) with respect to condenser temperature (Tc [°C]) and the variation of COP with respect to compressor work (W [kW]) are shown in figure2 & 3 on the basis of estimation. It indicates a huge variation in compressor work and COP of the system. It is to mention that the authors ensured the phase of refrigerants (R290) across the compression stage should be in the gaseous phase while selecting the possible temperature ranges for the evaporator studying with the P-H diagram.

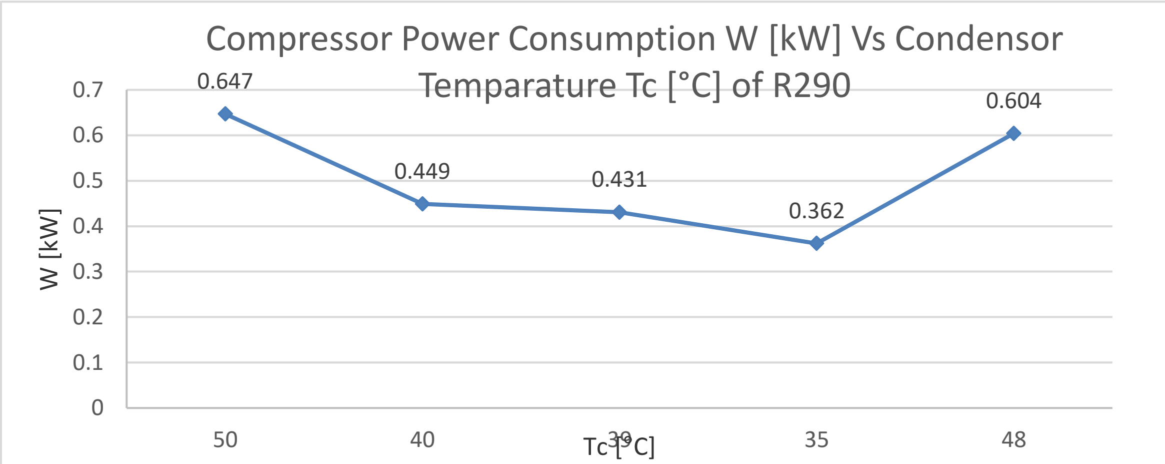

Figure 2: Compressor Power Consumption W [kW] Vs Condenser Temperature Tc [°C] of R290

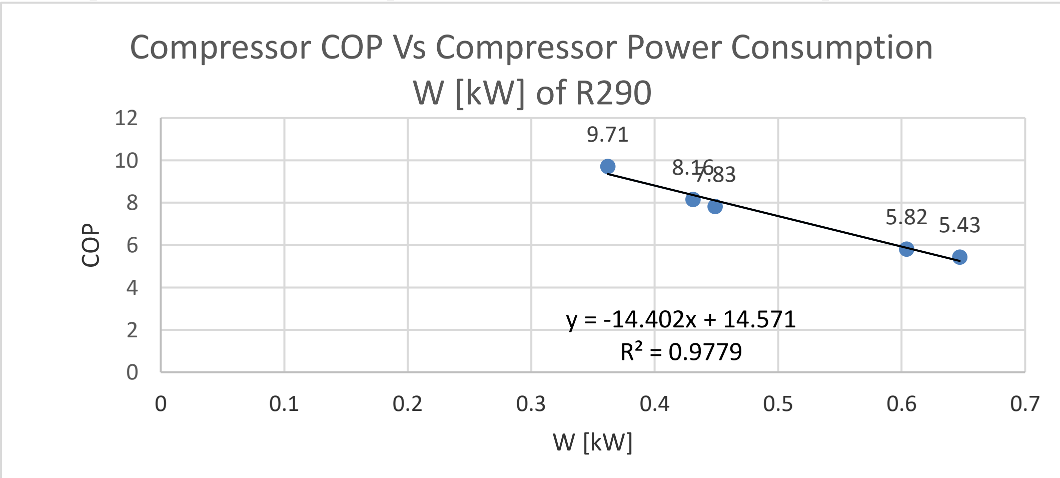

Figure 3: Compressor COP Vs Compressor Power Consumption W [kW] of R290

Similarly, the effects on the variation of evaporator temperature (Te) are performed keeping condenser temperature (Tc) constant. In that regard, condenser temperature (Tc) is kept at 50^0C and evaporator temperature (Te) is varied from 0^0C to 20^0C based on possibilities in the air-conditioning system keeping in mind the indoor comfort climatic condition and the output as evaporator heat removal, Qe [kW], condenser heat removal, Qc [kW], Compressor work, W [kW], and Coefficient of Performance (COP) is estimated. Also, the variation of compressor work (W [kW]) with respect to condenser temperature (Tc [°C]) and the variation of COP with respect to compressor work (W [kW]) are shown in Figures4 & 5 on the basis of estimation by cool Pack software. It also indicates huge power saving opportunities on compressor work and improvements of COP of the system by proper tuning of expansion valve based on environmental conditions.

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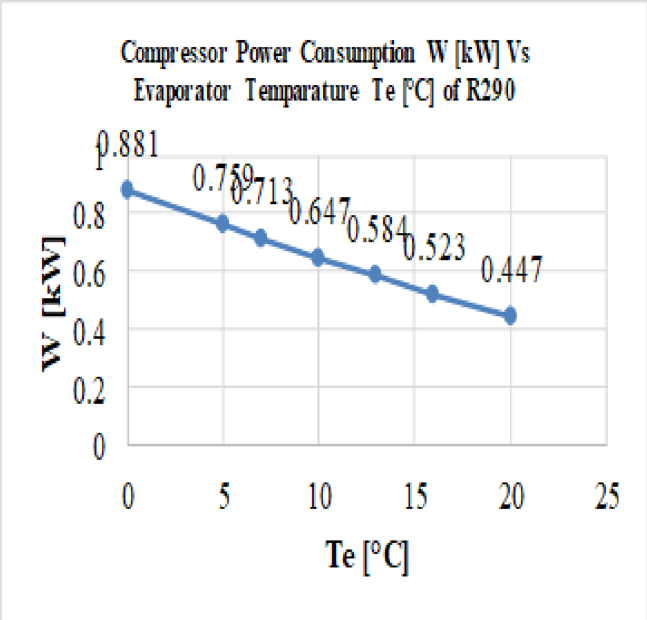

Figure 4:Compressor Power Consumption W [kW] Vs Evaporator Temperature Te [°C] of R290

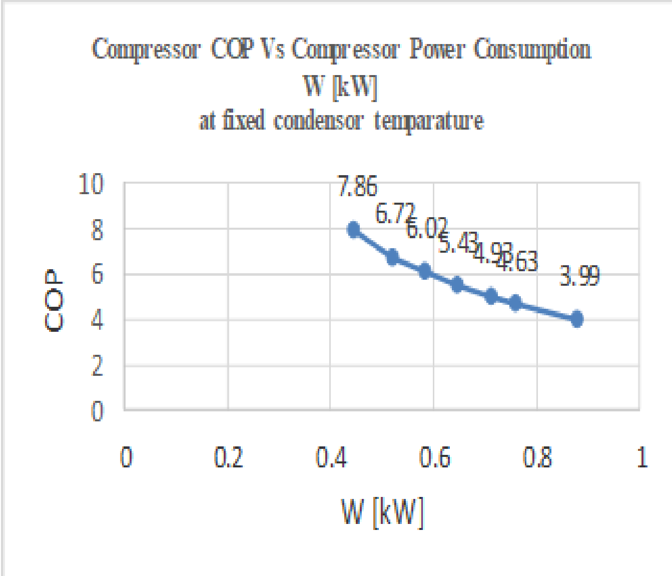

Figure 5:Compressor COP Vs Compressor Power Consumption W [kW] at fixed condensertemperature

From the above discussion, it is found that the lowest condenser temperature shows the lowest compressor power consumption and gives it the highest COP. So, from these results, it is clear that a considerable amount of energy can be saved by selecting proper refrigerant working temperature zone-wise compared to a common design of a wide range of temperature control.

Further, the analysis is carried out based on five climatic zones as mentioned earlier, and compared the result with standard design considerations as the evaporator temperature is 10^0C and the condenser temperature is 50^0C. Now the dew point temperature is taken as 14 ^{0}C as a reference as comfort condition (25^0C & RH 50%) for each climatic zone. Also, condenser temperatures (Tc) are kept at 5^0C more than the maximum environment temperature of that zone. All the performance parameters i.e., compressor work, COP, etc. are calculated with the variation evaporator temperature keeping condenser temperature constant for each zone. All the results are shown in tabular form in Table 3. The maximum possible energy-saving possibilities with respect to full load conditions of the standard system are estimated and mentioned in the remarks column of each table. It shows a huge number of energy-saving possibilities i.e., 12.99 % in a Hot and Dry Climate Zone; 41.73% in a Warm and Humid Climate Zone; 44.36% in a Temperate Climate Zone; 54.41% in a Cold (Sunny/ Cloudy) Climate Zone; 19.17% in Composite Climate Zone. From the present analysis, the authors suggested resizing compressor capacity based on the different climatic zone to achieve the best performance of the system with optimized energy consumption.

Table 3: Estimated performance parameters for Different Climate Zones:

Hot and Dry Climate Zone (45^0C & RH 40%) MAX.	**Present standard Design**	**Case 1 Hot and Dry Climate Zone (45^0C & RH 40%) MAX.**	**Case 2 Warm and Humid Climate Zone (35^0C & RH 90%) MAX**	**Case 3 Temperate Climate Zone (34^0C & RH 85%) MAX**	**Case 4 Cold (Sunny/ Cloudy) Climate Zone (30^0C & RH 80%) MAX**	**Case 5 Composite Climate Zone (43^0C & RH 95%) MAX**
Te [°C]	10^0C	**14^0C**	14^0C	**14^0C**	**14^0C**	14^0C
Tc [°C]	50^0C	**50^0C**	**40^0C**	**39^0C**	**35^0C**	**48^0C**
Qe [kW]	3.516	**3.516**	**3.516**	**3.516**	**3.516**	**3.516**

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Qc [kW]	4.163	**4.079**	**3.893**	**3.876**	**3.811**	**4.039**
Qe [kJ/kg]	249.983	**254.074**	**283.047**	**285.871**	**297.051**	**259.986**
Qc [kJ/kg]	295.988	**294.782**	**313.418**	**315.168**	**321.979**	**298.685**
COP	5.43	**6.24**	**9.32**	**9.76**	**11.92**	**6.72**
W [kJ/kg]	46.005	**40.708**	**30.372**	**29.298**	**24.928**	**38.699**
W [kW]	**0.647**	**0.563**	**0.377**	**0.360**	**0.295**	**0.523**
REMARKS	As per present standard design across all over India for 1 TON Airconditioning capacity	As per Zone-wise AC selection Case 1, will be more suitable and the power saving per ton from the present standard unit is (0.647-0.563) = 0.084 kW unit. i.e. **12.99 % Unit saving on existing AC unit.**	As per Zone-wise AC selection Case 2, will be more suitable and the power saving per ton from the present standard unit is (0.647-0.377) = 0.270 kW unit. i.e. **41.73 % Unit save on existing AC unit.**	As per Zone-wise AC selection Case 3, will be more suitable and the power saving per ton from the present standard unit is (0.647-0.360) = 0.287 kW unit. i.e. **44.36 % Unit save on existing AC unit.**	As per Zone-wise AC selection Case 4, will be more suitable and the power saving per ton from the present standard unit is (0.647-0.295) = 0.352 kW unit. i.e. **54.41 % Unit save on existing AC unit.**	As per Zone-wise AC selection Case 5, will be more suitable and the power saving per ton from the present standard unit is (0.647-0.523) = 0.124 kW unit. i.e. **19.17 % Unit save on existing AC unit.**

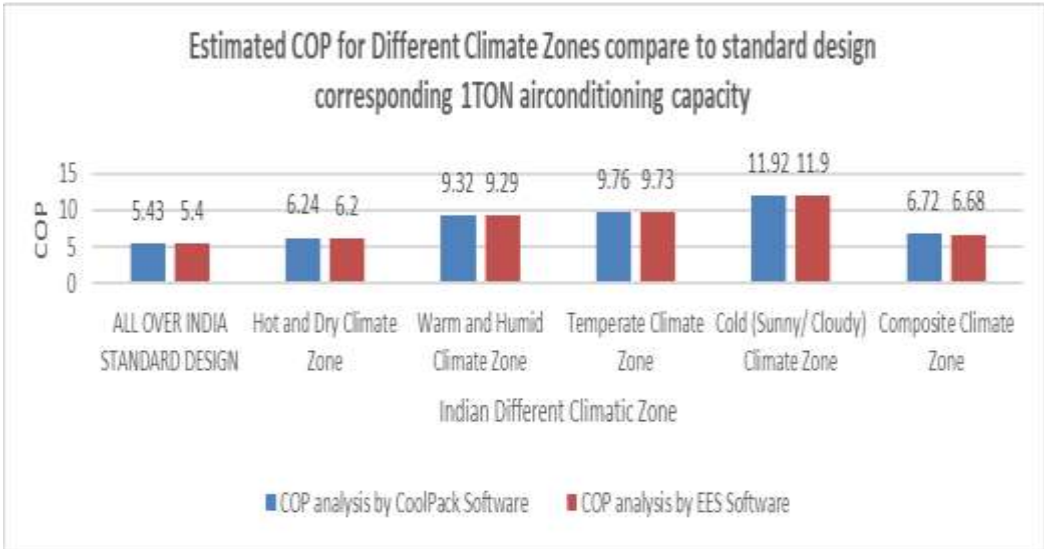

Figure 6: Estimated COP for Different Climatic Zones compare to standard design corresponding 1TON air-conditioning capacity by EES & Cool Pack Software's

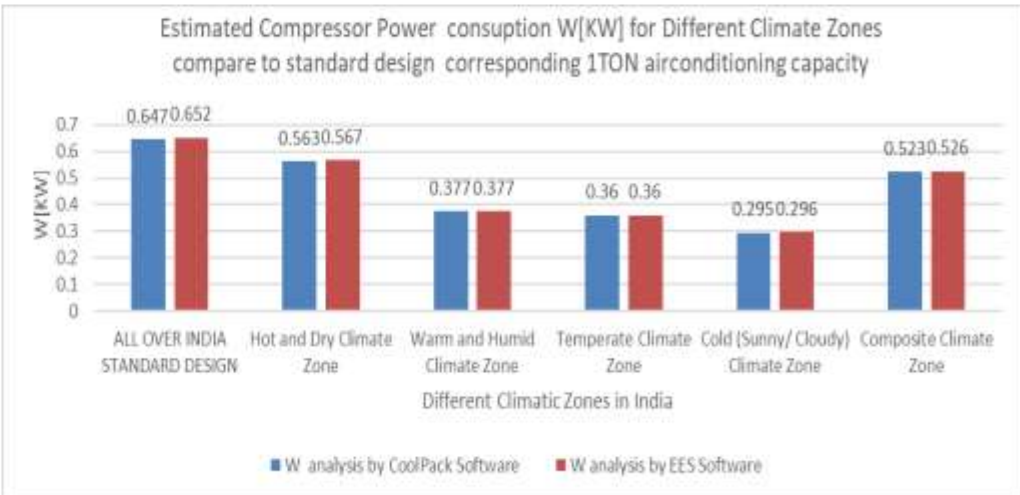

Figure 7: Estimated Compressor Power consumption W [kW] for Different Climate Zones compare to standard design corresponding to 1TON air-conditioning capacity

4. Conclusion

In this present work, the authors give a direction toward the micro design of the air conditioning system based on different Indian climatic conditions by resizing all necessary components like the compressor, evaporator, and condenser for optimum power consumption as well as economical aspect. The opportunities of energy saving potential compact to a fixed standard design are estimated using software named Cool Pack version 1.50.and the result is cross verified by EES Software Professional V9.478 version 11.319 which reflects the same result. Here natural refrigerant R290 is considered for its environmental behavior. Especially compressor work and COP of the system is estimated considering comfort climate conditions as the temperature of 25^0C and RH 50%. The results indicate huge saving opportunities in energy consumption by the compressor if the evaporator and condenser temperatures are varied according to the different climatic zones. i.e., 12.99 % in a Hot and Dry Climate Zone; 41.73% in a Warm and Humid Climate Zone; 44.36% in a Temperate Climate Zone; 54.41% in a Cold (Sunny/ Cloudy) Climate Zone; 19.17% in Composite Climate Zone. This work emphasizes resizing air conditioning system components, especially the compressor system to have optimum power consumption. This paper is also directed towards solar thermal (Superheating) and photovoltaic power utilization to run Air conditioners for a sustainable future.

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