World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(Research Article)

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Performance investigation of solar ejector cooling system: Case study area-Addis Ababa, Ethiopia

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World Journal of Advanced Research and Reviews, 2024, 21(03), 1146–1155

Publication history: Received on 28 January 2024; revised on 12 March 2024; accepted on 14 March 2024

Article DOI: https://doi.org/10.30574/wjarr.2024.21.3.0784

Abstract

This study investigates the performance of a solar ejector cooling system under both on-design and off-design operating conditions, focusing on the case study area of Addis Ababa, Ethiopia. Data crucial to the analysis were gathered from the Ethiopian National Meteorology Agency (ENMA) over six consecutive years (2013-2018). The system's performance was evaluated through hourly and monthly analyses under on-design conditions, yielding promising results. Under on-design conditions, the system demonstrated favorable performance metrics. Specifically, at noontime in March, when the design points were set at T_g = 90°C, T_c = 30°C, and T_e= 12°C, the system achieved a total hourly maximum coefficient of performance (COP) of 0.2049 and a cooling capacity of 186.9 W/m^2. Furthermore, the study determined that a collector area of 22.3 m^2 per ton of cooling capacity is required during noontime for all cooling seasons in Addis Ababa, Ethiopia. Additionally, an off-design operating condition map was developed for the system. The findings indicate that the solar ejector cooling system can effectively provide cooling during office hours (8:00-15:00) in Addis Ababa, Ethiopia.

Keywords: Performance analysis; Ejector; Solar cooling system; On and off-design; Operating condition map

1. Introduction

SoECS is one of the attractive technologies in refrigeration and air conditioning system which uses low-grade energy so that it could be driven with solar energy, geothermal energy, waste heat, etc. The Ejector (Thermal compressor) technology used for over greater than one hundred years and has recently undergone a revival in interest for space conditioning applications and this technology offers an alternative whereby the electricity consumption largely reduced. It is the oldest methods of producing a cooling effect [1].

The idea is not new; Albel Pifre [2] first recorded a solar-driven refrigerator in Paris in 1872. A small amount of ice produced from crude absorption machine by using a solar boiler as a heat source. After that, many countries installed solar powered refrigeration system e.g. Australia, Spain, and the USA. For air conditioning application, thermally driven absorption system designed.

The energy needed to Refrigeration and Air Conditioning systems consists a vital role in this world. From the total electrical consumption in the world, around 15% used by the refrigeration and air conditioning systems. Therefore, the use of solar energy is a logical way to meet the growing demand for cooling, so there has been a lot of research on this topic in recent years, but mainly on the absorption cycle. [3]

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Recently the direction in research in the area of refrigeration focusses on decreasing and/or elimination of adverse environmental effects. There are two sources of pollution occurs from Refrigeration systems: ozone depletion from CFCs refrigerants and greenhouse gas emission from electricity production. This creates the crucial need to replace the conventional refrigerants with environment-friendly working fluids as well as applying renewable and non-polluting energies to run these systems.

The growing population and fast depleting reserves of fossil fuels have led scientists in the fields of engineering, meteorology, and industry to pursue the development and use of renewable energy resources like solar energy. Solar power is insignificant in pollution and does not causes emission of greenhouse gases during installation.

Ethiopia is in Tropical zone and lays between equator and tropic of cancer its solar resource is obviously of significant potential. This makes Ethiopia one of the highest solar energy potential. There are four climate seasons for Ethiopia such as summer (June-August), autonomy (Sept-Nov), winter (Dec-Feb) and spring (March-May). Winter and spring are the hot months and during summer, there is heavy rainfall according to Ethiopia National treasure (ENT), April 2019.

The annual average daily radiation in Ethiopia reaching the ground is 5.8 $KWh/m^2/day$, which varies from a minimum of a 4.8 $KWh/m^2/day$ in July to a maximum value of 6.8 $KWh/m^2/day$ in February and March. This is a long-term average Global Horizontal Irradiance for a period of 1994-2015 according to Solaris Energy Sector Management Association program (ESMA) 2019. Here in the research Addis Ababa selected for the study due to its annual average daily radiation is approximately the average of the country 5.789 $KWh/m^2/day$.

Different country investigated the performance of the Solar Ejector Cooling System but Ethiopia is not. In general, investigation of this system will show some way to decrease the electricity consumption of the country in the side of Refrigeration and Air conditioning system secondly it will provide the necessary information or data to the Designers and Operators who want to install the system. Solar ejector cooling system investigated for different countries in the world and this investigation helped those countries to use the system for cooling application.

The performance of the solar ejector cooling system investigated by taking the southern region of Turkey as the case study using computer programs. Meteorological data collected from Turkish meteorological agency for the study. At noontime on August, the hourly cooling capacity of solar jet cooling system in some cities altered from 163W/m^2 to 178W/m^2. The monthly maximum average of COP and cooling load in July were 0.167 and 108 W/m^2 in Urfa, respectively. The problem faced them were to use this system in off-design conditions. Controlling mechanism is needed for the off - design conditions by varying one of the components of ejector. [4]

Bangkok researchers examined SERS that used iso-butane (R600a) as a refrigerant. Operating at different working conditions and using different solar collector type's influence on the performance of the system also examined. Climate data generated by METEONORM. TRNSYS was used to model the entire environment system, but the ejector cooling subsystem model was developed in an engineering equation solver. At the selected simulation site Bangkok, the condenser temperature is 5 K which is above ambient temperature, the evaporator temperature is +150 °C, the evacuated collector area is 50 m^2, the heat storage volume is 2 m^3, and the annual average system heat ratio (STR) is approx. 0.22, the COP for the ejector is about 0.48, and the solar collector efficiency is about 0.47. The evacuated tube system has an average solar share of 75% in one year, and the collector area is 80 square meters. They concluded that at high evaporator temperature ejector works efficiently and the COP of ejector component depends on the evaporator temperature. The operating condition and collector type also influence the performance of the ejector system according to their study. [5]

Solar ejector system performance investigated in the hot season for six months using the meteorological data from the Institute of the Tunis city by using three flat plate collector types. Based on empirical correlation, many environmentally friendly refrigerants including, R245fa, R142b, R141b, R152a, R290, R717 and R600 were investigated. Thermodynamic characteristics of operating fluids as determined using the REFPROP7 program. Athens researchers looked at the impact of the temperature of the generator, condenser, and evaporator as well as the compression ratio on the entrainment ratio (secondary fluid to primary fluid). They explained the operation of a solar-powered ejector cooling system using R134a as the working fluid in the Athens region. When the generator temperature is (82-90^{0}C), the condenser temperature is (32-40^{0}C), and the evaporator temperature is (82-90^{0}C), the ejector cooling system's coefficient of performance (COP) varies from 0.035 to 0.199. (-10-0^{0}C). In July, total solar radiation ranged from 536 W/m^2 to 838 W/m^2, while overall COP varied between 0.014 and 0.101. [6]

A simplified 1D technique was used in the theoretical analysis of a solar-assisted ejector cooling system conducted in a Mediterranean nation. The efficiency of the model and the needed collector area were investigated using meteorological data while using water as the working fluid. For better COP and system efficiency, the generator temperature should not be lower than 90^{0}C in order to obtain acceptable numbers. Evacuated tube collectors are suitable for the ejector cooling system when a collector output temperature of 100^{0}C is required. Additionally, very poor system performance (COP < 0.1) was caused by evaporator temperatures below 10^{0}C. At very low temperature (<4^{0}C) using water as a working fluid is not suitable for ejector cooling system. The needed collector area is larger than 50 m^2 for condenser temperatures of more than 35^{0}C and for evaporator temperatures of less than 10^{0}C. Auxiliary heating is required in the Mediterranean region even with relatively high solar radiation (800 W/m^2). It is believed that using a more detailed approach give good results. Using refrigerants will improve the system's performance because some refrigerants work better than water. By raising the entrainment ratio, ejector geometry can be optimized to increase COP. [7]

Ethiopia is one of highest solar annual energy potential when compared to other non-tropical zone countries. The annual average daily radiation in Ethiopia reaching the ground is 5.8 KWh/m^2/day. The above research tells us that the importance of solar ejector cooling system and its performance analysis in different countries. The application of SoECS done in many countries and they are using it now. When we come to Ethiopia Solar ejector cooling system not investigated yet. There are researches conducted in solar water heating and solar assisted vapor absorption-refrigeration system but not in solar ejector refrigeration system specifically.

In this research, Investigation of solar ejector cooling system for Addis Ababa for the application of cooling system carried out. Using computer programs investigation of performance analysis of the system is determined. It will become a resource for the researchers and will show the way to designers, and operators in order to install the system in the country with confidence. It will fill the resource gaps of solar ejector cooling system performance analysis of the country a little bit.

1.1. Solar radiation in Addis Ababa

Addis Ababa is the city found in Ethiopia, which is the capital city of the country. It is located 9.02 latitude and 38.7475 longitude situated at elevation 2405 meters above sea level. The annual average daily solar radiation reaches ground in Addis Ababa is 5.789 KWh/m^2/day, which is approximately the average of Ethiopia solar radiation according to Energy Sector Management Association program 2019. Now except for Addis Ababa other cities in Ethiopia have no direct solar radiation-measuring device. Other cities except Addis Ababa have an instrument, which measures Sunshine Hours, Ambient Temperature relative humidity and so on. Using bright sunshine hour and meteorological parameters solar radiation will be estimated using suitable empirical models. The average annual solar radiation needed for this research in ordered to predict for the country

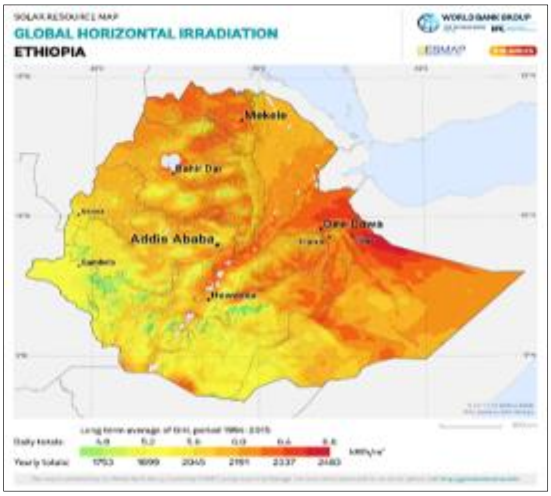


Figure 1 The variation of Global Horizontal Radiation in Ethiopia ESMA 2019

According to the above information approximately the average Global horizontal radiation of the country lies in Addis Ababa not only this we can get genuine data relative to other cities in Ethiopia.

1.2. Description of the SECS

A schematic view of the SoECS together with its T–s diagram shown below in fig 2. The technology uses ejector cooling cycles and solar energy. The essential components of the former cycle are a circulation pump, a generator, and solar collector. A vapor generator, ejector, condenser, evaporator, expansion valve, and liquid pump are the major components of the latter cycle.

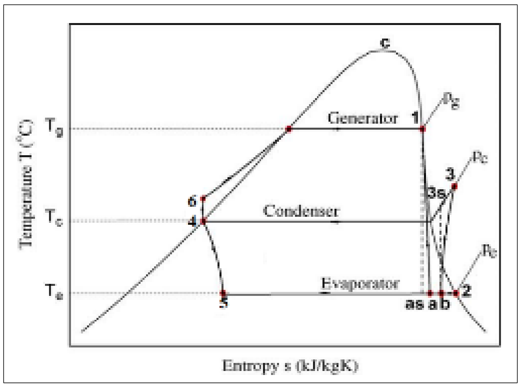


Figure 2 **T**-s diagram

Two coupled power and cooling cycles made up the refrigeration cycle. The refrigerant passes the generator, ejector, condenser, and liquid pump in that succession however, power cycle occurs in clockwise direction.

The cooling cycle takes place in anticlockwise direction. The Refrigerant, which leaves the evaporator continually, passes through ejector, condenser and expansion valve and requite to the evaporator. The cooling cycle powered by the energy extracted from the power cycle. The ejector in the ECS takes the place of a compressor using a vapor-compression system.

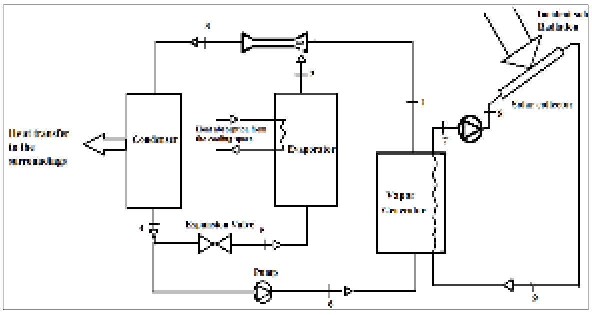


Figure 3 Solar ejector cooling system cycle

1.3. The working principle of the System

The pressure and temperature becomes higher for refrigerant vapor at state - 1 due to heat is added to the fluid using solar energy. We can call the fluid at this state as primary fluid, which is the system activator.

After passing the Vapor generator, it becomes saturated vapor & enters to the ejector with high pressure and temperature. Ejector is a component, which called thermal compressor, which compresses the fluid to desired point. Inside the ejector, there is a supersonic nozzle, which helps to increase primary fluid velocity. This supersonic nozzle expands primary vapor which means primary vapor become low-pressure after passing supersonic nozzle. This causes the suction of the secondary fluid from the Evaporator state 2

At state - 2 low-pressure vapor from the evaporator will be entrained due to the high velocity formed supersonic nozzle outlet.

In mixing chamber, primary and secondary fluid blend with each other. After passing the mixing section it enters to the diffuser in ordered to regain its pressure. This mixed vapor is then compressed to the condenser pressure in diffuser state - 3

Mixed vapor which leaves ejector enters to condenser in order to reject the heat to the surroundings and condenses to state -4

After passing state-4 the fluid split into two parts, one go in to evaporator by expansion process state-4 to state -5 and the second goes back to vapor generator by passing liquid pump.

Due to the pressure difference between vapor generator and condenser is higher the liquid pump is used in state (4-6)

Fluid entering vapor generator is vaporized using solar energy accordingly, state change occurs 6-1.

Cooling effect produced in evaporator due to the fluid, which passes the evaporator, absorbs heat from cooling space. Afterward the fluid enters to the ejector again.

1.4. Modelling of Ejector cooling cycle

The system performance calculation proceeds by a sequential simulation process. There are important assumptions, which are considered here

- The approach developed by Huang et al. used in design calculation and ejector performance investigation.[9]
- Steady-state operation
- Pressure losses in all components and connecting pipes are negligible.
- Refrigerant kinetic energy at the ejector inlet/exit are negligible
- With the exception of the components exchanging energy with the environment, there are very few or negligible heat losses to the ambient.
- The operating fluid is in a saturated vapor state at the outputs of the generator and evaporator.
- The operating fluid is in a saturated liquid state at the output exit of condenser.
- Throttling process occurs during the expansion process in ex-valve
- The thermodynamic and transport properties data bank incorporated within EES used to directly extract the refrigerant properties.

2. Result and discussion

2.1. Estimation of monthly average daily maximum, minimum and average temperature on horizontal surface in Addis Ababa

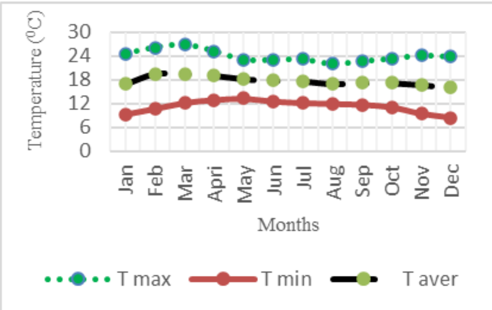


Figure 4 Monthly Ambient Temperature Form in Addis Ababa, from 2013 to 2018 Years

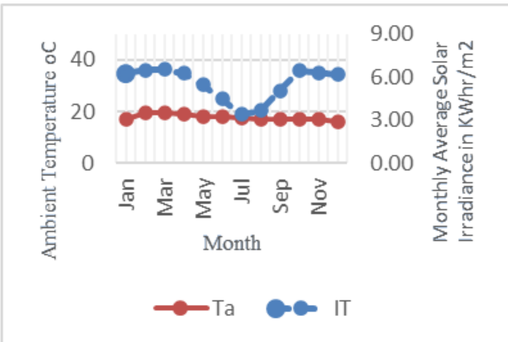


Figure 5 On an inclined surface, the monthly averages for daily sun radiation and ambient temperature.

2.2. Design point solar ejector cooling system performance analysis

The above figure shows monthly average solar ejector cooling system performance variation for the design point (T_g = 90^{0}C, T_C = 30^{0}C and T_e= 12^{0}C). On the left side of the graph, there is collector useful energy with cooling capacity per unit collector area. Design point temperatures suggest that for each month, various cooling capabilities achieved because of fluctuations in solar radiation and ambient temperature in Fig 4. Monthly highest $COP_{overall}$ & Q_e are found 0.1319 & 73.62 W/m^2 respectively in February. In February, the collector efficiency ranges from 0.1397 to 0.2631 for the specified operating conditions. February is the month, which has maximum collector efficiency. The useful collector energy per unit collector area (q_{coll}) varies from 146.8 W/m^2 in February to 63.21 W/m^2 in July. Collector efficiency is directly correlated with useful collector energy, overall COP and cooling capacity.

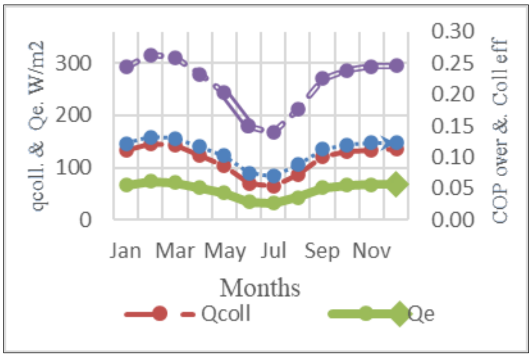


Figure 6 Monthly performances of the SECS for Addis Ababa at designed conditions of ($\boldsymbol{T_g}$ = 90^{0}C, $\boldsymbol{T_C}$ = 30^{0}C and $\boldsymbol{T_e}$= 12^{0}C).

2.3. Hourly performance Variation of the SoECS in Addis Ababa at design point in March

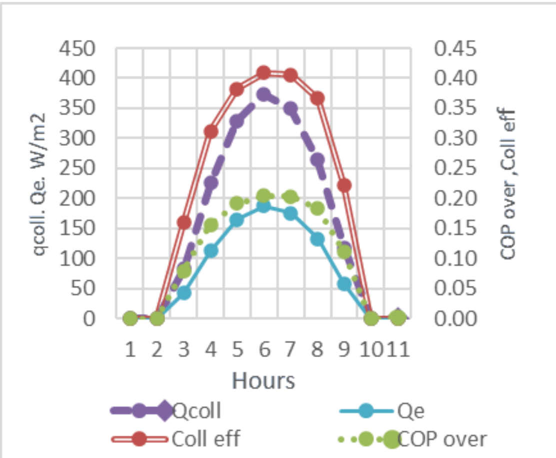
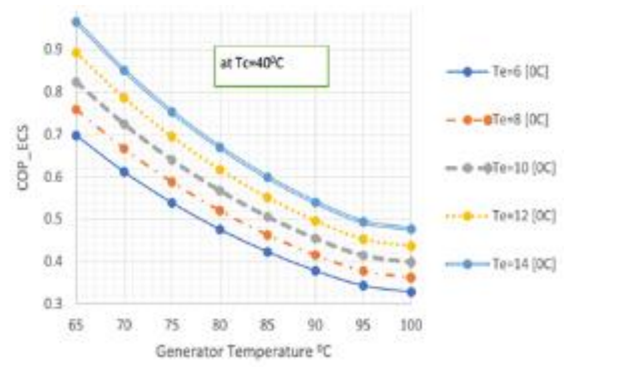


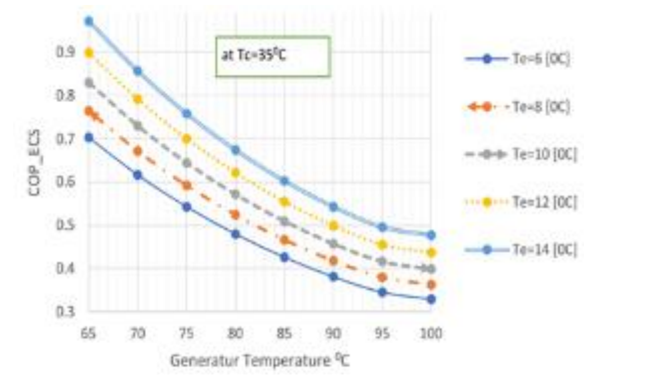
Figure 7 Hourly Average performances of the SECS for Addis Ababa at designed conditions of ($\boldsymbol{T_g}$ = 90^{0}C, $\boldsymbol{T_C}$ = 30^{0}C and $\boldsymbol{T_e}$ = 12^{0}C).

Similar hourly performance of the SoECS throughout the cooling season shown in fig. 7. Due to the decreased solar energy and lower ambient temperature in the morning, the collector efficiency decreases. With the rising in sun radiation for March, the performance rises and achieves a maximum value at 12:00. After then, it starts to drop throughout the day and reaches zero at 16:00. The results show that 0.20 and 186.9 W/m2 are the highest hourly COP overall and Q_e, respectively. The maximum collector efficiency for the specified operating circumstances is 0.41 at 12:00. At noon, 372.7 W/m2 is the highest useful collector energy per unit collector area. The graph above illustrates how Q_e, COP overall, and q_{col} are affected by changes in collector efficiency.

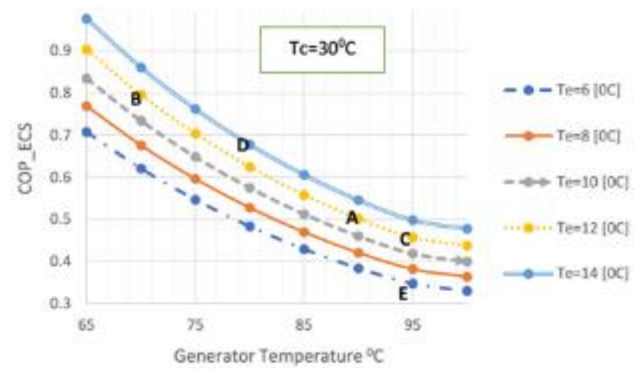
2.4. Performance of the system at different operating (Off-design) conditions



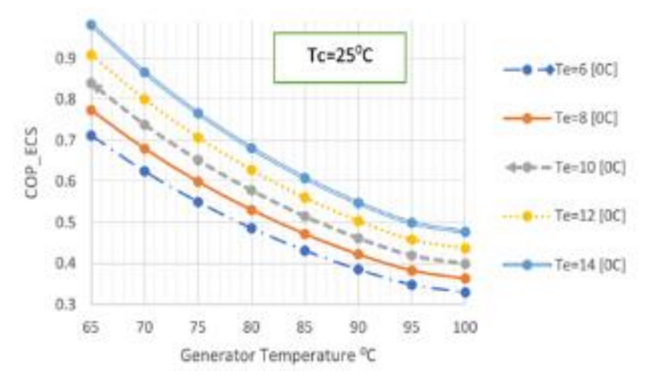
A



B



C



D

Figure 8 Performance of the ECS during operation (a, T_c=40⁰C, b, T_c=35⁰C, c, T_c=30⁰C and d, Tc=25⁰C)

The above figures (a, b, c and d) shows the coefficient of performance (COP) variation of the system for different operating conditions. The above graphs show a performance at constant condenser temperature when the generator temperature decreases with slight increase in evaporator temperature the performance of the system increases. The figure c is better explaining the rest figures due to the map, which represented by the letters [A-E].

Figure 8.c displays the design points in addition to being unique from the others in that it displays the performance map based on the operating condition temperature, which is indicated by the letters A, B, C, D, and E. Point A represents the design point of the system B, C, D and E are the off-design operating conditions.

When the temperatures changes from one to point to the another for instance

Since the condenser and evaporator temperatures remained constant while the generator temperature dropped, the system's coefficient of performance (COP_{ECS}) improved from point A to point B.

In the same way when from A-C the performance decreased when the generator temperature increased with constant condenser and evaporator temperature.

From A-D happened when both evaporator and generator temperature is changed means with decreasing temperatures of generator and increasing evaporator resulted in increasing the performance

From A-E Performance is decreased due increasing generator temperature with decreasing evaporator temperature with constant temperature

Therefore, to increase the performance of the system generator temperature must decrease with constant evaporator and condenser temperature. The results of the current study show a trend that is comparable to those of Huang et al. [9] and Ersoy et al. [10]'s experimental study.

2.4.1. Variation in March's cooling capacity according to the performance map and operational conditions (A-E) as a function of hour of day

A,B &C

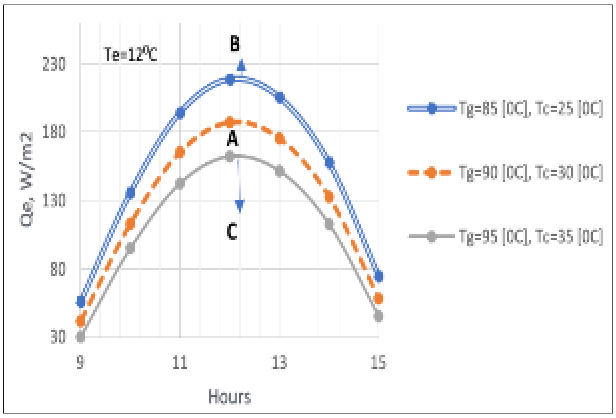


Figure 9 The cooling capacity hourly variation at different generator and condenser temperature with constant evaporator temperature.

D,E &F

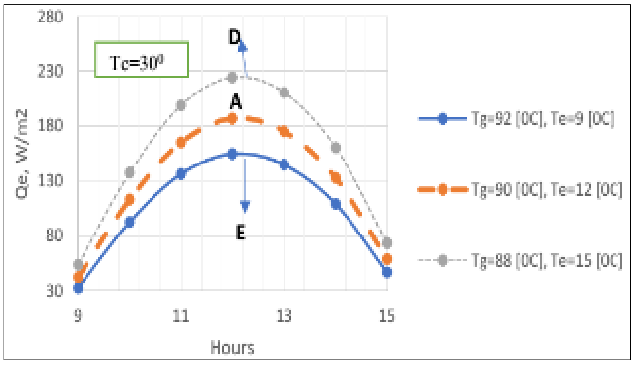


Figure 10 Cooling capacity hourly variation at different generator and Evaporator temperature with constant Condenser temperature.

Both figures (9 & 10) above shows the cooling effects variation with different operating conditions that;

- Fig 9.
- Letter A shows cooling capacity variation of design point at hourly
- A-B the cooling capacity is increased due to that both generator and condenser temperature decreased with constant evaporator temperature
- A to C the cooling capacity is decreased because of the generator and condenser temperature is increased with constant evaporator temperature
- Fig 10.
- Letter A shows cooling capacity variation of the design point at hourly
- (A to D) the cooling capacity is increased due to decreased generator and increased evaporator temperature with constant condenser temperature
- (A to E) the cooling capacity is decreased because of the increased generator and decreased evaporator temperature with constant Condenser temperature

Therefore, the condenser& generator temperature must drop while maintaining a constant evaporator temperature in order to maximize the system's cooling capability. In addition to that again to increase the cooling capacity of the system it is must to decrease the generator temperature and slight increase in evaporator temperature with constant condenser temperature. The results presented here demonstrates a similar trend to the experimental research findings of Huang et al. [9] & Ersoy et al. [10].

The system's performance map shows the better performance under a variety of operating states. The temperatures of the generator, condenser, and evaporator automatically regulated in accordance with the performance map to ensure the optimum operational efficiency. As a result, the performance map will direct the automatic control system and make installation simple for designers or operators. By using this analysis, researchers can enhance the system performance figuring out the problems easily.

2.5. Required surface area of the collector per ton cooling capacity

The required collector surface area per ton cooling capacity for Addis Ababa at 12:00, per the results shown below.

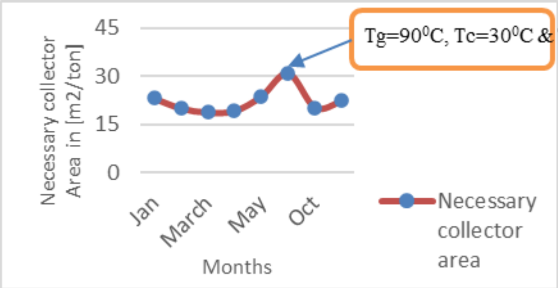


Figure 11 Necessary collector area per ton cooling capacity of eight months at 12:00

At on-design operating condition (T_g=90^{0}C, T_c=30^{0}C & T_e=12^{0}C) in Jan, Feb, March, April, May Sept, Oct and Nov are 23.18 m^2, 20.01 m^2, 18.72 m^2, 19.15 m^2, 23.72 m^2, 30.91 m^2, 20.25 m^2 and 22.26 m^2 at 12:00 in, respectively.

3. Conclusion and Recommendation

In this present, study the performance analysis of the solar ejector cooling system in Addis Ababa. Hourly and monthly SoECS studied by taking Addis Ababa as a case study. R-134a is the refrigerant used by the SoECS, which is based on a constant pressure ejector-flow mechanism. Solar radiation and ambient temperature data which is gathered from Ethiopian national meteorology agency (EMA) is used to compute the maximum cooling Capacity of the system. Here is a summary of the findings:

- The solar radiation and the ambient temperature for the month and day had a significant impact on the solar collector's efficiency. The solar collector efficiency variation affected $COP_{overall}$. Q_e & q_{coll}.
- The monthly variation in solar collector efficiency ranged from 0.1397 in July to 0.2631 in February.
- Solar collector efficiency reached 0.41 in hourly bases in march at 12:00
- At 12:00 in March, the cooling capacity and hourly maximum overall COP were 0.2049 and 186.9 W/m^2, respectively.
- The cooling capacity and the monthly maximum overall COP were 0.1319 and 72.62 W/m^2, respectively, in February.
- Cooling capacities of the SoECS were very close to each other for the given conditions for most months.
- For off-design operating conditions, the performance map of SoECS was developed to offer designers and operators meaningful data. The following conclusion drawn for the off-design operating conditions
- To ensure greater performance generator temperature must decrease with constant evaporator and condenser temperature.
- To ensure greater cooling capacity generator and condenser temperature must decrease with constant evaporator temperature.

In addition to that, again to achieve better cooling capacity it is must to decrease the generator temperature and slight increase in evaporator temperature with constant condenser temperature.

The temperatures of the generator, condenser, and evaporator should be automatically regulated in accordance with the performance map to obtain the best operational efficiency. Automatic control system of ECS guided by the performance map, which also makes it easier for designers or operators to install the system. By using this analysis, researchers can enhance the system performance figuring out the problems easily.

According to the study, the SoECS can be used in Addis Ababa for office cooling aim up until 15:00 during the cooling season. It is determined that the SoECS would not maintain cooling in any month at 17:00 under the specified operating parameters. Additionally, about 16:00, the evacuated-tube solar collector efficiency roughly fell to zero. As a result, an auxiliary heat source should be used rather than solar energy to run the system after 15:00. The obtained results show that Addis Ababa's required collector surface area per ton cooling capacity at on-design operating circumstances is 22.28 m^2 at midday.

It is better to use the hot water storage and cold-water storage to increase the system performance as well as to use the system at nighttime. Since the solar energy is used in daytime only and affects the performance in nighttime. It is better if auxiliary heater used in nighttime. It is better if there is a controlling mechanism.

Compliance with ethical standards

Acknowledgments

I am deeply thankful to the dedicated staff members of the Ethiopian National Meteorology Agency (ENMA) for their invaluable assistance during the data gathering process. Their expertise and cooperation were instrumental in the success of this research.

I extend my sincere appreciation to my family for their unwavering encouragement and support, which have been pillars of strength during this endeavor.

I am immensely grateful to my advisor, Mr. Balewgize (Assistant Professor, PhD Candidate), for his patient guidance, insightful feedback, and unwavering encouragement. His constructive comments have significantly enriched my research journey. Additionally, I extend my special thanks to my friend, Mr. Gutema Teshome (PhD Candidate), for his support and camaraderie throughout this endeavor.

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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