International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 3 Issue 8, August - 2014

Energy, Economic and Environmental Analysis of Compact Solar Refrigeration System

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Abstract*—Energy consumption in cooling loads like Air conditioning and cold storage applications are growing enormously as the concern of the food storage is getting prominence towards zero wastage. A Compact Solar Refrigeration System was designed and fabricated in a town at South India and it was tested for its performance and provided a good performance. It is essential to evaluate economic and energy expenses towards the CSRS system. In this article a detailed analysis on energy consumption of CSRS and expenses towards the consumption is discussed. Economic and the energy analysis are done in comparison with conventional vapour compression refrigeration system. The analysis on emission of CSRS and conventional is done using the RETSCREEN software and presented. Financial analysis of the CSRS is also done for to read the cash flow during the payback period and concluded to be economically lucrative.

***Keywords*—CSRS, energy economics, solar refrigeration, cooling load**

I. Introduction

A Background

Energy supply to refrigeration and air-conditioning systems constitutes a momentous role in the world. The International Institute of Refrigeration(IIR) has estimated that approximately 15% of all electricity produced worldwide is used for refrigeration and air-conditioning processes of various kinds (Lucas, 1988) and the global growth rate is about 17%.The cooling load is generally high when solar radiation is high. Together with existing technologies, solar energy can be converted to both electricity and heat; either of which can be used to power refrigeration systems. The idea is not new; a solar-driven refrigerator was first recorded in Parisin 1872 by AlbelPifre (Thévenot, 1979). A solar boiler was used to supply heat to a crude absorption machine, producing a small amount of ice. Later, solar powered refrigeration systems have been installed worldwide in many countries e.g. Australia, Spain, and the USA. Most are thermally driven absorption systems, designed for air-conditioning purposes.

There are a few commercial systems currently available, e.g. a vapor-compression system using PV and an absorption system using thermal collector. Solar air-conditioning systems have also been regularly in operation. Commercial absorption cooling machines e.g. Yazaki (Japanese) are available. According to Hans-Martin Henning (Fraunhofer Institute Ise, Germany), about 70 solar air-conditioning systems driven by the solar energy are in operation in Europe, with a total cooling capacity of 6.3 MW, corresponding to 17 500 m2 of installed solar thermal collector area (Meyer, 2005).

The obvious consequence of this growing air-conditioning use is increased power consumption. Recently, India has seen a number of power grid breakdowns in summer caused by a seasonal peak use of air-conditioners in combination with reduced power plant output. Another consequence of excessive air-conditioning is locally higher temperatures in metropolitan areas, commonly referred to as heat islands. As a part, these inner city temperature peaks are the result of heat conveyed from building inside to outside, released at a temperature level above ambient temperature. Both these consequences are strong arguments for alternative air-conditioning or cooling methods.

The latest development of absorption chillers with small cooling capacities up to 10 kW now provides such an alternative. Solar cooling systems using these chillers can provide cooling comfort with reduced power consumption and CO_2 emissions. However, despite their ecological advantages, solar cooling systems also have to yield an economic advantage for the customer. At present, investment costs are higher for solar cooling systems than for comparable compressor based cooling units. Thus, the full potential of solar cooling is far from being realised, however building owners, occupants and architects are becoming more and more sensitive towards energy issues. The economic advantage of solar cooling systems results from much lower operation costs which include the costs for power, water and maintenance. Especially the electrical power consumption of a solar cooling system influences the economics strongly. The main idea of such a system is to use thermal energy for most of the process work, thus the remaining power consumption should be kept as low as possible. In India more than 20% of the population are living in remote and rural areas where the people are not accessing the electric power and hence they are much aware of application of the refrigeration purpose. Also it is noted that the most of the rare spices and honey are produced in such areas and produced things can’t be preserved properly because of non-availability of cold storage which requires electric power to operate. Solar energy is the promising energy source which can be readily recovered and can be utilised for the purpose. Hence the focus is given to design and develop effective low capacity solar operated refrigeration system which can considerably improve the quality of living of the remote rural community.

B Experimental layout of CSRS

This CSRS works on the absorption refrigeration system utilising the solar energy. Construction of the CSRS is shown in the Figure 1.1. It contains two vessels connected by tubes. The upper vessel is divided into two compartments by a short wall where the left side compartment a strong solution sprayed over the hot water tubes receiving the heat energy from the solar collector. Strong solution will absorb heat from the hot water; thereby the refrigerant in the strong solution evaporates and will pass over the condenser tubes which are in the right side compartment of the same vessel. The cold water circulated in the condenser coil takes off the heat from the refrigerant vapour for condensing the same.

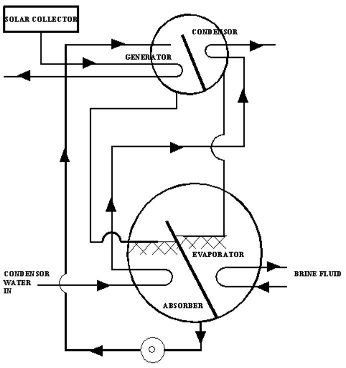

Fig.1.1.*Layout of CSRS*

In the lower vessel the condensed refrigerant will be sprayed on evaporator coils and it takes the heat from the fluid circulated in the evaporator coils and start evaporating and the cooling effect is obtained. The evaporated refrigerant vapour will be absorbed by the absorbent which is available in the next compartment of the same vessel and forms strong solution. In between the upper and lower vessels pumps are used to circulate the fluids. The performance of the CSRS is obtained by evaluating the co-efficient of performance and the cooling effect obtained in the evaporator with respect to the heat supplied to the generator. The power input for the pumps is negligible relative to the heat input at the generator; therefore the working of the pump is often neglected during analysis.

II. DESIGN OF ENERGY MODEL

Design of the energy model includes the system description, proposed load on the system and the details of the conventional vapour compression refrigeration system which is compared for the analysis.

Table.2.2 System Description with consumption and costof energy

		Base case	Proposed
Cooled floor area for building	m²	15	15
Energy efficiency measures			10%
Cooling load for building	W/m²	85	77
Non-weather dependant cooling	%	10%	10%
Total cooling	MWh	9	8
Base load cooling system			
Technology		**Vapour Compression**	**CSRS**
Capacity	kW	1.3	2.5
Cooling delivered	MWh	9.1	8.2
Fuel type		Electricity	Solar Power
Coefficient of performance - seasonal		3.50	0.80
Fuel consumption - annual	MWh	3	1,852
Fuel rate	Rs/kWh	4.500	0.200
Fuel cost	Rs	11,759	370

The climate data in the location is presented in the table 2.1 which is used to estimate the load on the cooling system and the number of cooling degree days per month. The table contains the metrological data like monthly average solar insolation, temperature, humidity and heating degree days and the cooling degree days. Since the location is having good solar potential it is noted that there is no degree heating days ie. no day of the year require space heating. Whereas many number of degree cooling days are required in all the months of a year and is presented.

The following design values are also proposed in the particular location based on the climatical conditions

Latitude	(˚N)	12.9
Longitude	(˚E)	79.1
Elevation	(m)	121
Heating design temperature	(°C)	20.9
Cooling design temperature	(°C)	33.3
Earth temperature amplitude	(°C)	10.4

It was assumed that the energy consumed by the CSRS was negligible since the energy required to run the system was obtained from the solar collector. Power required running the solution circulation pump and the coolant circulation pump were considered and is very minimum as shown in the table 2.2 hence the total cost of running the system is almost negligible while comparing the conventional refrigeration system of same capacity. Apart from the metrological data recorded the following details are proposed the system for the energy and the economic analysis. For the analysis purpose it is approximated that the proposed CSRS is capable of cooling 15 square meters are building. The energy efficiency measure percentage is taken as 10%. It is the percent of the base case cooling load for the building that is reduced as a result of implementing the proposed CSRS end-use energy efficiency measures and in general is assumed in the range of 0 to 25%.

It is further specified that the cooling load on the system for the base case as 85 W/m2 and for the proposed case it is 77 W/m2. The non-weather cooling load which is weather independent cooling load such as computer server room or a refrigerator etc. is fixed as 10% of the total load.

Hence the total load on the base load is estimated as 9 MWh. and that of CSRS is estimated as 8 MWh. Since we have installed comparatively higher capacity CSRS to meet the load requirements.

The performance evaluation on the CSRS indicates the maximum COP that can be achieved is 0.8 and is fixed as the performance of the proposed system and for the conventional system it is fixed as 3.5.accordingly the cooling delivered by the conventional and CSRS is evaluated as 9.1 and 8.2 MWh respectively. The fuel consumption for the conventional system is estimated for a year as 9.1 MWh costs Rs.11759.00 per annum and for CSRS 1852 kg fuel costs Rs.0.2 equivalent to the solar energy recovery.

Table 3.1 Energy and cost recording of Conventional and CSRS

Sl. No.	*Month*	*Average Working Hour*	*Power consumption in Conventional System (kW)*	*Cost (Rs)*	*Power consumption in CSRS(kW)*	*Cost (Rs)*
1	June	180	315	473	6.0	9
2	July	186	326	488	6.2	9
3	Aug.	186	326	488	6.2	9
4	Sep.	180	315	473	6.0	9
5	Oct.	186	326	488	6.2	9
6	Nov.	180	315	473	6.0	9
7	Dec.	186	326	488	6.2	9
8	Jan.	186	326	488	6.2	9
9	Feb.	168	294	441	5.6	8
10	Mar.	186	326	488	6.2	9
11	April	180	315	473	6.0	9
12	May	186	326	488	6.2	9

III. Basic Energy and Economic Analysis

Further to the details provided the cost of the energy consumption is tabulated in the table 3.1 and is analysed. The average working time of the CSRS and corresponding vapour compression system, the energy consumption and the cost analysis also presented. Operating cost for the CSRS was estimated and compared with the conventional cooling. The trend for the experimented year is given in Figure.3.1 and it was noted to be just 2% to 3% of the operating cost of the conventional system.

Table 2.1 Climate data for energy analysis

Month	*Air temp.*	*Relative humidity*	*Daily solar radiation - horizontal*	*Atm. Pre.*	*Wind speed*	*Earth temp.*	*Heating degree-days*	*Cooling degree -days*
	°C	*%*	*kWh/m²/d*	*kPa*	*m/s*	*°C*	*°C-d*	*°C-d*
Jan	24.5	66.7	4.82	99.0	2.2	26.5	0	449
Feb	25.6	62.9	5.72	98.9	2.3	29.0	0	438
Mar	27.0	62.1	6.43	98.8	2.6	31.3	0	528
April	27.7	70.1	6.28	98.6	2.9	31.4	0	532
May	29.1	67.7	5.92	98.3	3.1	31.8	0	591
June	29.1	64.0	5.19	98.2	3.4	30.6	0	574
July	28.7	64.5	4.75	98.3	3.1	30.0	0	579
Aug	28.7	64.1	4.88	98.4	3.0	30.3	0	581
Sep	28.1	68.2	5.11	98.5	2.3	30.0	0	543
Oct	26.4	75.6	4.37	98.7	1.9	27.8	0	509
Nov	25.2	75.0	3.99	98.9	2.1	26.2	0	457
Dec	24.7	69.8	4.16	99.1	2.3	25.7	0	454
Annual	27.1	67.6	5.13	98.6	2.6	29.2	0	6,234

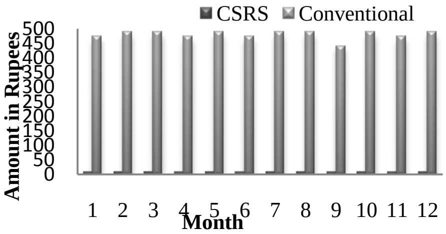

Fig.3.1. *System Operating Cost in a Year*

IV. ENVIRONMENTAL EMISSION ANALYSIS

In India Carbon Dioxide (equivalent) Emissions (in tons) per capita from fuel consumption is 1.18 (tCO2) and it is from all the sources of energy consumption. 25 to 30 % of the emission is by cooling application. Hence it is planned to analyse the GHG emission in this research work.

The emission due to running of the CSRS and the conventional system is estimated and compared. According to the average running of the CSRS and the conventional system , the fuel burnt to produce the required energy for a year of the conventional system was estimated by RETSCREEN analysis as 3.2 tCO2 whereas for the CSRS it was nil. Hence greenhouse gases (GHG) emission reduction by using the CSRS is evaluated as 3.1 tCO2. The GHG emission for the conventional system and the CSRS is presented in the table 4.1.

V ENVIRONMENTAL EMISSION ANALYSIS

The cost invested for the CSRS is Rs. 50000.00 and an additional expense of Rs. 5000.00 put together including fabrication and installation of CSRS and solar collector assembly, storage tank and labour cost etc. Whereas costs of same capacity conventional vapour compression system is Rs. 20,000.00. The financial analysis is made based on the following assumption as given in the table 5.1. The inflation rate in India is 5.0%, the project life of this CSRS is taken as 10 years and dept ratio is 90% since there is no other dept made. The dept term as per the Indian government for the renewable energy sources given as minimum of 20 years but the estimated and spent amount for the project is less. Hence the dept period is fixed as 6 years.

The interest rate for the dept is 7.00% which is normally fixed by the financial institutions as per the guidance of the Department of non-conventional and renewable energy, India. Also this project is eligible to get 30% subsidy since it is supported by the government to encourage the non-renewable energy installations. This project is funded by Arunai Engineering College, Tiruvannamalai as research grant. Further to that this project received a grant of Rs.25000.00 from the Department of non-conventional and renewable energy, Government of Tamilnadu.

Table 5.1 Financial Data

Financial parameters		
Inflation rate	%	5.0%
Project life	yr	10
Debt ratio	%	90%
Debt interest rate	%	7.00%
Debt term	yr	6
Initial costs		
Cooling system	Rs	50,000
Other	Rs	5,000
Total initial costs	Rs	55,000
Incentives and grants	Rs	25,000
Annual costs and debt payments		
O&M (savings) costs	Rs	3,500
Fuel cost - proposed case	Rs	370
Debt payments - 6 yrs	Rs	10,385
Other	Rs	500
Total annual costs	Rs	14,755
Annual savings and income		
Fuel cost - base case	Rs	11,759
GHG reduction income - 7 yrs	Rs	155
Other	Rs	50
Total annual savings and income	Rs	11,963
Financial viability		
Pre-tax IRR - equity	%	positive
Pre-tax IRR - assets	%	2.1%
Simple payback	yr	4.0
Equity payback	yr	Immediate

Table 4.1 Comparison of GHG emission

GHG emission		
Conventional system	(tCO2)	3.2
CSRS	(tCO2)	0.0
Gross annual GHG emission reduction	(tCO2)	3.2
GHG credits transaction fee	(%)	2.0
Net annual GHG emission reduction	tCO2)	3.1
GHG reduction income		
GHG reduction credit rate	(Rs/tCO2)	50.00
GHG reduction credit duration	(Yr)	7
GHG reduction credit escalation rate	(%)	1.5

Apart from that the operation and the maintenance cost for this system fixed as Rs. 3500.00 per year. According to the interest rate and the payment period annual repayment for this system is estimated as Rs.10385.00 which leads to the annual expense on the system is Rs.14755.00.

The other interesting part of the analysis is that comparing the expenses towards the conventional refrigeration system with this CSRS is done. The cost savings by replacing with CSRS to meet the same load is estimated as Rs.11759.00 which is estimated by considering the fuel cost. The cost for the reduction of GHG is assumed as Rs.155.00 and after paying the dept and other expenses the annual savings is estimated as Rs.11963.00 and hence it is considered immediate pay back system.

Since the payback period for this project is started immediately in the starting of the project period because of the grant of Rs.25000.00 received as grant from the government. The cash inflow is getting decreased till sixth as shown in the fig.5.1 since the grant was given once and which is in the first year, even then the cash inflow is positive because the system is saving the money compared with the conventional system. The cumulative cash flow analysis further indicates that the amount saving after sixth year it is linearly increasing and at the end of tenth year the earned cash flow will be Rs.58.000.00.

In the further financial analysis, if the CSRS system is not granted with the financial aid by the government and the full initial investment has been invested by the institution. In such situation the cash inflow will be a negative for the invested money till the repayment period of six year and beyond one year to make it positive that is without incurring any expense and getting gain which is expressed in the Fig.5.2.

The negative cash inflow is increasing till sixth year because of the interest rate for the debt and repayment of the debt; once the repayment is made the cash inflow is turning positive at the end of tenth year the earning will be around Rs.32000.00.

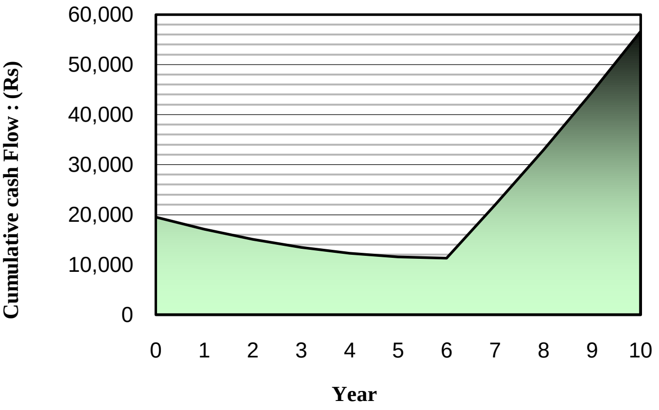

Figure 5.1.Cumulative Cash flow chart with Grant

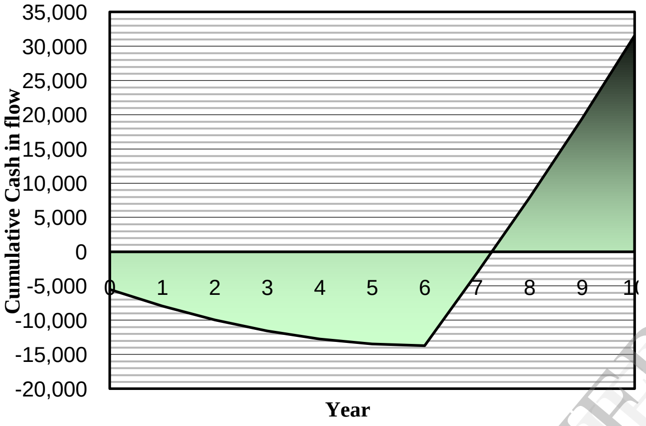

Figure 5.2.Cumulative cash flow chart without grant

VI CONCLUSIONS

From the above analysis it is very clear that the investment cost of the CSRS system is very high compared to the conventional system, and the performance also less comparing to the conventional system from the literature review. CSRS utilise no energy thereby no cost of energy, usage of green energy ie. Solar power and no GHG emission are possible.

It is also concluded that from the cash inflow analysis it is viable to install small capacity solar refrigeration system ie. CSRS.

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