

Conceptual design and performance analysis of a parabolic trough collector supported multi-commodity cold storage

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Abstract. In this paper, a conceptual design of a parabolic trough collector supported multi-commodity cold storage based on LiBr–water absorption system has been proposed to reduce wastage of food grains. The cold storage has been designed to store three high value perishable commodities namely: potato, olive and grapefruit for different months of a calendar year. A thermal model has been developed to predict the performance of the proposed cold storage on an hourly basis. A parabolic trough collector based heating system has also been designed to meet the heat load of the generator during the sunshine hours. To make the system operational in rural areas where grid electricity may not be available, an outline for the power system based on a combination of solar PV and thermal system has been proposed. To provide power backup, an integrated solar hydrogen system has been introduced in the scheme. Finally, the performance of the proposed cold storage has been analysed for representative days of various months of a climatic cycle of Kolkata, India (22.57°N, 88.36°E). The study reinforces the need and viability of utilization of single commodity cold storages for the storage of multi-commodities round the year, powered through solar energy.

1. Introduction

The postharvest loss of food grains is one of the major threats to food security, especially in the poor and developing countries of the world. However; this is a matter of universal concern as roughly one-third of the edible parts of worldwide food production gets wasted annually, which amounts to about 1.3 billion tons [1]. The issue is more vital in the countries like India, where agriculture represents a major part of the economy. The country has the distinction of producing almost all-tropical and exotic fruits as well as vegetables. However; due to the short shelf life of these crops and insufficient storage facility, as much as 30–35% of fruits and vegetables perish every year [2]. Over the past few years, the annual demand of a number of seasonal fruits, vegetables and flowers has increased rapidly. This emphasises upon the need for establishment of more number of cold storages in the nation. At present the country has 6156 number of cold storage facility [3] which is not sufficient at all. Also, the majority of the existing cold storages are dedicated towards storage of a single commodity namely: potato, having a specific reaping and harvesting season. This leads to insufficient utilization of the cold storage facilities during the remaining part of the year. This also may be one of the reasons that for a country like India, the wastage of food is as large as what the whole of the United Kingdom consumes annually [4]. Thus, the development of large number of cold storage is of paramount importance especially in the developing countries of the world. However, this is a cost intensive



solution to the problem. Therefore, the utilization of existing single commodity cold storages for storing various high value perishable commodities round the year is the need of the hour.

At present almost all the cold storages are powered through grid electricity which is not available on reliable and sustainable basis in the remote villages of developing countries like India. Thus the diesel generators are also used as a power backup system, which causes significant environmental pollution. In this context, for powering the cold storages, the solar energy is the one of most attractive and promising option as it is practically inexhaustible, non-polluting in nature and available in any site at free of cost. Also, the plains of Indian subcontinent receive abundant solar radiation almost round the year.

In the recent years, some research and development works have been reported in the field of cold storages. In a recent work, a conceptual design of a grid-interactive SPV/thermal-powered potato cold storage has been presented [1]. A few works have been reported on cold storage supported with flat plate collectors [1, 5]. However; the cold storage powered through parabolic trough collectors is not available in literature. It is also found in literature that for a potato cold storage, even 50 numbers of flat plate collectors along with 165 numbers of solar photovoltaic module of PM-150 (in parallel) are not sufficient to meet the heat load of the generator for a significant part of a calendar year [1]. This emphasis upon the need for the use of concentrating collectors and parabolic trough collectors are one of the best possible options. Some works are also found on combined SPV-PEM fuel cell systems for supplying electricity [6]. However; no work is found that proposes a standalone solar hydrogen system supported multi-commodity cold storage powered through parabolic trough collectors. This is the motivation behind the present work.

In this paper, a novel scheme of a solar hydrogen system supported multi-commodity cold storage based on LiBr-water absorption system has been proposed. Three high value products namely potato, olive and grapefruit have been selected for storage whose compatibility in terms of storage temperature is close to one another, such that the same cold storage facility may be used with minimum modifications. Also, the three products have different harvesting and storage period (as provided in Table 1) which makes them very much suitable for warehousing one after the other. The said strategy can reduce the post-harvest wastage of the food grains to a significant extent. A parabolic trough collector based heating system has been designed to meet the heat load of the generator during sunshine hours. Finally, the year round performance has been analysed to justify the viability of the proposed system.

Table 1. Details of commodities to be stored.

Data	Potato	Olive	Grapefruit
Storage Temperature	8°C [7]	8°C[7]	10°C [7]
Storage Duration	Seven months [7]	Six Weeks [7]	Two months [7]
Harvesting Time	February	September	November
Storage Span	March–September	October–November	December–January
Specific heat	3.67 kJ/kg K [8]	3.76 kJ/kg K [8]	3.96 kJ/kg K [8]
Bulk Density	769 kg/m ³ [9]	657 kg/m ³ [9]	561 kg/m ³ [9]
Heat of respiration	0.018 W/kg [8]	0.064 W/kg [8]	0.0265 W/kg [10]

The schematic of the proposed system is shown in Figure 1. The low pressure water vapor leaving the evaporator at state point 10 is readily absorbed in the absorber as it comes in contact with the weak solution of LiBr–H₂O. The absorber is cooled by using a cooling fan which releases the latent heat and maintains a constant temperature. The strong solution leaving the absorber at state point 1 is pumped to the generator where heat is supplied from PTC based heating system. The water vapor fraction goes off from the solution at high pressure at state point 7, while the weak solution leaves the generator at state point 4 and returns back to the absorber through a pressure reducing valve. The water vapor at high pressure gets condensed to water in the condenser releasing the latent heat of condensation. Thereafter, high pressure water expands from state point 8–9 to very low pressure and finally evaporates in the evaporator during the process 9–10 by taking the latent heat of evaporation from the cold storage unit. The mass flow rate of the refrigerant is adjusted such that the desired cold storage temperature is maintained. A small portion of the refrigerant leaves the evaporator as liquid spill-over at state point 11. A heat exchanger has been provided to preheat the strong solution and to pre-cool the weak solution.

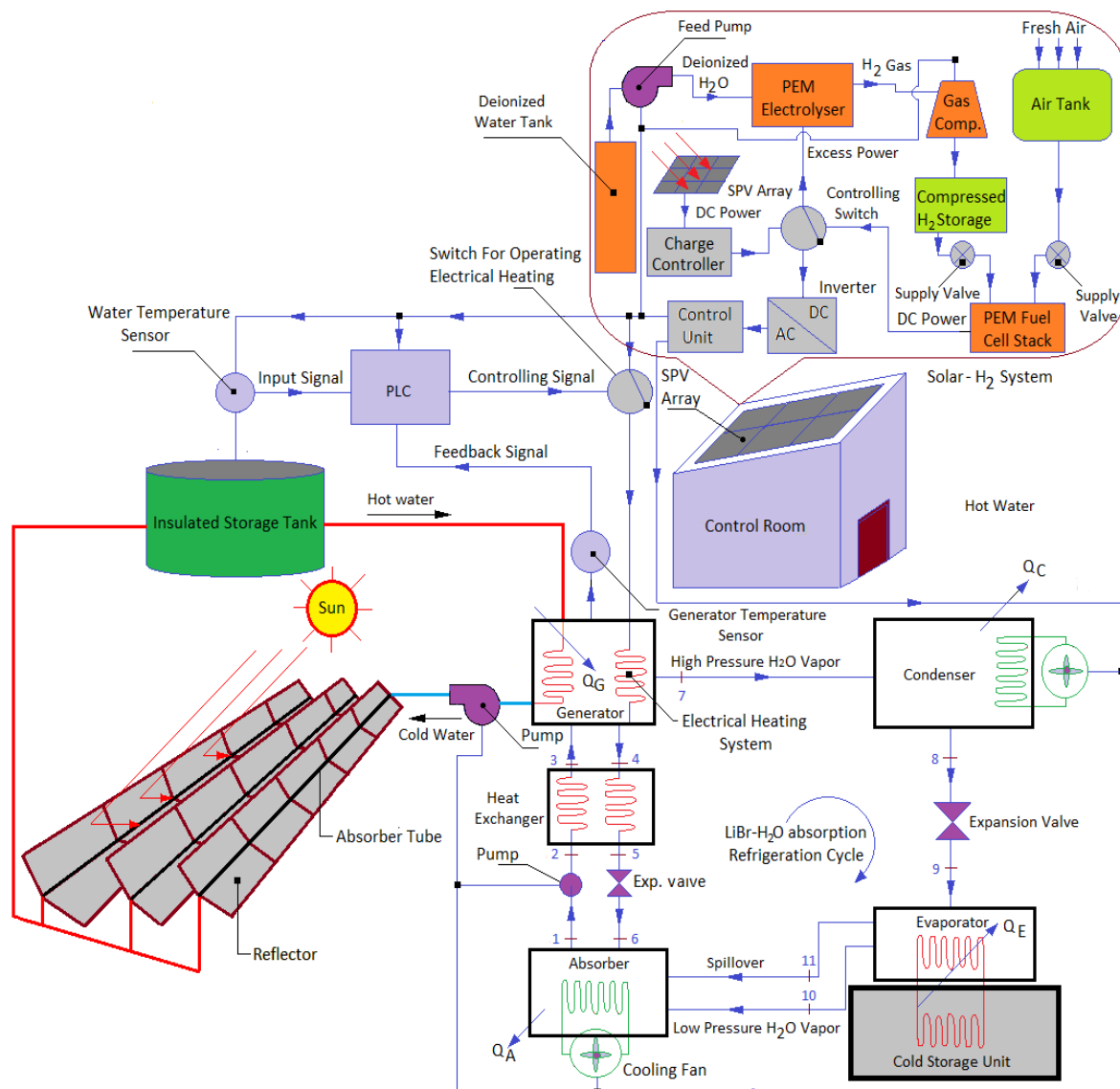


Figure 1. Scheme of the proposed standalone multi-commodity cold storage

A parabolic trough collector based heating system has been used to track the solar energy for heating the water. The hot water, thus produced, is stored in an insulated storage tank and the same is re-circulated using a pump across the generator continuously to maintain a constant generator temperature of 90°C. An auxiliary electrical heating system has also been included for supplying heat to the working fluid in the generator if the hot water fails to meet the required temperature alone in the adverse weather conditions. For operating the electrical heating system an electronic control system consists of a programmable logic controller (PLC), two temperature sensors and a controlling switch has been proposed (as shown in Figure 1). To operate the cold storage in a stand-alone fashion, a solar photovoltaic array along with solar hydrogen based backup system has been used. An inverter has been used to convert the DC power generated by the solar photovoltaic array during the sunshine hours to AC power to meet the in-house requirements. After meeting the demand, the excess power is utilized to generate hydrogen gas in the electrolyser bank. The hydrogen gas thus produced is compressed using a gas compressor which is supplied to the PEM fuel cell stack to produce electricity during the energy deficit hours on a sustainable basis.

2. Thermal Model Development

2.1. Thermal modeling of the cold storage

Total cooling load of the cold storage consist of several components such as: structural, infiltration, product, human occupancy and equipment load as shown in the Figure 1 and can be estimated as [1]:

$$\dot{Q}_{total} = \dot{Q}_{str} + \dot{Q}_{inf} + \dot{Q}_{prod} + \dot{Q}_{man} + \dot{Q}_{equip} \quad (1)$$

In Eq. (1), the structural load is the load due to heat gain through building envelope and can be given by [1]:

$$\dot{Q}_{str} = \dot{Q}_{wall} + \dot{Q}_{roof} + \dot{Q}_{floor} + \dot{Q}_{door} \quad (2)$$

The infiltration load can be expressed as:

$$\dot{Q}_{inf} = \dot{V}_{air} \rho_{air} c_{p_{air}} (T_{ambient} - T_{storage}) \quad (3)$$

The product load can be given by:

$$\dot{Q}_{prod} = \frac{\dot{m}_{prod} c_p [T_{initial} - T_{store}]}{24 \times 3600} + \frac{M_{prod} H_{resp}}{1000} \quad (4)$$

Where \dot{m}_{prod} and H_{resp} denote the rate of product loading and heat of respiration respectively. It is assumed that the three commodities are loaded into the cold storage at a uniform rate over the period of 20 days.

The human occupancy load in kW can be expressed as [1]:

$$\dot{Q}_{man} = \frac{N_p \dot{Q}_{avg} \left[\frac{t}{24} \right]}{1000} \quad (5)$$

Here ' N_p ' represents the number of persons present in the cold storage for t hours in a day.

The heat added to the cold storage space by the electrical appliances can be given by:

$$\dot{Q}_{equip} = \frac{1.25 W_{total}}{1000} \quad (6)$$

Where W_{total} represents the total wattage of the electrical appliances.

A safety factor of 10% is considered on the final value to encounter for the unpredicted leakages and inaccuracies. Hence, the net cooling load or the evaporator load can be given by:

$$\dot{Q}_E = 1.1 \dot{Q}_{total} \quad (7)$$

2.2. Thermal modeling of VAR system

The evaporator load can be estimated from the energy balance as [11]:

$$\dot{Q}_E = \dot{m}_{10}h_{10} + \dot{m}_{11}h_{11} - \dot{m}_9h_9 \quad (8)$$

The power consumed by the solution pump can be estimated as:

$$\dot{W}_P = \frac{\dot{m}_1}{\eta_P} \int_{P_1}^{P_2} v dp = \dot{m}_1 (h_2 - h_1) \quad (9)$$

The energy balance across the absorber can be expressed as [11]:

$$\dot{Q}_A = \dot{m}_{10}h_{10} + \dot{m}_{11}h_{11} + \dot{m}_6h_6 - \dot{m}_1h_1 \quad (10)$$

The generator load can be obtained from the energy balance across the generator as [11]:

$$\dot{Q}_G = \dot{m}_4h_4 + \dot{m}_7h_7 - \dot{m}_3h_3 \quad (11)$$

The heat releases by the condenser or condenser load can be presented as [11]:

$$\dot{Q}_C = \dot{m}_7(h_7 - h_8) \quad (12)$$

The enthalpy at all the state points of vapor absorption refrigeration system are estimated from the curve fit [11].

The total power consumed by the cooling fans can be estimated as:

$$\dot{W}_F = \frac{N_F \dot{V}_{air} \Delta P_{fan}}{\eta_{fan}} \quad (13)$$

Where the efficiency of the fan (η_{fan}) is assumed to be 80% in the present work.

Finally, the COP of the system can be expressed as [1]:

$$COP = \frac{\dot{Q}_E}{\dot{Q}_G + \dot{W}_P + \dot{W}_F} \quad (14)$$

For analysing the performance of the proposed cold storage, the values of some design parameters are taken from literature [1, 11].

2.3. Design of parabolic trough collector based heating system

The design parameters of parabolic trough collectors and their values are detailed in Table 2 where, the aperture width (W), focal length (f), concentration ratio (C), aperture area (A_a) and absorber tube area (A_r) of the PTC modules have been estimated based on the assumed parameters, using the relations available in literature [12].

Table 2. Design parameters of parabolic trough collectors

Assumed Parameter	Values	Estimated Parameter	Values
D_i	0.04m	W	1.5m
D_o	0.05m	C	9.23
D_{ci}	0.08m	f	0.375m
D_{co}	0.085m	A_r	0.628m ²
D	1.5m	A_a	5.8 m ²
L	4m		
ϕ_r	90 ⁰		
ε_c	0.87		
ε_a	0.92		

2.4. Thermal model of parabolic trough collectors

The rate of useful heat gain by each parabolic trough collector can be given by [13]:

$$\dot{Q}_u = \dot{m}c_p (T_{fo} - T_{fi}) \quad (15)$$

The rate of useful heat gain can also be expressed as [13]:

$$\dot{Q}_u = F_R [SA_a - A_r U_l (T_{fi} - T_a)] \quad (16)$$

Where the collector heat removal factor (F_R) can be presented as [13]

$$F_R = \frac{\dot{m}c_p}{A_r U_l} \left[1 - \exp \left(- \frac{F' A_r U_l}{\dot{m}c_p} \right) \right] \quad (17)$$

Number of parabolic trough collectors required to meet the generator load of the proposed cold storage can be estimated as:

$$N_C = \frac{\dot{Q}_G}{\dot{Q}_u} \quad (18)$$

3. Results and Discussions

A computer program in MATLAB-R2017a has been developed based on the thermal model discussed in the previous section. The program takes hourly values of climate data for the chosen location (Kolkata, India), data related to the product to be stored along with the value of some design parameters of the system as inputs and estimates the cooling load, generator load, absorber load, the

load on the condenser, power consumed by the solution pump, cooling fan and the system COP on an hourly basis. Program also calculates the rate of useful heat gain by each parabolic trough collectors and number of collectors required to meet the heat load of the generator during the sunshine hours.

3.1. Performance analysis

Figure 2 represents the hourly variation of cooling load of the proposed cold storage for representative days of various months of a full climatic cycle for the city of Kolkata, located in India. As evident from the figure and as usually expected that the cooling load of the cold storage is found to be minimum in the early morning around 5:00 hours for all the months of the year, while the same is maximum in the afternoon between 12:00 Noon to 14:00 hours. Thus, the variation of cooling load is found to be very similar to that of the hourly variation in ambient temperature. This is due to the fact that the product load, structural load and the load due to infiltration vary directly with the ambient temperature and thus the total cooling load also follows a similar trend. It is also found that the hourly values of cooling load is maximum in the month of October and it is significantly higher compared to that of the month of May, although the ambient temperature and humidity are relatively higher in May. The possible reason for such variation of cooling load is due to the fact that the product load which is the major contributor to the total cooling load comprises of product sensible load and the heat of respiration. The product sensible load exists only in the month of product loading, while the heat of respiration exists during the entire storage span. As in the present work, three different commodities (potato, olive and grapefruit) have been considered; hence the product load exists at their peak during their respective period of product loading that is March, October and December respectively.

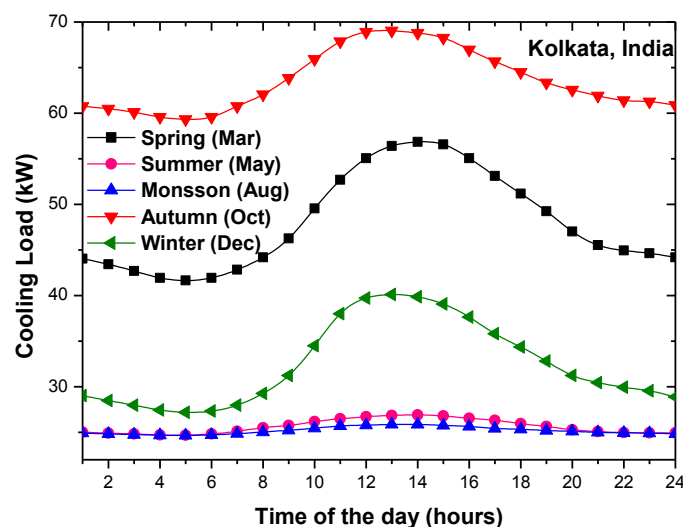


Figure 2. Hourly variation of cooling load for various seasons of a full climatic cycle

Figure 3 represents the monthly variation of various cold storage loads on a daily average basis. It is observed that the value of daily average cooling load is 48 kW in the month of March then it decreases and reaches to about 26 kW. The cooling load then remains almost constant during the period of April to September. The cooling load is found to be minimum in the month of August while it reaches at its peak in October with an increase of almost 175% and then it decreases again. The possible reason for this variation is mainly due to the contribution of product load in the total cooling load which is much higher for olive compared to that of grapefruit and potato. The product load for olive is significantly higher owing to the heat of respiration, which is almost 3.5 times and 2.5 times

higher compared to that of potato and grapefruit respectively (as evident from Table 1) and also due to the contribution of the product sensible load, which exists in the month of October only for olive as stated earlier. The figure also indicates that the generator and condenser load follow a trend similar to that of cooling load. This is due to the fact that the load on the generator and condenser varies proportionally with cooling load.

The capacity of the cold storage has been estimated to be 20 tonnes of refrigeration (TR) corresponding to the maximum cooling load, which has been obtained in the month of October during the storage of olive. Hence the 20 TR capacity cold storage can store all the three commodities safely.

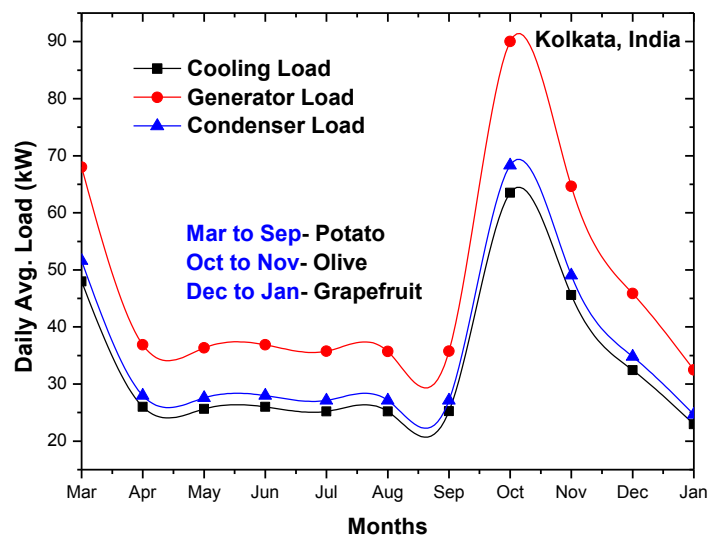


Figure 3. Monthly variation of daily average cold storage loads

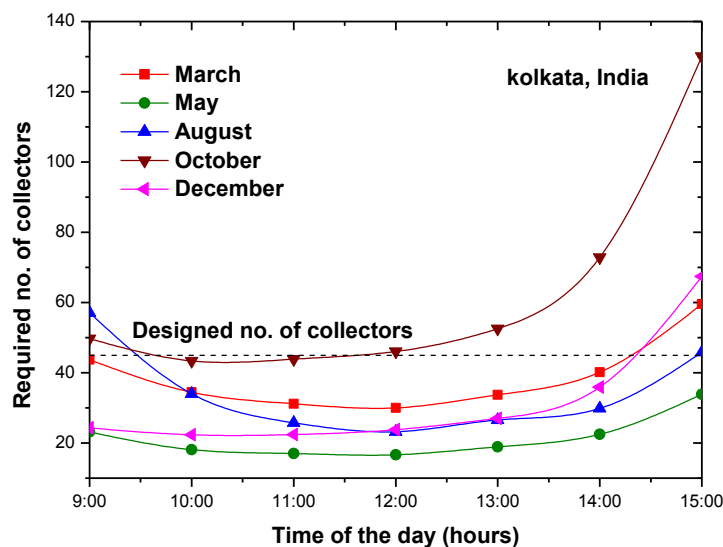


Figure 4. Number of parabolic trough collectors required for powering the cold storage

Figure 4 shows the number of collectors required to meet the generator load of the proposed cold storage. It is evident from the figure and as expected that the required number of collectors is high in early morning and late afternoon owing to low intensity of radiation. The required number of collectors is 130 at 15:00 hours in the month of October, which is maximum among all the months. However; from economic point of view the number of collectors for the proposed system is set to be 45, which is sufficient to meet the generator load of the cold storage for most of the months of a calendar year, while, the shortfall of heat for a few hours in the early morning and late afternoon and also during the off sunshine hours for all the months are designed to be met through a combination of thermal energy storage and electrical heating. The figure also indicates that the required number of collectors is found to be maximum in the month of October, though the number of collector is expected to be maximum in August as the intensity of beam radiation is usually low in this month. The possible reason for this variation is due to the fact that the generator load is relatively higher in October when the cold storage is loaded with olive. The required number of collectors is found to be minimum in the month of May owing to high intensity of beam radiation and lower generator load as well.

4. Conclusions

The following points are revealed from the present study:

- 1 The value of daily average cooling load is minimum in the month of August, while it reaches at its peak in the month of October during the loading of Olive with an increase of almost 175%.
- 2 The capacity of the cold storage is estimated to be 20 TR corresponding to the maximum cooling load, which is obtained during the loading of olive.
- 3 The required number of PTC is designed to be 45, which can meet the generator load of the cold storage satisfactorily during sunshine hours for most of the months of a calendar year.
- 4 The study reinforces the need and viability of utilization of single commodity cold storages for the storage of multi commodities, powered through solar energy.

5. References

- [1] Basu D N and Ganguly A 2016 Solar thermal–photovoltaic powered potato cold storage–Conceptual design and performance analyses, *Applied Energy*.**165**,308-317
- [2] http://www.dsir.gov.in/reports/ittp_tedo/agro/AF_Farm_Fruits_Vegetables_Intro.pdf
- [3] <http://www.novonous.com/publications/cold-storage-market-india-2015-2020>
- [4] <http://thecsrjournal.in/food-wastage-in-india-a-serious-concern/>
- [5] Sethu M R, Kumar A and Yardi N R 1986 Design, Installation & Performance Of A 10 Tr Solar Powered Cold Storage In India, *Intersol Eighty Five* ,1013-1017
- [6] Ozden E and Tari I 2016. Energy–exergy and economic analyses of a hybrid solar–hydrogen renewable energy system in Ankara Turkey, *Applied Thermal Engineering*. **99**,169-78
- [7] http://ftp.demec.ufpr.br/disciplinas/TM140/PROJETO_REFRIGERACAO/Material%20de%20estudo/COMMODITY%20STORAGE%20REQUIREMENTS%20_R02_10SI.pdf
- [8] <https://www.researchgate.net/file.PostFileLoader.html?id=57dc0df6dc332d6c7a2b0e94&assetKey=AS%3A406964417908742%401474039286881>
- [9] <http://go.key.net/rs/key/images/Bulk%20Density%20Averages%20100630.pdf>
- [10] Arora CP 2012 *Refrigeration and air conditioning*, 3rd edition, New Delhi: McGraw-Hill Education Private Limited
- [11] Florides G A, Kalogirou S A, Tassou S A and Wrobel L C 2003 Design and construction of a LiBr–water absorption machine, *Energy Conversion and Management*.**44**, 2483-2508

- [12] Sukhatme SP 2010 *Solar Energy*, 4th edition (Chennai: McGraw-Hill Education Private Limited) , 245-247
- [13] Kizilkan O , Kabul A and Dincer I , 2016 Development and performance assessment of a parabolic trough solar collector-based integrated system for an ice-cream factory, *Energy*. **100**, 167-176.