Integration of solar charged PCM storage with VAR system for low capacity vegetable cold storage

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Abstract. In this work a solar-assisted vapour absorption refrigeration (VAR) system, suitable for 10 MT vegetable cold storage for a small village, has been modelled and analysed for day-night operation. Solar parabolic trough collector (PTC) has been considered for integration with a LiBr-H$_2$O based VAR system. Thermal energy from solar thermal system is stored in a phase change material (PCM) energy storage, which is integrated with the VAR system. Apart from system integration, operational strategy of the storage based system has been evolved and performance of the system on hourly basis for representative days has been reported. The PCM quantity and the number of PTC modules have been decided based on the cooling demand. Hitec salt has been considered as PCM material. The study reveals that 5 PTC modules, each of 30 m$^2$ aperture area, and a PCM mass of 12.5 ton can effectively cater the energy demand of the VAR system to successfully maintain the 10 MT cold room at 6 °C.

1. Introduction

The solar power falling on earth is approximately $1.8 \times 10^{11}$ MW which is many thousand times higher than the present energy demand (109,136 TWh in 2015) of the whole world [1, 2]. Solar collectors are one of the promising technologies to harness this potential of solar energy. Parabolic trough collectors (PTC) are concentrating solar collectors that are popular for low-to-medium temperature applications in the range of 65 °C to 177 °C [3]. Absorption refrigeration systems are driven by heat and can be efficiently integrated with solar thermal systems. Solar insolation is available only for a limited period of a day. Therefore, running an absorption system for 24 hours by solar energy is not possible without any provision of energy storage. In this context, phase change materials (PCM) can play a pivotal role to store the solar energy.

Some of the researchers studied various PCMs as potential energy storage medium having different melting temperature ranges. Cunha et al. [4] studied the suitability of different PCMs in different temperature ranges. They found that organic compounds and salt hydrates seem to be more promising below 100 °C, eutectic mixtures with urea seem to be promising around 100 °C and eutectic mixtures of inorganic salts appear most suitable in the range from 130 °C up to 1250 °C. Ibrahim et al. [5] studied the operational and performance characteristics of a solar driven lithium bromide-water absorption chiller integrated with absorption energy storage of the same working fluid. They found the cooling COP of the integrated system during cooling/charging and discharging to be 0.69 and the energy storage density of the absorption energy storage to be 119.6 kWh/m$^3$. Keniserin et al. [6] have discussed practically all available original experimental data on the phase change diagram of salt-water systems,
melting temperatures, heat of fusion, specific heat, density, thermal conductivity, and thermal diffusivity in solid and liquid states and viscosity in the liquid state for 18 salt hydrates.

Solar driven absorption systems are already developed but integration of solar charged phase change material for day night operation of absorption system has apparently not been undertaken. In this study integration of PTC modules and PCM storage with absorption system has been rendered for day-night cycle operation. A 10 MT capacity cold room has been considered to be maintained at 6 °C by the evaporator of absorption unit. Therminol is used in the PTC to collect and store the solar thermal energy, and also used to charge the PCM storage. The operational strategy of the developed system has been discussed in this study. The required PCM mass and PTC area have been decided based on the cooling demand. The hourly analysis of solar collector with solar insolation during the sunshine hours has been done to calculate the useful heat gain. Hourly analysis of therminol storage tank and PCM storage system have been done to study the temperature profile for 24 hours of a working day. The detailed performance analysis of the system has been studied.

2. System description
The schematic diagram of solar absorption refrigeration system (LiBr-H2O) with solar charged PCM energy storage is shown in Figure 1. There are two cycles in this system, first one is collection cycle, in which solar energy is collected and stored in PCM storage tank and second one is the supply cycle, where heat is supplied from the PCM tank to the generator of VAR. In collection cycle therminol VP1 from therminol storage tank (1) is pumped through the parabolic trough collector where it absorbs solar thermal energy (3) and again returns to the therminol tank. The thermal energy from the therminol tank is supplied (4) to the PCM storage tank to charge the PCM. The temperature of PCM increases up to the melting temperature and then the PCM melts taking the latent heat of fusion. As the PCM temperature reaches 10 °C above the melting temperature, PCM tank starts supplying heat to the VAR generator (GEN). In generator the water evaporates from the solution of LiBr-H2O and the steam (12) goes to the condenser (CON) where it gets condensed. The liquid water(13) coming from the condenser is throttled in an expansion valve (REV) and its pressure decreases. At this pressure the refrigerant (14) passes through the evaporator (EVP) and evaporates absorbing the latent heat of evaporation. After evaporation the water vapour (15) flows to the absorber where it is absorbed by the LiBr solution. The weak LiBr-H2O solution (16) is pumped to the VAR generator through the solution heat exchanger (SHX). The water evaporates in the generator and the remaining strong solution of LiBr (19) returns backs to absorber while exchanging heat with weak solution in the solution heat exchanger.

![Figure 1. Vapour absorption refrigeration system powered by solar charged PCM storage](image-url)
3. Model development
The basic thermodynamic model of the VAR system, parabolic trough collector and PCM energy storage unit have been developed and integrated for the study.

3.1 VAR system
The first law model of LiBr-H₂O based absorption system has been developed. The water as refrigerant is absorbed and liberated from the absorbent (LiBr). The operating temperature of condenser, generator and evaporator of the VAR system are maintained at 40 °C, 85 °C and 6 °C, respectively [7]. The mass fraction of strong solution and weak solution are considered as 0.6 and 0.55, respectively. The motor efficiency of the VAR solution pump and the effectiveness of the solution heat exchanger are considered as 90% and 75%, respectively [8, 9].

3.2 Parabolic trough collector
The following input parameters are assumed to develop the model of PTC as shown in Table 1 [10].

| Parameters                               | Value   | Unit             |
|------------------------------------------|---------|------------------|
| Absorber tube length                     | 10      | m                |
| Aperture width                           | 3       | m                |
| Focal distance of reflecting surface     | 0.8     | m                |
| Cover to absorber spacing                | 0.023   | m                |
| Rim angle                                | 13      | °                |
| Specific tube flow rate                  | 0.03    | kg/sec per m² of aperture area |
| Cover emittance                          | 0.88    | -                |
| Absorber emittance                       | 0.1     | -                |
| Trough reflectance                       | 0.9     | -                |
| Receiver absorbance                      | 0.95    | -                |
| Cover transmittance                      | 0.85    | -                |
| Incidence angle modifier                 | 1       | -                |
| Ambient pressure                         | 101.325 | kPa              |

It is necessary to calculate the optical efficiency of the PTC for the calculation of useful heat gain. The optical efficiency for the PTC can be calculated as

\[ \eta_0 = \rho \tau \alpha \gamma K \]  

(1)

where \( \rho \) is concentrator reflectance, \( \tau \) cover transmittance, \( \alpha \) is absorber absorbance and \( \gamma \) known as intercept factor, is defined as the fraction of reflected radiation in the absorber to the total reflected radiation.

In PTC, the inner absorber tube and the outer glass cover are separated by vacuum for reducing the convection heat losses between the absorber and the glass cover. The following assumptions were made for PTC:

1. The heat transfer fluid is incompressible.
2. The conduction thermal losses have not been taken into consideration.
3. The parabolic shape of the concentrator is symmetrical.
4. The solar flux is uniform in the absorber.
5. The ambient temperature close to the concentrator is uniform.
6. The effect of shadow among the PTC modules is negligible.

The solar radiation data for the month of June is assumed to be constant as there is very small variation in solar radiation intensity and ambient temperature.
The useful heat gain from the collector can be obtained from the following two equations:

\[ Q_u = I_b \eta_b A_{ap} - A_r U_L (T_r - T_a) \]  
\[ Q_u = F_R \{ I_b \eta_b A_{ap} - A_r U_L (T_r - T_a) \} \]

where \( I_b \) is intensity of beam radiation, \( A_{ap} \) is aperture area, \( A_r \) is receiver area, \( U_L \) is thermal loss coefficient, \( T_r \) is mean temperature of the receiver and \( T_a \) is ambient temperature.

The useful heat gain can be written also

\[ Q_u = \frac{m_c c_p}{A_r U_L} \left[ 1 - \exp \left( \frac{-A_r U_L F'}{m_c c_p} \right) \right] \]

where \( m_c \) is mass flow rate of therminol through the collector, \( c_p \) is specific heat of therminol and \( F' \) is the collector efficiency factor which is given by

\[ F' = \frac{1}{U_L} \left( \frac{1}{U_L} + \frac{D_{ro}}{h_{fi} D_{ri}} + \frac{D_{ro}}{2 K_m} \ln \frac{D_{ro}}{D_{ri}} \right) \]

where \( h_{fi} \) is the heat transfer coefficient inside receiver tube, \( D_{ri} \) is the inner diameter of receiver tube and \( K_m \) is the thermal conductivity of the receiver tube material.

The mean temperature of therminol in the receiver can be calculated as

\[ T_r = T_i + \frac{Q_u}{A_r U_L F_R} (1 - F_R) \]

where \( U_L \) is heat loss coefficient which can be written as

\[ U_L = \frac{1}{\left( h_{ca} + h_{rcam} \right) A_c + h_{rec}} \]

where \( h_{rcam} \) is convection heat transfer coefficient between cover and air, \( h_{rcam} \) is radiation coefficient between cover and sky, \( h_{rec} \) is radiation coefficient between receiver and cover and \( A_c \) is area of cover.

The radiation coefficient between receiver and cover can be given as

\[ h_{rec} = \frac{\sigma (T_r^2 + T_c^2) (T_r + T_c)}{1 + \frac{1}{\varepsilon_r - 1} \frac{A_r}{A_c}} \]

where \( \sigma \) is Stefan Boltzmann constant, \( T_r \) is the temperature of the glass cover, \( \varepsilon_r \) is emissivity of receiver and \( \varepsilon_c \) is emissivity of glass cover.

The radiation coefficient between the cover and the sky can be given as

\[ h_{rcam} = \varepsilon_c \sigma (T_c^2 + T_{sky}^2) (T_c + T_{sky}) \]

where \( T_{sky} \) is the sky temperature which is assumed to be 6 °C less than the ambient temperature.
The convection coefficient for the therminol inside the tube \((h_{fi})\) is calculated by the heat transfer theory. It is considered that the flow inside the receiver tube is turbulent \((Re > 2300)\). Therefore, the Nusselt number is calculated by using the Dittus-Boelter equation.

\[
Nu = 0.023 \, Re^{0.8} \, Pr^{0.4}
\]  

(10)

where \(Re\) is Reynolds number and \(Pr\) is Prandtl number inside the tube.

In case of PTC, only beam radiation component is used because these collectors are imaging collectors with a specific image of sun in the receiver. The thermal efficiency of the collector is defined as

\[
\eta = \frac{Q_o}{I_o \, A_{ap}}
\]  

(11)

The specific mass flow rate of therminol in the collector can be determined as

\[
m_a = \frac{m_c}{A_{ap}}
\]  

(12)

The temperature of the therminol at the outlet of the collector can be obtained by

\[
Q_o = m_c c_p (T_o - T_i)
\]  

(13)

where \(T_o\) is outlet temperature of therminol from PTC.

### 3.3 PCM storage

The PCM chosen for this system is Hitec salt \((53\% \text{ KNO}_3 + 6\% \text{ NaNO}_3 + 41\% \text{ NaNO}_2)\). The thermophysical properties of the Hitec salt are shown in Table 2 [4]. The PCM mass has been decided on the basis of total cooling load for 24 hours of operation in a working day, assuming that 75% of heat transfer efficiency in both thermal energy storing and releasing. It has been considered that liquid mass fraction of PCM will not drop below 0.5 during its operation and maximum temperature of PCM will not rise above 152 °C during thermal charging.

| Property                  | Value | Unit |
|---------------------------|-------|------|
| Melting temperature       | 142   | °C   |
| Latent heat of fusion     | 110   | kJ/kg |
| Solid state specific heat | 1.17  | kJ/kg-K |
| Liquid state specific heat| 1.73  | kJ/kg-K |
| Density                   | 2006  | Kg/m³ |

The energy balance equation for PCM is as follows

\[
m_{pcm} (L + c_l \Delta T) = (Q_{input} - Q_{load} - Q_{loss}) \Delta t
\]  

(14)

where \(m_{pcm}\) is the mass of PCM, \(L\) is the latent heat of fusion of PCM, \(c_l\) is the specific heat at liquid state of PCM, \(\Delta T\) is the liquid state temperature, \(\Delta t\) is the time interval, \(Q_{input}\) is the heat supplied to the PCM storage unit, \(Q_{load}\) is the heat supplied from the PCM tank to the VAR system and \(Q_{loss}\) is the heat loss to the environment from the PCM tank.

Solid state sensible heating has not been considered in above equation as the liquid state mass fraction doesn’t drop below 0.5 in working cycle. It has been assumed that the specific heat of PCM does not change with temperature.
4. Operation strategy
In starting condition the therminol tank and the PCM tank both are considered to be at ambient temperature. First the therminol temperature is raised to 440 K by collecting the solar energy and there is no heat supply to the PCM tank during this warm up period of therminol tank. As 440 K temperature is reached in therminol tank, heat is supplied to the PCM storage to raise the temperature of PCM up to 425 K. During this charging time of PCM, the PCM storage unit is disconnected with the VAR system. As the PCM storage completely charged i.e. attains 425 K temperature, VAR generator starts taking heat from PCM storage.

5. Result and discussion
PCM storage system reaches the desired temperature of 425 K and then it is connected with the VAR system to supply heat at the required generator temperature. Five number of PTC modules have been decided based on the cooling demand and the capacity of PCM storage unit. As discussed in operation strategy it takes around 79 hours to reach PCM storage at supply condition with total 150 m² of PTC area. This time can be reduced by providing an auxiliary heating of 3214.625 MJ to the PCM tank. The working day analysis of this system has been shown in Table 3.

The variation of solar insolation (beam radiation) and change of ambient temperature with time in a day (June 15, Kolkata, India, 22.5726° N, 88.3639° E) are shown in Figure 2. The solar insolation is available between 5 am to 5 pm and the peak insolation is available at about 12 pm.

![Figure 2. Variation of beam radiation intensity and ambient temperature with hours in a day of June](image)

The thermal energy loss from therminol tank and from PCM tank with time in working hours are shown in Figure 3. The minimum heat losses from therminol tank and from PCM tank are observed at 1:00 pm and 12:00 pm, respectively.

The variation of PCM temperature and the PCM liquid mass fraction with time in working hours is shown in Figure 4. As the heat supply to VAR generator starts, the PCM starts cooling sensibly and its temperature reaches to melting temperature at 11:32 pm and then phase change starts and at constant temperature the liquid mass fraction of PCM decreases up to 0.804 at 8:00 am. After that with increase of solar insolation, the liquid mass fraction starts increasing and completely melts at 12:42 pm (X = 1). Then liquid state sensible heating starts and reaches to desire 425 K temperature at 2:56 pm.

The hourly variation of cooling load of 10 MT cold storage unit has been shown in Figure 5. The peak demand (about 7.3 kW) of cooling on VAR system is at 1:00 pm and this load is minimum (about 4 kW) at 5:00 am. The total load of the VAR system has been estimated as 122 kWh [11, 12].
Figure 3. Heat loss from therminol tank and PCM tank in a working day
6. Conclusions
In this study a LiBr-H₂O based VAR system has been integrated with PTC through a PCM based thermal energy storage system for 24 hours of operation. A 10 MT capacity cold room has been considered to maintain at 6 °C temperature for the application of rural small scale vegetable cold storage. Therminol is used in the PTC to collect and store the solar thermal energy. Solar charged PCM storage has been considered for day-night operation of the VAR system. Hitec salt has been decided as PCM material. Based on the cooling demand, the required PCM mass of 12.5 ton and five PTC modules of total area 150 m² have been calculated. It has been observed that using this PCM storage, a 10 MT cold room can be successfully maintained at 6 °C temperature for 24 hours.

7. References
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