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Thermal Model Development and Performance Optimization of a Solar-assisted Absorption-based Cold Storage Using the Genetic Algorithm

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Abstract

This paper presents a scheme of a solar-powered single-effect vapor absorption cooling system for a potato cold storage application. The cold storage works on Lithium Bromide-Water (LiBr-H_2O) based vapor absorption refrigeration system, where water is the refrigerant and Li-Br acts as the absorbent. A computer code using MATLAB R2022a software is developed based on the proposed mathematical model, and the system's performance is analyzed considering the climatic condition of Kolkata, India. The cold storage's cooling load is estimated to be 68.16 kW (≈20 TR), with the evaporator temperature set at 8 °C. The impact of various parameters on the system performance is studied. Finally, the process parameters are optimized for useful heat gain from flat plate collectors with a genetic algorithm. The strong and weak solution concentrations for best performance are 55% and 52%, respectively. Also, the generator outlet temperatures between 85 to 90 °C are identified as the best for the system's operation.

Keywords

Cold storage, Genetic algorithm, Optimization, VAR, Solar energy

Introduction

Solar, wind, ocean, and geothermal energy are considered clean, environmentally friendly, and virtually limitless energy sources [1]. These resources can meet rising energy demand and also lower pollution levels. The energy usage for space cooling has increased over the years due to climate change and urbanization. Loss of food grains after the harvest is considered to be the most severe threat to global food security, particularly in developing countries like India [2]. According to recent data, India has 8186 cold storages with a total capacity of 374.25 Lakh MT for storing short-lived horticulture products such as fruits and vegetables [2]. Every year, India generates around 400 million MT of perishables (horticultural produce). In India, perishables waste rates range from 4.6 to 15.9% for fruits and vegetables [2]. The estimated yearly value of agricultural production losses is 92,651 crores [2]. Losses in fruits and vegetables are anticipated to be annually valued 50,473 crores [2]. To reduce perishables and supply chain losses, adequate and effective cold chain infrastructures from local farms to the customer are necessary. The Potato production in India was estimated to be 38.30 lakh tons in 2021-22 against 39.13 lakh tons in 2020-21 [2]. Domestic demand for potatoes in India has gradually increased over the last few decades. Potatoes occupied approximately 21.58 lakh hectares in 2019-20, and cultivation was approximately 51.30 MT, compared to 21.73 lakh ha-area and 50.19 MT cultivation in 2018-19 [2]. The potato industry's waste is estimated to be around 12 - 20% of its total production [2]. So, developing cold storage for potatoes is the need of the hour.

Florides et al. [1] observed that solar-assisted vapor absorption is a propitious alternative to the vapor compression system for a cold storage utility. Basu and Ganguly [3] proposed a theoretical design for potato cold storage with the help of solar thermal and photovoltaic systems. They found that 165 photovoltaic modules running in parallel alongside fifty flat plate collectors can adequately power the cold storage yearly. Said et al. [4] reviewed the development of various alternative designs of solar-powered VARS for Saudi Arabia's weather conditions. Abid et al. [8] observed that the most common solar collectors used for absorption-based systems are the flat plate collectors and evacuated tube collectors, which could be used to obtain higher temperatures performing best in cloudy and cold conditions. Ketjoy et al. [5] investigated the performance of a LiBr-H_2O cooling system with a 35 kW refrigeration capacity. The average daily COP (coefficient of performance) for the solar absorption system is found to be 0.33, with a collector area ratio of 2.05 square meters for each kilowatt of refrigerated space. A brief literature review thus reveals that solar energy-based VAR systems can be designed and implemented for cold storage applications. However, rudimentary work has been done to optimize the process parameters of a VAR system for potato storage concerning useful heat gain through flat plate collectors. Thus, in this paper, a solar energy-based VAR system is designed, and its performance parameters are optimized using a genetic algorithm which renders the novelty of the work.

Experimentation

Schematic of the proposed setup and model equations

The proposed schematic of the cold storage system is presented in figure 1. The cold storage cooling setup employs a basic LiBr-H_2O absorption refrigeration cycle to uphold a supportive microclimate within the storage space [6]. The additional component is a solar flat plate collector for catering to the need for generator heat addition. The following assumptions were made in the thermal model development:

1. The cold storage's walls, roof, and floor are all considered airtight [3].
2. There are no pressure changes other than those caused by flow restrictions, pumps, and cooling fans [1].

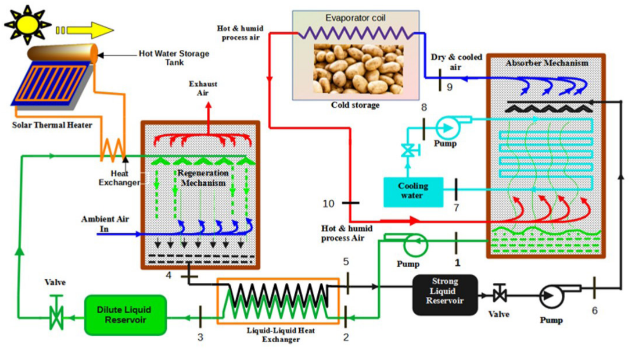

Figure 1: Schematic of solar-driven Li-Br water absorption-based cold storage.

3. The working fluid is in a saturated liquid state at points 1, 4, and 8 and in a saturated vapor state at point 10 [1].
4. To achieve a reasonable heat transfer rate, the immediate temperature of the condenser and absorber is set to be 5 degrees higher than the ambient temperature [3].
5. For adequate heat transport, the evaporator temperature is 5 degrees lower than the cold storage space temperature [3].

Thermal model of the cold storage

The overall cooling load experienced by a cold storage facility is made up of several components, which include structural, penetration, product, living person occupancy, and device load. It can be expressed as follows [3]:

$$\dot{Q}_{\text{total}} = \dot{Q}_{\text{str}} + \dot{Q}_{\text{inf}} + \dot{Q}_{\text{prod}} + \dot{Q}_{\text{man}} + \dot{Q}_{\text{equip}} \tag{1}$$

The structural load ($\dot{Q}_{str}$) is the load caused by the heat gain through the building structure, which is determined by the materials used to build the refrigerated space's walls, floor, roof, and door, the surface area, the air movement in or out of the space, and the difference in temperature between surrounding and storage compartment. The same can be described as [3]:

$$\dot{Q}_{\text{str}} = \dot{Q}_{\text{wall}} + \dot{Q}_{\text{roof}} + \dot{Q}_{\text{floor}} + \dot{Q}_{\text{door}} \tag{2}$$

The heat gain rate through the exposed walls can be expressed as [3]:

$$\dot{Q}_{\text{wall}} = \frac{\Delta T}{R_{wall}} \tag{3}$$

And the wall resistance is given by [3]:

$$R_{\text{wall}} = \frac{1}{A_{wall}}\left[\frac{1}{f_o} + \frac{1}{f_i} + \sum_{j=1}^{n} \frac{\Delta x}{k}\right] \tag{4}$$

In Eq (4), A_{wall} symbolizes the wall's surface area, which can be estimated using the size of the recommended cold storage available in the literature [3]. Thermal conductivity (k) values for various materials are also obtained from the literature [3]. Excess heat from the ambient air incoming through the open door is treated as an intrusion load. The load can be calculated using the change in enthalpy of the incoming air [3].

$$\dot{Q}_{\text{inf}} = \left(\frac{\text{L x B x H x N}}{\text{24 x 3600}}\right)\rho_{air}\Delta h_{air} \tag{5}$$

$$\dot{Q}_{\text{prod}} = \frac{m_p c_{p(T_{initial} - T_{store})}}{\text{24 x 3600}} + \frac{M_{prod} H_{resp}}{1000} \tag{6}$$

In Eq (6), the frequency of product stack ($\dot{m}_p$) is calculated using the product's volume density (b) and appropriate storage volume (V_{eff}) [7]. It is assumed that the commodities are loaded into cold storage at a consistent rate over 20 days [7]. The amount of the product (M_{prod}) is calculated based on the last stacking day [7].

$$\dot{Q}_{prod} = \frac{N_p Q_{avg}\left[\frac{t}{24}\right]}{1000} \tag{7}$$

$$\dot{Q}_{lightning} = \frac{1.25W_{total}}{1000} \tag{8}$$

A 10% safety factor is applied to the final value to account for unanticipated leakages and inconsistencies [7].

$$\dot{Q}_E = 1.1\ Q_{total} \tag{9}$$

Thermal modeling of the VAR system

The LiBr-H_2O absorption system can be modeled by modeling the system's components, which are listed below. The energy balance across the evaporator can be used to calculate the evaporator load, which is as follows [7]:

$$\dot{Q}_E = m_{10}h_{10} + m_{11}h_{11} - m_9h_9 \tag{10}$$

The solution pump's power consumption can be given by [7]:

$$\dot{W}_p = \frac{\dot{m}_1}{ç_p}\int_{p1}^{p2} vdp = \dot{m}_1(h_2\text{-}h_1) \tag{11}$$

The curve fit estimates enthalpy at all state points [5]:

$$\dot{Q}_A = \dot{m}_{10}h_{10} + \dot{m}_{11}h_{11} + \dot{m}_6h_6 - \dot{m}_1h_1 \tag{12}$$

Generator heat addition is given by [7]:

$$\dot{Q}_G = \dot{m}_4h_4 + \dot{m}_7h_7 - \dot{m}_3h_3 \tag{13}$$

Condenser heat rejection with the help of cooling water is:

$$\dot{Q}_C = \dot{m}_7\left(h_7 - h_8\right) \tag{14}$$

Finally, the system's COP can be expressed as [7]:

$$COP = \frac{\dot{Q}_E}{\dot{Q}_G + \dot{W}_p} \tag{15}$$

The values of design parameters, referred from [3], are considered when analyzing the proposed cold storage performance.

Solar unit modeling

The utilizable heat gain from the collector's working fluid can be expressed as [8]:

$$\dot{Q}ç_u = Ac\ x\ I\ x \tag{16}$$

Where, Ac represents the size of the solar collector, I the intensity of the sun, and ηc is the collector efficiency as described by [8]:

$$ç_c = F_R\left[(\tau\alpha) - U_L\frac{T_{in} - T_o}{I}\right] \tag{17}$$

In Eq 17, the transmittance and absorptance multiplication is denoted by $(\tau\alpha)$, U_L represents the total heat transfer coefficient. T_{in} represents the collector flow temperature at the inlet, T_o Represents surrounding temperature, and F_R represents the collector heat removal factor given by [8]:

$$F_R = \frac{\dot{m}C_p}{A_cU_L}\left[1 - \exp\left(\frac{-A_cU_LF}{I}\right)\right] \tag{18}$$

A hot water storage tank is required in solar-powered absorption systems, where $\acute{F}$ is the collector efficiency index. It is a buffer reservoir with a relatively constant heat input [8]. The storage vessel temperature can be found for each time interval by assuming perfect mixing conditions in the vessel and a reasonable amount of addition and rejection of heat taking place for an appropriate period of time [8].

$$T_S^{New} = T_s + \frac{\Delta T}{m_sC_{pw}}\left[\dot{Q}_u - \dot{Q}_L - \dot{Q}_S\right] \tag{19}$$

Where, $\dot{Q}_s = (UA)_s\ (T_s - T_o)$ represents the heat losses from the tank, $\dot{Q}_L$ represents the energy taken from the water vessel, T_s represents the preliminary temperature levels for the time under consideration, and m_s represents the storage vessel mass [9]. The system's overall performance COP_{sys} provided is used to study the complete performance of the system using the following [8]:

$$çCOP_{sys} = COP\ x\ \ _c \tag{20}$$

Genetic algorithm (GA)

A GA is a subclass of an evolutionary computation that models biological processes to minimize the cost function of very complicated situations. A genetic algorithm allows a population of many people to evolve to a condition that optimizes "fitness," or in our case, minimizes the absolute difference between useful solar energy from collectors (Q̇u) and heat added to the generator (Q̇g) on a defined selection constraint [10].

Results and Discussion

Initially, the developed computer code is substantiated by relating simulation results to some available confirmations in the literature. Both investigations employ the same parameter values, TE = T10 = 6 °C and QE = 10 kW. As noticed in figure 2, the current study's findings match well with the work of De and Ganguly [7] with a mean square error of about 3.0036 x e^{-5} because of some additional assumptions. Figure 2 depicts the fluctuation in COP of the setup as the concentration of Li-Br in the mixture of solution exiting the absorber changes

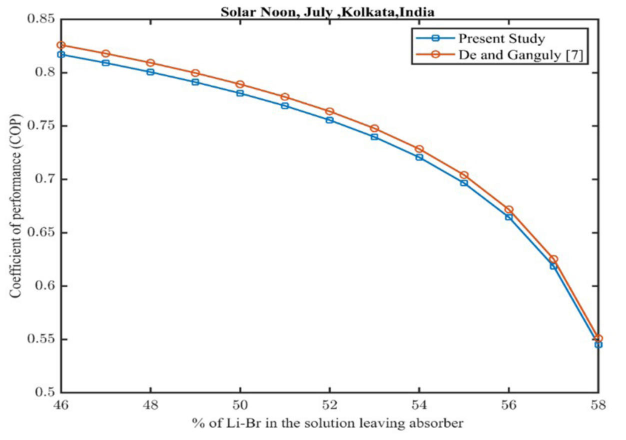

Figure 2: The effect of Li-Br concentration exiting the absorber was validated with De and Ganguly [7] having a mean square error of 3.0036 x e^{-5}.

while the other variables remain constant. It is observed from the above comparison that the results predicted by the model follow a similar trend as reported in the work of De and Ganguly [7]. Thus, the validated model can be used to analyze the system's performance for Kolkata, India's climatic conditions. On July 1, the thermodynamic analysis of the absorption cooling system was performed in Howrah, Kolkata (India; latitude 22.57° N, longitude 88.36° E). Each system component is subjected to the principles of mass conservation and the first and second thermodynamic laws.

For thermodynamic analysis, a computer program in MATLAB R2022a is built. The program is built on each reference point's energy balance, exergy balance, and thermodynamic parameters. This study uses a collection of efficient formulations of the thermodynamic properties of lithium bromide/water solution and liquid water [6]. Figure 3 depicts the hourly variation of evaporator load about the usable solar intensity incident on July 1, 2021. The variation of strong and weak solution concentrations with the time of the day is shown in figure 4.

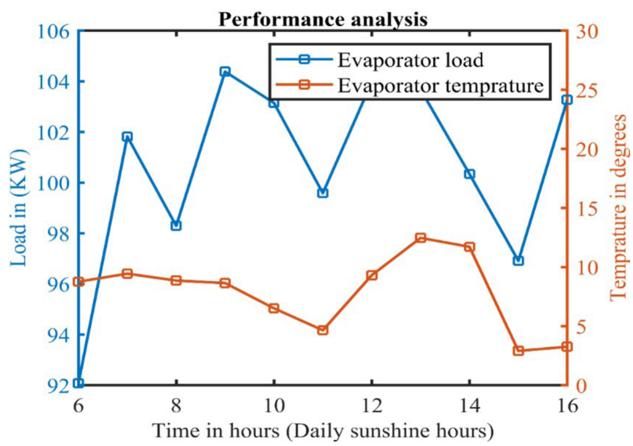

Figure 3: Variation of evaporator load and temperature with time (Daily sunshine hours).

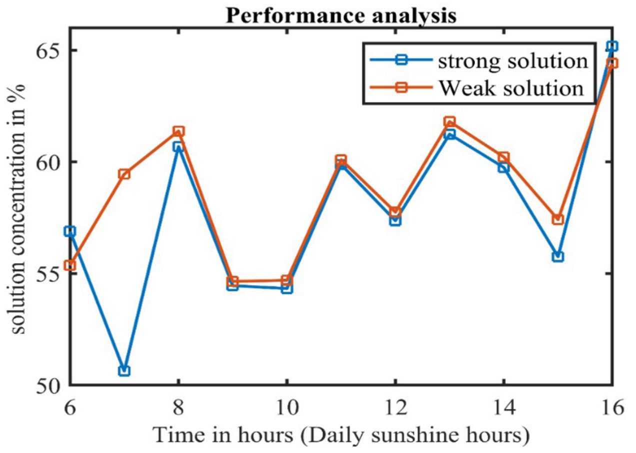

Figure 4: Variation of strong and weak solution concentrations, with time (Daily sunshine hours).

Solar radiant energy over India [11], collector kind and its area, storage vessel mass [5], and cooling water temperature limits are inputs to the simulation. These inputs are used to calculate the components' usable heat, storage vessel temperature, heat transfer estimates, and performance characteristics. The optimized parameters obtained from the GA ensure that the utilizable energy obtained from flat plate collectors is fully utilized. Figure 5a shows the relationship between evaporator load Q_E and practical heat gain from collectors; it can be seen that evaporator load increases during early sunlight hours because of low direct normal irradiance from the sun. Figure 5b shows the variation of evaporator temperature (T10) with heat gain. It is noticed that fluctuations occur only at low heat gains; as the heat gain increases, the evaporator attains a constant temperature. Figure 5c and 5d illustrates strong and weak solution concentrations in percentage varying according to heat gain, respectively; it is observed that the concentrations vary in the range of 50 to 60, but it is observed that peak fluctuations occur at 130 kW of heat gain. Figure 5e shows a variation of inlet temperature to the generator (T3), and figure 5f shows temperature variation of condenser inlet temperature (T7) with heat gain; lastly, figure 5g shows generator outlet temperature variations with collectors' practical heat gain. The curve fitting toolbox from MATLAB 2022a is used to generate simple polynomial and sinusoidal functions for the process

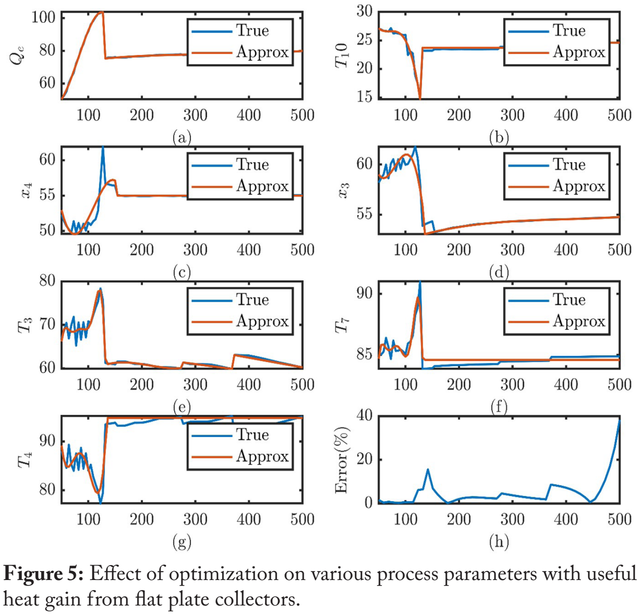

Figure 5: Effect of optimization on various process parameters with useful heat gain from flat plate collectors.

Table 1: Bounds of decision variables.

Decision Variables	Limits
Evaporator load (Q_E) in kW	5 - 110
Evaporator temperature (T_{10}) in °C	4 - 50
Strong solution concentration (X_4) in %	45 - 65
Weak solution concentration (X_3) in %	45 - 65
Generator inlet temperature (T_3) in °C	50 - 80
Condenser inlet temperature (T_7) in °C	70 - 100
Generator exit temperature (T_4) in °C	75 - 105

parameter values against the useful heat gain (Qu). Figure 5h shows the percentage error between actual values indicating optimized parameters and approximated values estimated by a curve fit; the errors are observed to be well below 20%. So, these functions can be easily used for real-time adaptation of control parameters in a simple open-loop control system. Hence, parameter tuning can be achieved without any human intervention.

Conclusion

This paper aims to use a GA to optimize the performance of a solar-assisted single-effect absorption chiller for the storage of potatoes. The cold storage's cooling load is calculated to be 68.16 kW (≈20 TR) with the evaporator temperature set at 8 °C. The impact of various parameters on the system performance is studied. Finally, the process parameters are optimized for useful heat gain from flat plate collectors using a genetic algorithm. The study reveals the following:

- The optimal evaporator load obtained during various test cases concerning the useful heat gain from collectors is found to be in the range of 60 to 90 kW.
- The strong and weak solution concentrations for best performance for a given day are observed to be 55% and 52%, respectively.
- The generator outlet temperature, ranging between 85 to 90 °C, is the best range for achieving good performance from the system.

Additionally, although the model is developed considering the climatic conditions of Kolkata, India, the model is equally efficient for adapting to other climatic conditions.

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Conflict of Interest

The authors affirm that they have no known financial or interpersonal conflicts that would have seemed to have an impact on the research presented in this study.

Credit Author Statement

Swapnil Bhosale: Conceptualization, Methodology, Software, Data curation, Writing - original draft preparation, Writing - review and editing; Aritra Ganguly: Conceptualization, Formal analysis, Writing - review and editing, Supervision; Pradip Mondal: Conceptualization, Formal analysis, Writing - review and editing, Supervision; Swapnil Dhobale: Software, Data analysis, Formal analysis. All the authors read and approved the manuscript.

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