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Feasibility and Basic Design of Solar Integrated Absorption Refrigeration for an Industry

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Abstract

This paper presents a review of existing solar cooling technologies and a feasibility study of a solar absorption cooling system for a packaging facility at Tetrapak Lahore, Pakistan. The review includes brief description of existing chiller technologies and solar collectors. The case study includes analysis of the solar potential and design of the cooling system at considered site. The design calculations upon which the feasibility analysis is carried out are solar collector area and type, cooling capacity, cooling area. A comparison is made between solar cooling potential of Pakistan and existing sites all across the globe. Finally an economic analysis is carried out to demonstrate the financial viability of the new cooling system.

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Keywords: Solar cooling technologies; Absorption cycle; Solar collector; Solar cooling potential; Economic analysis.

1. Introduction

The evaluation of solar potential of different parts of Pakistan has been a subject of many studies. Sahir *et al.* [1] present a comprehensive overview of the studies conducted over the years to elucidate the solar utilization potential and solar energy intensity levels for different areas of Pakistan. The study reaffirms huge existing potential for solar energy utilization in Pakistan.

The solar based cooling systems comprise of two important parts. First one is solar portion consisting of solar collectors, storage tank and auxiliary heater etc. Second portion consists of the chiller, cooling tower and refrigerated space. First 5 sections of the paper include a brief review and evaluation of various

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solar cooling technologies that are available for these two parts. Section 6 presents feasibility analysis of a solar cooling plant that may be installed at the Tetrapak facility in Pakistan. The latter portion of the paper presents all the necessary calculations required for the design and also establishes the advantage of a Solar Absorption cycle plant over the conventional system by doing a cost analysis.

Nomenclature

a_1	First-order coefficient in collector efficiency equation
a_2	Second-order coefficient in collector efficiency equation
a_0	Intercept of the collector efficiency
m	Mass flow rate
$\dot{Q}$	Heat energy
T	Temperature
U_L	Heat loss coefficient
η	Efficiency
τa	Transmittance–absorbance product

2. Existing Chiller Technologies

2.1 Closed Cycle Systems

The major component of closed cycle systems is the thermally driven chiller. It provides chilled water which can be used either in air handling units for cooling and de-humidification processes or is distributed with a chilled water network within the building to the rooms to operate decentralized room installations i.e. fan coils and chilled ceilings.

2.1.1 Absorption Cycle:

Absorption cycle thermodynamically, constitutes a heat engine driving a heat pump. The absorption cooling cycle can be described in three phases:

Evaporation: A liquid refrigerant evaporates in a low partial pressure environment, thus extracting heat from its surroundings – the refrigerator.

Absorption: The gaseous refrigerant is absorbed – dissolved into another liquid - reducing its partial pressure in the evaporator and allowing more liquid to evaporate.

Regeneration: The refrigerant-laden liquid is heated, causing the refrigerant to evaporate. It is then condensed in condenser to replenish the supply of liquid refrigerant in evaporator.

2.1.2 Adsorption Cycle

It is also possible to adsorb the refrigerant on the internal surfaces of a highly porous solid. This process is called adsorption. Typical examples of working pairs are water/silica gel, water/zeolite, ammonia/activated carbon or methanol/activated carbon etc. However, only machines using the water/silica gel working pair are currently available in the market. In adsorption machines, the solid sorbent has to be alternately cooled and heated to be able to adsorb and desorb the refrigerant. The operation is, therefore, by nature periodic in time.

2.2 Open cycle systems

Desiccant systems are essentially open sorption cycles, utilizing water as the refrigerant in direct contact with air. The desiccant (sorbent) can be either solid or liquid and is used to facilitate the exchange of sensible and latent heat of the conditioned air stream. The sorbent is regenerated with ambient or exhaust

air heated to the required temperature by the solar heat source. Most of the currently used desiccant systems use a solid sorption material such as silica gel.
Systems employing liquid sorption materials are less widespread but also available on the market. They have several advantages such as the ability to contain, pump and filter the desiccant, the possibility of energy storage by means of concentrated hygroscopic solutions, as well as bacteriostatic qualities.

3. **Comparison**

This study encompasses close cycle systems only for analysis. The major difference between the two closed cycle technologies is the construction and working mechanism of chiller used. The following table outlines the major differences among them.

Table 1: Comparison of Absorption and Adsorption Chillers [2]

FACTORS	ADSORPTION CHILLERS	ABSORPTION CHILLERS
Weight and Volume	Large	Small
Corrosion Protection	Not Required	High Corrosion Protection Required
Crystallization	No Crystallization	Very High
Life Expectancy	Greater than 30 Years	7 to 9 Years
Typical Cooling Capacity	5.5-500 kW	4.5 kW- 5 MW
Typical COP	0.5 - 0.7	0.6 - 0.75 (single effect)
Temperature	Down to 122°F	Shut down at 180°F, Needs Back-up Heater
Chilled Water Output	40°- 55°F	48°F or More
Environmental Impact	Low carbon emissions	No CFC's or Freon
Cost	Very High	Comparatively low
Efficiency	Comparatively Low	High

Chillers with absorption as well as adsorption technology are available in the market. The most part of them (about 88 %) use absorption technology, while only about 12 % use adsorption technology [3]. Approximately 70 % of the systems employ an absorption chiller for chilled water supply, 10 % use adsorption chillers and 10 % use desiccant cooling systems [3]. The major reason to why adsorption technology is not widely used is its large weight and volume along with its high cost and low capacity. However, a lot of research is focused on developing adsorption technology as it offers numerous other advantages. Still the current adsorption chillers are too big and costly to employ widely. However, adsorption cycles may prove to be a good replacement of absorption cycle in future. Only absorption cycles are considered for detailed analysis in the current study.

4. Solar Collectors

Solar collectors are primarily distinguished by their motion. Two classifications are stationary collectors and axis tracking collectors. Stationary collectors are selected for this study since they are relatively cheap and easily available. The two types of stationary solar collectors namely, flat plate and evacuated tube, are compared below. Based on comparison more suitable is selected for further analysis.

4.1 Flat Plate vs. Evacuated Tube Collector [4]

Flat Plate Collector (FPC) type of collector which absorbs the incident solar radiation on a flat surface whose absorptivity is very high and transmit that energy to fluid running through different channels. FPC is by far the most used type of collector. They are inefficient for high temperature applications such as steam generation but are cost effective for low temperature applications. Well established technology and higher life time are few of the desirable properties. Disadvantages include increased heat losses at higher temperatures due to highly exposed surface area and inability to bear intensive weathering conditions.

Evacuated Tube Collector (ETC) comprises of many evacuated tubes connected in series that absorb solar radiation and convert them to thermal energy. The outer tube has small reflectivity and absorptivity but high transmissivity. The space between outer and inner tube is vacuum (hence the name evacuated) so that no convective heat loss takes place. The inner plate has high absorptivity and it performs the function of transferring this energy as heat to the fluid. This construction ensures its efficient performance at high temperatures.

For a given absorber area, evacuated tubes can maintain their efficiency over a wide range of ambient temperatures and heating requirements. Another advantage is easy maintenance of such systems due to modular design of the commercially available collectors. One disadvantage is that efficiency is strongly dependent on weather conditions. It drops significantly in cloudy or rainy weather.
Keeping in mind the weather conditions of Pakistan ETC being more efficient has been selected for the analysis purpose.

5. Solar Irradiation Data for Lahore

In Pakistan there are no proper meteorological stations to measure the diffused radiation experimentally. Ahmed et al [5] describes a set of empirical relations to estimate the direct and diffused radiation on a region. Our focus is on Lahore which is located at latitude 31.56 N and longitude 74.36 east. Using the data and correlations of Ahmed et al. [5] the monthly data for diffused radiation is calculated. The data for Lahore depicts bright solar energy utilization potential. The global values of diffused and direct radiation show that solar energy can be a very viable source to meet the energy deficit in the country [5].

6. Solar Absorption System Modelling

Solar absorption system consists of two portions. First one is solar portion consisting of solar collectors, storage tank and auxiliary heater etc. Second portion consists of the absorption cycle, cooling tower and Refrigerated space.

Table 2: ETC Characteristics [6, 8]

Parameters	Value	units
Flow rate	70	kg/h.m^2
Number of tubes	30	
Aperture area	2.79	m^3
U	0.7	W/m^2.K
a_o	0.734	
a_1	1.529	W/m^2.K
a_2	0.0166	W/m^2.K

The metrological data for Lahore (latitude 31.56 is assumed from Ahmed et al. [5]. The solar collector technical specifications and absorption cycle technical data is provided in table 2 and table 3 respectively. The useful heat of collector is calculated using the following formula [8]:

$$\dot{Q}_{useful} = \dot{m}C_p(T_o - T_i) = AF_R\left[G(\tau a) - U_L(T_{avg} - T_{amb})\right], \qquad (1)$$

Here C_p is specific heat capacity of the fluid, F_R is the collective heat removal factor given by [8]

$$F_R U_L = a_1 + a_2(T_{avg} - T_{amb}). \qquad (2)$$

The efficiency of the evacuated tube solar collector is calculated using the following formula, [8]:

$$\eta_{th} = \frac{\dot{Q}_{useful}}{AG} = a_o - a_1 \frac{\Delta\tau_{avg}}{G} - a_2 \frac{(\Delta\tau_{avg})^2}{G}, \quad (3)$$

Table 3: Absorption Cycle technical Data [6]

Device	**Heat Exchanger Capacity (kW)**	**Fluid stream**	**Temperature (ºC)**
Evaporator	211	Cooling Water Out	35
Condenser & Absorber	223	Heating Water In	95
Generator	305	Heating Water Out	80
Fluid stream	**Temperature (ºC)**	**Fluid Stream**	**Mass Flow Rate (GPM)**
Chilled Water In	12.2	Chilled water	144
Chilled Water Out	6.67	Cooling water	345
Cooling Water In	29.5	Heating water	77

Here G is the global solar irradiation and A is the aperture area. The solar Factor is given by the relation:

$$SF = 1 - \frac{\dot{Q}_{heater}}{\dot{Q}_{gen}}. \quad (4)$$

The absorption cycle considered in this paper is water cooled NH_3/H_2O whose characteristics are given in the table 3. This absorption cooling system is to be modified such that use of solar energy is maximized and dependency on electricity is minimized.

Using the above equations and the data received from Tetrapak Lahore facility, the values of different parameters of the system are shown in table 4.

Table 4: Final results[TSK1]

Total Collector Area (m^2)	998.4
Global Solar Radiation (W/m^2)	356.46
Solar Collector Efficiency	0.59
$Q_{generator}$ (kW)	305.6
$Q_{auxiliary}$ (kW)	96.1
Q_{useful} (kW)	209.5
Solar factor	0.69

The global solar radiation used is an average value for the region of Lahore. The collector area is determined in accordance with the availability of useable area at considered site. Q_{useful} is the contribution of solar energy to the required heat ($Q_{generator}$). The Auxiliary heater is assumed to be powered by electricity.

7. Economic Analysis

The economic analysis includes determining the payback period of the modified setup. The initial capital investment for this venture is compared with the savings due to the new system. The cost along with the list of the new components to be installed is given in Table 5.

Payback period (PBP) is the time required by savings to equal the expenses incurred due to installation of the new setup. The PBP is given by the formula:

$$PBP = \frac{\ln(C_{sys})}{\ln(1+i)} \quad (5)$$

The cost of the system is found out through the relation:

$$C_{sys} = C_{tank} + C_{collector} + C_{tower} + C_{pump} \quad (6)$$

The number of units of electricity (kWh) saved due to increased contribution of solar thermal heat is calculated using the relation:

$$E_{saved} = Q_{useful} * Hours \text{ (per day, full year average)} \quad (7)$$

Table 6 shows the results of the economic calculations.

Table 5: Cost of main components [7]

Components	Value	Unit
Solar Collector	268	USD/m^2
Water tank	798	USD/m^3
Cooling tower	66	USD/kW
Cost of electricity [11]	0.08 (variable)	USD/kWh
Inflation rate of electricity [10]	29	%

Table 6: Total Cost incurred

Components	Value	Unit
Cost of Collectors	26,757,3	USD
Cost of water tank	1,594,8	USD
Cooling tower	3,366,3	USD
Cost of Pumps	228,5	USD
Electricity Savings	935,5	USD/Month
Operation cost	9	USD/Month

Based on economic analysis payback period came out to be 4.1 years. This is noteworthy that payback period is reasonable for this case due to two main reasons. One reason is higher useful heat generated because of high global radiation intensity. The global radiation energy for Lahore is almost 6 times higher than Dortmund, Germany and 5 times higher than Athens, Greece on average per year [3]. This shows an increased solar cooling potential for Pakistan as compared to some of the other countries where solar cooling projects are being implemented on a large scale [3]. Other reason is high electricity tariff for industries in Pakistan.

Conclusion

Feasibility of installing solar absorption cycle is investigated for an industrial facility in Pakistan. The results showed a solar factor of 69% clearly demonstrating the dominance of solar power utilization. The payback period came out to be around 4 years for this specific case. Reduction in prices of the solar collectors and increasing electricity tariff can further decrease the payback period making this system an enticing choice for the future. Due to the environmental and energy benefits of solar air conditioners, it is recommended that policy makers should provide economic incentives for greater utilization of these systems.

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