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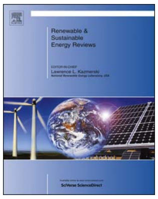

A review of solar driven absorption cooling with photovoltaic thermal systems

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ABSTRACT

The aim of this investigation is to evaluate the recent advances in the field of solar absorption cooling systems from the viewpoint of solar collector types. A review in the area of photovoltaic thermal (PVT) absorption cooling systems is conducted. This review includes experimental and computational work focusing on collector types and their efficiencies and performance indicators. Compared to vapour compression air conditioning systems, 50% of primary energy was saved by using solar absorption cooling systems and 10–35% maximum electrical efficiency of PVT was achieved.

This review shows that Coefficient of Performance (COP) for solar cooling systems is in the range of 0.1–0.91 while the thermal collector efficiencies are in the range of 0.06–0.64. The average area to produce cooling for single effect absorption chillers for experimental and computational projects is 4.95 m^2/kW_c and 5.61 m^2/kW_c respectively. The specific area for flat plat collector (FPC) is in the range of 2.18–9.4 m^2/kW_c, while for evacuated tube collector (ETC) is in the range of 1.27–12.5 m^2/kW_c. For concentrated photovoltaic thermal collector (CPVT) and PVT, the average area to produce cooling for solar absorption chillers are 2.72 m^2/kW_c and 3.1 m^2/kW_c respectively.

1. Introduction

The demand for energy is increasing around the world due to population growth and industrialisation. Fossil fuels such as oil and natural gas are considered as primary sources of energy. In 2035, more than 80% of the energy consumption will be produced by fossil fuels in some developed countries [1]. Producing energy by traditional methods leads to more gas emissions and accelerated global warming. Alternative renewable sources of energy such as solar energy, wind energy and geothermal energy are required [2].

In response to the need for alternative energy sources, solar cooling technologies have become an important factor especially in hot countries due to the huge amount of solar radiation and the need for cooling. Solar cooling systems are environmentally friendly compared to conventional cooling systems and are an important technology to reduce emissions [3].

Pazheri et al. [4] estimated that a 20 MW solar plant, which would need an area of 1.25 km^2, can generate 200–300 GWh/year and that could save 500,000 barrels of oil per year. The potential for solar energy and the opportunity to utilise it for cooling purposes depend on the location in the world. For example, Europe, North America, most of Latin American and western Asia have a 100–200 W/m^2 average annual rate of solar radiation while in the Middle East, the value reaches up to 250 W/m^2 [4].

In Europe, the residential sector accounts for about 40% of energy consumption and heating purposes represents about 68% of this sector [5,6]. In contrast, cooling systems have been the main energy consumer in the residential sectors in hot climatic conditions. In Saudi Arabia, 72% of residential electricity is consumed by cooling equipment [7].

However, in the last decade, many researchers has focused on solar cooling systems and so different types of solar thermal cooling systems have been reviewed [8,9]. The use of solar collectors such as FPC and ETC for thermally driven solar cooling systems and photovoltaic panels (PV) to provide electricity for vapour compression air conditioning units has been discussed [10–12]. The application of thermally driven systems such as absorption, adsorption, desiccant and ejector systems have been highlighted in the review papers [13–15]. Options for thermal and cold storage have also been discussed [16]. There are limitations in some of these reviews because they were specified in a particular region or application [13].

Alili et al. [9] reviewed solar thermal air conditioning technologies

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and reported a number of research outcomes from the point of view of working fluid temperature, collector type, collector area, storage volume and COP values. The authors evaluated research depending on conditions such as the temperature of evaporators, condensers and generators. From this research, evaporator temperature is in the range of −9 °C and 26 °C, condenser temperature in the range of 24 °C and 45 °C and generator temperature between 74.1 °C and 120 °C. The paper analysed six experimental and five simulation studies and reported that the average area of solar collector for a solar absorption cooling system is 4.67 m^2/kW_c. The areas required of evacuated tube collectors ranged between 2.7 and 9.4 m^2/kW_c while these areas were 1.4–3.3 m^2/kW_c for flat plat collector.

Review papers that focus on solar cooling absorption technology are scarce; Zhai et al. [17] provided a literature survey of solar cooling absorption systems but did not mention the use of PVT and only include one project that used CPVT with single absorption chillers. Raja and Shanmugam [18] also reviewed solar absorption systems, aiming to reduce the initial cost of the systems. The authors discussed auxiliary components that are typically used in the systems such as backup heating and some solar collector types. The paper did not report any existing PVT collectors and only one CPVT project was mentioned. Different types of absorption solar cooling systems which include single effect, double effect and half effect absorption cycle have been also reported in the review papers [19–21]. The required heat source temperature, refrigeration output, capacity range, COPs and fluid pairs have been reported for single-effect absorption refrigeration cooling technologies in Table 1. Table 2 illustrates small capacity absorption chillers in market which is in the range of 4.5–17.6 kW. Table 2 also show that COP is in the range of 0.63–0.77 and the driving temperature for absorption chillers is in the range of 75 °C to 90 °C.

The incorporation of solar collectors such as ETC and FPC with absorption chillers have been highlighted but there is a lack of data in the use of photovoltaic thermal collectors (PVT) with absorption chillers [22].

Based on the performance and the initial cost of solar cooling systems, single effect absorption systems were estimated to be more efficient with lower costs. The majority of this research analysed the incorporation of solar collectors such as ETC and FPC with absorption chillers, but most did not report the cost of solar collectors, their efficiencies and the overall system cost. From previous review papers, there is a lack of data on the combination of photovoltaic thermal collectors (PVT) with absorption chillers [18]. In these studies, absorption systems shows an opportunity to achieve a relatively high COP (0.5–0.8) for generation temperature in the range of 70 °C and 90 °C [8,18].

The aim of this review is to establish the current developments in the field of photovoltaic thermal collectors (PVT) for cooling purposes and to identify the opportunity of using PVT for absorption cooling system. The review also includes the current developments in the field of solar absorption cooling systems from the point of view of solar collecting options. The review includes experimental and computational studies and focuses on collectors' types and their efficiencies. Heat source, refrigeration output, capacity range, performance indicators and economic viability for the overall solar absorption systems are discussed. In Section 2, previous work relating to thermal absorption cooling systems including experimental and simulation studies are reported. In Section 3, the use of photovoltaic thermal collector for cooling system are highlighted with focussing on thermal and electrical efficiency for the collector. In Section 4, the economic viability of PVT are discussed with focusing on performance and economic indicators. Finally, in Section 5, the solar thermal and photovoltaic cooling systems are discussed and summarised in Tables 5–7 with a focus on collector types, thermal and electrical efficiency, COP and the capacity of the projects.

2. Thermal collectors' absorption cooling systems

The dominant driving power in solar absorption cooling systems is the thermal power from solar energy collectors. Solar radiation is absorbed by solar collectors then delivered to the storage tank through a hydraulic pump. A backup heater is fixed with the storage tank and the temperatures in the system should be managed to meet the required temperature for the absorption chiller. The most common working fluid in absorption systems are $H_2O/LiBr$ (Water is refrigerant) and NH_3/H_2O (Ammonia is refrigerant) [12]. Fig. 1 shows a schematic diagram of the solar cooling system which consists of a thermal solar absorption system, made up of solar collector, storage tank and absorption chiller.

Fong et al. [23] carried out a comparison study of different solar cooling systems which included solar electric compression refrigeration, solar mechanical compression refrigeration, solar absorption refrigeration, solar adsorption refrigeration and solar solid desiccant cooling based on their performance throughout the year. The study was based on the simulation program TRNSYS to calculate the performance indicators which include solar fraction (SF), coefficient of performance (COP), solar thermal gain (G_{solar}) and primary energy consumption in order to meet the cooling load of 29 kW_c. The driving temperature, which is the water temperature supplied to the generator, was in the range of 67–90 °C. The work provided good performance indicators and the findings from the study indicated that solar absorption refrigeration and solar electric compression refrigeration had the highest energy saving. The work further found that the solar absorption system achieved a solar factor of 50% throughout the year and the COP was 0.769, total global solar radiation (G_{solar}) was 37,234 kWh and the primary energy consumption (Ep) was 72,797 kWh. Fig. 2 details the schematic of the solar absorption refrigeration system.

Hartmann et al. [24] also carried out a comparison between a solar electric compression refrigeration system and a solar adsorption refrigeration system to evaluate the primary energy savings and the cost to meet the demand for heating and cooling of a typical building in Germany and Spain. The cooling and heating load throughout the year, the performance of photovoltaic PV system and the performance of a FPC system were simulated in TRNSYS for varying solar collector areas. The study highlighted that the annual cost of a solar cooling system was 128% higher than a conventional compression chiller in Spain and 134% in Germany whilst the annual cost for solar electric cooling varied between 102–127% in Spain and 102–125% in Germany. They concluded that for the same energy saving in the PV cooling systems with a defined of PV field area, six times this area would need to be covered by FPC solar collectors. Fig. 3 shows the

Table 1
Single-effect Absorption refrigeration cooling technologies [8,14].

Capacity KW	Working fluid pairs	Driving temperature °C	Chilled water Temperature °C	COP	Cooling applications
5–7000	$LiBr–H_2O$	70–90	5–10	0.5–0.8	Industry, large-scale building, and small units for residential use
10–6500	$H_2O–NH_3$	100–200	−60 – 0	0.25–0.6	Large capacity for industrial refrigeration, and small size for light commercial use
10–90	$H_2O–NH_3$	80–200	5–10	0.5–0.6	Residential and small commercial building cooling