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Technical evaluation for a solar absorption cooling system to be applied for greenhouse climate control

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Abstract

The management of the greenhouse environment depends on the manipulation of the climatic parameters, such as solar radiation, air temperature, relative humidity and carbon dioxide concentration, in order to guarantee suitable growing condition for the crop, safety condition for the workers and energy savings. Evaporative systems are generally used in warm regions for commercial greenhouse cooling, however such systems require large quantity of water that is often a scarce natural resource in Mediterranean areas. Solar absorption cooling systems can be applied for greenhouse climate control in regions with high values of solar irradiation as alternative to evaporative systems by exploiting renewable energy sources. The solar cooling system could provide significant energy-saving opportunities for cooling greenhouses in hot climates allowing the reduction of electricity and water consumption by exploiting the contemporaneity between the cooling requirements and the solar energy availability. The paper presents the technical considerations on the application of a solar absorption cooling system to a Mediterranean greenhouse. The aim of the research was to define the potential of the system in terms of energy absorption and the solar collector surface related to the greenhouse cultivated area. The simulation study was realized based on the experimental data collected at the experimental centre of the University of Bari, Southern Italy, in order to control the air temperature of a greenhouse covered with plastic film; the greenhouse was characterized by a surface of 300 m^2. The cooling system was designed by adopting suitable technologies of energy saving, in order to reduce cooling energy needs. The designed system consists of an absorption chiller having a cooling capacity of 18 kW fed by 60 m^2 of evacuated-tube solar collectors coupled to a new distribution system which provides the cooling power only for the air volume surrounding the crop and not for the whole greenhouse.

Keywords: solar energy, solar cooling, energy efficiency, greenhouse microclimate, renewable energy sources

1 Introduction

Sustainable greenhouse systems can be obtained through an efficient management of climatic parameters, using renewable energy sources, using innovative greenhouse covering materials, optimizing the water and nutrient delivery to the cultivation and with an integrated management of pest and diseases. The climatic management of the greenhouse environment relies on the manipulation of parameters such as solar radiation, air temperature and relative humidity, and carbon dioxide concentration, in order to guarantee suitable growing condition for the crop, safety condition for the workers and energy savings (Von Zabeltitz, 1999; Vox et al., 2010).

In the warm climate areas such as the Mediterranean basin, the cooling systems are often used to control the internal climate and to obtain balanced environmental parameters of the greenhouses because of the high internal temperatures recorded during the spring-summer period.

Natural ventilation is usually the preferred greenhouse cooling method because it is the cheapest and simplest method, though natural ventilation alone is generally not sufficient for adequately removing the surplus energy during warm periods. The mechanical refrigeration for greenhouse cooling is too expensive for the operating costs and maintenance required; that is why the evaporative cooling methods, such as fan-pad and fog systems, are the most efficient systems for controlling the internal air temperature in warm regions, requiring minimum power consumption.

Evaporative cooling is based on the conversion of sensible heat into latent heat through the evaporation of water supplied to the greenhouse (Katsoulas et al., 2001); this principle of cooling highlights that the evaporative cooling system can only remove room sensible heat; therefore, the evaporative cooling system works finest in hot and semi-arid climate where the maximum evaporative cooling will result (Ahmed et al., 2011; Kumar et al., 2009). The main evaporative cooling methods used today are based on the following systems: the fogging system, the roof cooling system and the fan-pad system (Arbel et al., 2003).

The fogging system uses water pump and fogging nozzles for supplying water in the form of small size drops, in the fog range that is diameter 2-60 µm (ASHRAE, 1972) in order to increase the water surface in contact with the air; the resulting heat and mass exchange rate between the water and the air is enhanced. Mainly fogging systems are based on high pressure nozzles, having high cooling efficiency and low cost in comparison with other systems (Arbel et al., 2003). Air greenhouse temperature can be lowered by 3-8 °C than ambient temperature (Sethi and Sharma, 2007). This system is frequently applied in hot and dry climates and when plants transpiration is insufficient (ASABE, 2008), providing more uniformity in temperature and humidity levels against fan-pad systems.

The roof cooling method consists in the sprinkling of water onto the roof and the canopy to form a thin layer; consequently the higher water surface area leads to a greater evaporation rate; the evaporation process causes the cooling of the water that falls to the wet bulb temperature of the closely surrounded air and the cooling of the canopy. This system is less effective than fan-pad and fog system, allowing to reduce air greenhouse temperature of 3-5 °C (Sethi and Sharma, 2007). The rise of the internal air temperature can be reduced by 41% under wet shading cloth with an intermittent sprinkling of water, in comparison with a reduction of 18% under dry cloth (Willits and Peet, 2000).

The evaporative cooling carried out by means of the fan-pad evaporative cooling system is obtained by obliging the outside air to pass into the greenhouse through moistened evaporative pads combined with mechanical ventilation (fans); the so cooled outside air is then distributed throughout the greenhouse (Franco et al., 2011). This system can lower greenhouse temperature of about 4-5 °C (Jain and Tiwari, 2002); the reduction can increase up to about 12 °C if the system is integrated with shading application (Sethi and Sharma, 2007). The major effect of wet pads is to reduce the potential transpiration rate (Fuchs et al., 2006); minor contribution is due to the crop transpiration, providing additional cooling (Stanghellini and van Meurs, 1992). In dry climate regions, the outside air temperature can be lowered up to 10-25 °C in comparison to the ambient air temperature although the air temperature between fan and pad may vary in ranges of about 3-7 °C (Vox et al., 2010). The saturation efficiency of

the pad–fan system is higher, it consumes less water and energy and it is less expensive to install than the fogging system (Katsoulas et al., 2009; Sethi and Sharma, 2007).
The above described evaporative cooling systems are mainly based on fossil fuels and require large quantity of high quality water, that is a scarce natural resource in the Mediterranean area.
Research has been carried out on the application for greenhouse cooling of systems that use the potential of the earth ground or of the underground aquifer water, due to their constant year round temperature minor than ambient one in summer conditions. These composite systems, such as earth-to-air heat exchanger system and aquifer coupled cavity flow heat exchangers system (Ghosal et al., 2004; Sethi and Sharma, 2007; Sharan, 2009), can significantly reduce the greenhouse air temperature with favourable energy savings, as compared to other cooling systems, especially when solar and geothermal energy are combined (Yildiz et al., 2012). Among these systems, the earth air pipe system uses ground as a heat sink and air as the heat transfer medium for air cooling; during hot seasons, when the warm air passes through the earth air pipes, heat is transferred from air to the earth and consequently the resulting outlet air temperature is much lower than that of the ambient. During the last decades, several investigations have been carried out in the design, modeling and testing of underground air tunnel systems. Ozgener, L. and Ozgener, O. (2010) calculated the total average cooling coefficient of performances (COP) values for the system obtaining 10.09; the COP was calculated as amount of cooling produced by the air tunnel and the amount of power required to move the air through the experimental tunnel.
Greenhouse cooling using refrigeration or dehumidification is too expensive in terms of investment and operation cost, especially when a large quantity of heat must be removed from the internal ambient (Kumar et al., 2009; Vox et al., 2010).
An energy saving system, contributing to the reduction of the dependence on fossil fuel based energy, can be achieved by means of the solar cooling systems; in addition using solar energy for this purpose means to have the cooling requirements in phase with the solar energy availability (Al-Alili et al., 2012; Ghaddar et al., 1997) requiring no power back up systems.
Solar cooling systems can be classified in: solar photovoltaic-based electrical cooling systems, solar collector-based thermally driven cycles and solar combined power and cooling systems (Chidambaram et al., 2011; Hwang et al., 2008; Sarbu and Sebarchievici, 2013).
The solar photovoltaic-based electrical cooling systems use the solar energy to produce electricity by means of photovoltaic (PV) devices in order to satisfy the power demand both of Peltier cooling systems and of the vapour-compression systems (Hwang et al., 2008). In the solar collector-based thermally driven cycles the solar energy is used to produce thermal energy for cooling through the thermochemical or thermophysical processes by means of thermally activated energy conversion systems. These systems can be divided into three categories: closed cycles (adsorption and absorption cycles), open cycles (solid and liquid desiccant cycles) and thermo-mechanical cycles (ejector cycle). A solar combined power and cooling system combine a Rankine thermal power cycle with an absorption cooling cycle with ammonia/water mixture as working fluid (Hwang et al., 2008).
This paper presents the preliminary results of a research on the application of a solar absorption cooling system to a Mediterranean greenhouse. This system could provide significant energy-saving opportunities for cooling greenhouse in warm climates. Aim of the research was to assess the potential of the system in terms of energy absorption related to the solar collector surface and to the greenhouse covered area.

2 Materials and methods

The cooling system was designed for a greenhouse located at the experimental farm of the University of Bari in Valenzano (latitude 41° 05’ N, longitude 16° 53’ E), Italy. Recent researches have been carried out at the aforesaid farm on the application of renewable energy sources for greenhouse heating and climate control (Scarascia Mugnozza et al., 2011, 2012; Vox et al. 2008).
The experimental greenhouse is an arched roof type covered with plastic film, south-north oriented, with a covered area of 300 m^2; it is 30 m length and 10 m width, 4,45 m high along

the ridge and 2,45 m along the gutters (Fig. 1). The main structure is made of tubular galvanized steel and it is covered with an ethylene-vinyl acetate copolymer film (EVA) having a thickness of 200 µm. The base and the warheads (south and north-facing greenhouse surface) are polycarbonate (PC) sheets.

The covering film has a solar total transmissivity coefficient of about 85-90% in the wavelength range 300–3,000 nm.

The plants are grown in plastic pots (each pot was 1.00 m x 0.40 m x 0.40 m); the growing substrate is a mixture of soil and peat. An automated drip irrigation system ensures water availability to the plants.

The cooling system has been designed to lower the inside air temperature of the greenhouse regulating it closer to the external air temperature during warm months and in any case lower than 35 °C in order to allow crop cultivation.

The greenhouse is equipped with natural and forced ventilation. Four electrical fans are positioned on the north-facing greenhouse surface and two air inlet louvers on the south-facing greenhouse surface. Open ridge and side wall vents provide the natural ventilation (two vents on the greenhouse ridge and two respectively on the east and west sides). The greenhouse is also equipped with an electronically controlled horizontal shading net. The cooling system task is to mitigate the climate below the shading net, by distributing cooled air through pipes at the crop level. Therefore the solar cooling system has been designed to be combined with passive techniques of energy saving.

3 Results and Discussion

The average daily solar radiation incident on a horizontal surface, according to experimental data collected during 2010-2012 at the experimental field in Valenzano (Bari, Italy), is summarized in Fig. 2.

The cooling energy demand was evaluated setting two different design conditions: energy necessary to cool the whole greenhouse area (condition I) and energy necessary to cool locally the growing area around the plants (condition II). In the last case the pots containing the plants are placed on benches having the sides equipped with cooling radiating surfaces. The cooling capacity was calculated from the following heat balance equation:

$$Q_C = I_r * \tau_{cp} * (1-\rho) * S - U * S * \Delta T \qquad (1)$$

where: I_r is the incident solar radiation, assumed equal to 900 Wm^{-2}; τ_{cp} is the covering transmissivity, assumed equal to 0,85; ρ is the reflectance of the soil and of the shading net, assumed equal to 0.5; S is the covered area that must be cooled; U is the global heat transfer coefficient of the greehouse, assumed equal to 10 W m^{-2} $°C^{-1}$; ΔT is the temperature values difference between the inside and outside temperature of the greenhouse, equal to 1 °C. The area to be cooled was assumed equal to 300 m^2 for the condition I and to 40 m^2 for the condition II with reference to the area specifically involved in the cultivation. The design assumptions were made taking into account the climatic data recorded at the experimental centre.

The functional diagram of the solar absorption cooling system is shown in Fig. 3. The system consists mainly of an evacuated tube solar thermal collectors array providing heat to an absorption chiller that produces cooled water used to cool air. The plant cooling is obtained distributing the cooled water through plastic pipes.

The electrical energy necessary for the cooling system is partially supplied by an experimental solar photovoltaic-electrolyser-fuel cell power system with energy backup consisting of hydrogen storage; this power system allows to reduce the dependence from fossil sources and to operate continuously during power cut due to load-shedding or during breakdowns (Ganguly et al., 2010). The experimental greenhouse is provided with an array of photovoltaic panels with a power of 7.38 kW.

The cold storage tank is backed up by an auxiliary heat source, a geothermal heat pump, already provided with the experimental greenhouse, in order to ensure an optimal temperature input to the greenhouse even when the solar energy is not sufficient to feed the solar cooling system.

The design of the system has evaluated the cooling energy demand required for the solar thermal collectors: 112 kW for the Condition I and 15 kW for the Condition II.

The large surface of the solar collectors required by the system for the condition I, equal to about 350 m^2, makes its application difficult due to the high visual impact of the solar panels. For the condition II, a solution, based on the equipment available on the market, consists of a water-fired single effect absorption chiller with a cooling capacity of 18 kW with an heat input of 25.1 kW, using a combination of water/lithium bromide as fluid for absorption cooling; the system uses a cooling tower. The chiller has a electrical consumption of 1.45 kW, a $COP_{thermal}$ of 0.70 with a supply/return cooling water of 7.0/12.5 °C, nominally requiring an in/out temperature from the solar array of 88/80 °C. The system is provided with a cooling tower having a heat rejection of 42.7 kW and an inlet/outlet cooling water temperature of 31.0/35.0 °C, two boiler for the hot water storage, with a global capacity of 2 m^3 and a boiler for the chilled water storage with a capacity of 0.5 m^3. The solar thermal energy is provided by 60 m^2 of solar collectors having a tilt angle of 30°. The collectors can be positioned outside the greenhouse or inside in the north and south extreme parts of the greenhouse, at the level of the eaves, so that there is no shading over the cultivation area placed in the middle of the covered area. In the case of solar collectors positioned inside the greenhouse their surface must be increased by 10-15 % in order to compensate the reduction of the energy passing through the covering film.

The designed system has taken into consideration a single-effect absorption chiller because it requires lower temperatures than double and triple effect ones, operating with heat source temperatures above 85 °C (Hwang et al., 2008).

4 Conclusions

Renewable energy sources, such as solar energy, offer considerable promising advantages.

The application of the absorption chillers, using solar energy as the energy source reduces greatly the cost for electricity. Solar systems based on absorption chillers and evacuated tube solar thermal collectors can be reliably applied for greenhouse cooling when combined with passive techniques of energy savings, allowing the reduction of the use of water for cooling greenhouse. A reduction of the large capturing surface required for the solar collectors can be obtained if a localised cooling system is applied only near the plants; the effectiveness of this technique must be experimentally proven. Moreover solar cooling systems can exploit the electrical energy produced by photovoltaic systems. The main advantage of the solar-powered cooling systems is that it can be used when the cooling requirement is in phase with the solar energy availability, avoiding the necessity of a power back up system, being of particular interest for the application in remote areas where conventional cooling is difficult and where there is abundant solar energy.

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Figure 1: The experimental greenhouse at the University of Bari (Italy)

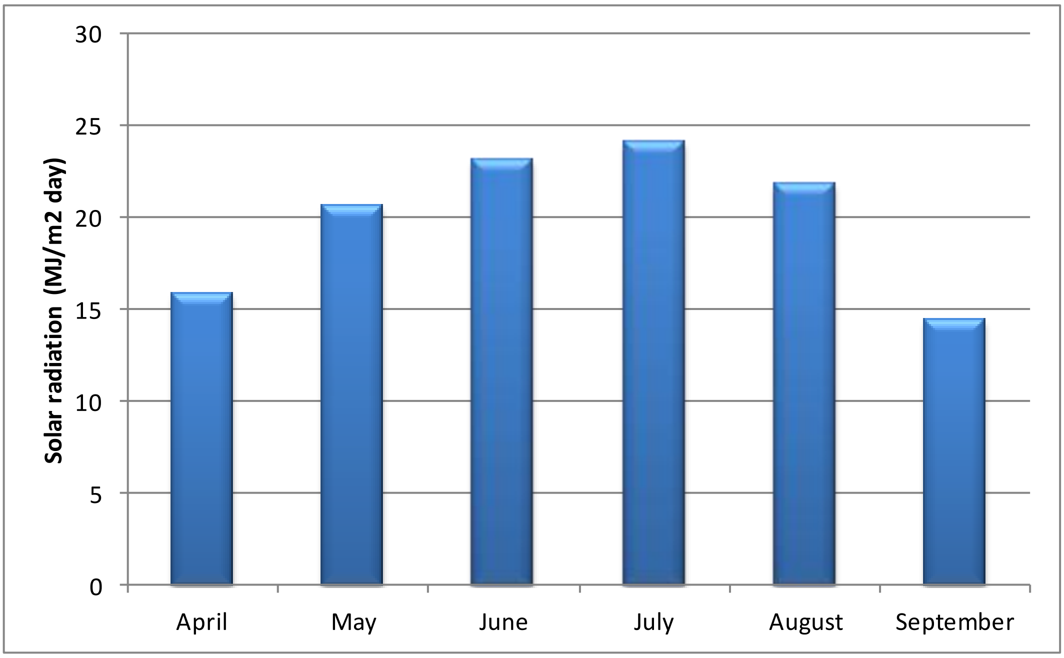

Figure 2: Average daily solar radiation experimental data (2010-2012).

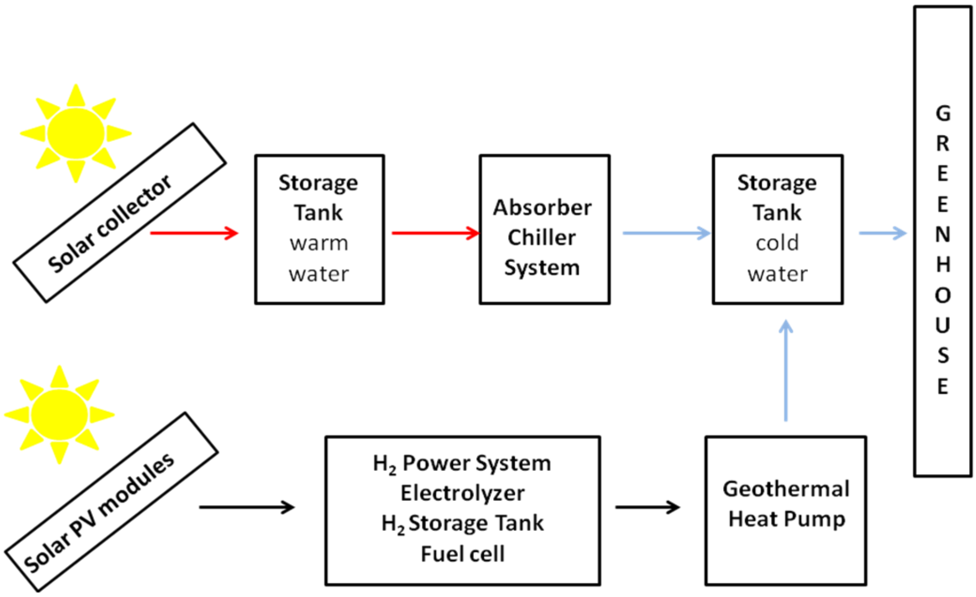

Figure 3: Functional diagram of the cooling system