Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 48 (2014) 806 – 812

Energy Procedia

SHC 2013, International Conference on Solar Heating and Cooling for Buildings and Industry
September 23-25, 2013, Freiburg, Germany

Optimizing solar collector tilt angle to improve energy harvesting in a solar cooling system

Paolo Corrada[a]*, John Bell[a], Lisa Guan[a], Nunzio Motta[a]

[a]Quuensland University of Technology, 2 George st, Brisbane 4001, Australia

Abstract

Solar cooling systems are gaining popularity due to continuously increasing of energy costs around the world. However, there are still some factors that are hindering the installation of solar cooling systems on a larger scale. One being the cost associated with the solar collectors required to provide heat to the absorption chiller. This study demonstrates the possibility of reducing the number of solar panels in a residential solar cooling system based on evacuated tubes producing hot water at a low temperature (90°C) and a water-ammonia absorption chiller.

Selection and peer review by the scientific conference committee of SHC 2013 under responsibility of PSE AG

Keywords: absorption chiller; solar air-conditioning; solar cooling; optimum tilt angle in Brisbane.

1. Introduction

Air conditioning systems are the largest user of electricity in Australia' households in [1]. The amount of electricity used in the cooling system is directly related to the heat load that needs to be removed. This heat is strongly related to both the weather condition and sun irradiation above the household. The constant increases in energy cost are making people increasingly interested in reducing electricity consumption particularly air-conditioning systems. One possible solution is to reduce the use of power from the grid by tapping solar energy, most commonly produced by photovoltaic panels, to power a standard split system. The direct use of thermal

* Corresponding author. Tel.: +61-7-3138-9158 ; fax: +61-7-3138-8381 .
E-mail address: paolo.corrada@qut.edu.au

Selection and peer review by the scientific conference committee of SHC 2013 under responsibility of PSE AG
doi:10.1016/j.egypro.2014.02.093

energy is becoming more popular in remote areas where solar radiation is abundant [2]. Solar cooling systems use thermal panels to produce hot water at low temperatures (90°C) combined with an absorption chiller. A limiting factor for the use of these systems is the installation cost, which is still too high to be compensated by benefits for a single household.

The key components to improve, and so produce more affordable solar cooling systems, are the solar collectors and the absorption chiller [3]. Solar collectors used only for cooling are uneconomical because they are used only for a part of the year, so it is necessary to use the solar system for both heating and cooling all year round [4]. Optimizing of the number of solar panels by addressing the seasonal variation of the solar angle can be the key to achieve the economic viability of this system.

Nomenclature

n_{day}	number of the day of year starting from the first of January
ϕ	of the site
β	angle with the horizontal
ω'_s	sunset hour angle for the tilted surface
H_b	direct or beam radiation
H_d	diffuse radiation
H_r	ground reflected radiation
Q	output power to the liquid circulating through solar panels
F'	collector efficiency factor
A_a	area of the solar collector
$(\tau\alpha)_{en}$	effective transmittance–absorptance product at normal incidence
G	global solar irradiance
U	overall heat loss coefficient
t_m	mean fluid temperature through solar field $(t_{out}-t_{in})/2$
t_a	ambient air temperature
η	efficiency of solar panels
G_{on}	extra-terrestrial radiation
G_{sc}	solar constant (1,367 W/m^2)
H_o	monthly average daily extra-terrestrial radiation on a horizontal surface
K_T	clearness index
H_d	diffuse daily radiation

2. Heating and cooling load

This study is based on a 120 m^2 dwelling in South East Queensland (SEQ), Australia, for which the predicted energy consumption for cooling and heating were estimated by a standard commercial mathematical model [5]. The prediction for the cooling power required by this dwelling is 12.2 kW whereas the heating power required is only 5 kW. The cooling power is supplied by the solar cooling system and the heating power is supplied directly by the hot water generated by the solar collectors used in the solar cooling system.

3. Solar thermal panel performance

One of the parameters influencing the amount of energy collected by a solar panel is the tilt angle with respect to the horizontal, which is usually set equal to the latitude of the installation location [6]. Other parameters influencing the performance of the solar panels are the ambient temperature and the hot water temperature required by the absorption chiller. This study found that choosing the tilt angle equal to the latitude of the installation does not maximize the energy collected by the solar system during summer time when the cooling requirement is at the maximum. A mathematical model was developed to address this calculating the best tilt angle for the SEQ. The dwelling optimum angle was computed by searching the maximum average daily radiation on the collector surface for each month of the year. Estimations of the average daily monthly radiation for a system using an inclination angle equal to 0° and equal to the latitude were also performed. As Brisbane is located at a latitude of -27.47 degree this value has been used in the calculations.

The same model includes the ambient temperature variation during the day.

Weather data was made available by the Bureau of Meteorology [7].

4. Methodology

The first step is the mathematical modeling of the solar radiation on a tilted surface, where the solar declination δ and the mean sunshine hour angle for the month (ω_s) were calculated using the following formula [8]:

$$\delta = 23.45 * \sin\left(\frac{360*(284+n_{day})}{365}\right) \tag{1}$$

$$\omega_s = \cos^{-1}*(-\tan\phi * \tan\delta) \tag{2}$$

The value of the declination angle varies between ±23,45 degrees which means the earth's axis sweeps a total declination angle of 46.90 degrees during the year. This variation of the declination angle is the cause of the cyclic changes in solar radiation levels.

The estimated value of δ and ω_s are used to calculate R_b which is the ratio of the average daily direct radiation on a tilted surface to that on a horizontal surface [9].

$$R_b = \frac{\cos(\phi-\beta)*\cos\delta*\sin\omega'_s + \left(\frac{\pi}{180}\right)*\omega'_s*\sin(\phi-\beta)*\sin\delta}{\cos\phi*\cos\delta*\sin\omega'_s + \left(\frac{\pi}{180}\right)*\omega'_s*\sin\phi*\sin\delta} \tag{3}$$

where:

$$\omega'_s = \min\begin{pmatrix} a\cos(-\tan\phi*\tan\delta) \\ a\cos(-\tan(\phi-\beta)*\tan\delta) \end{pmatrix} \tag{4}$$

In equation 4, the first line is the equation related to the horizontal surface and the second is related to the inclined surface [10]

The value of the extraterrestrial radiation G_{on} is then calculated as:

$$G_{on} = G_{sc} * \left(1 + 0.033 * \cos\left(\frac{360*n_{day}}{365}\right)\right) \tag{5}$$

where G_{sc} is the solar constant (1,367 W/m^2).

The value of G_{on} is used to calculate the monthly average daily extraterrestrial radiation on a horizontal surface as:

$$H_o = \frac{24}{\pi} * G_{on} * \left(\cos\phi*\cos\delta*\omega_s + \frac{\pi}{180}*\omega_s*\sin\phi*\sin\delta\right) \tag{6}$$

This value is then used to calculate the monthly average clearness index K_T which is defined as:

$$K_T = \frac{H}{H_o} \tag{7}$$

The fraction of the diffuse daily radiation H_d is a function of K_T and it is estimated [11] as:
For $K_T \leqslant 0.13$

$$\frac{H_d}{H} = 0.952 \tag{8}$$

For $0.13 \leqslant K_T \leqslant 0.8$

$$\frac{H_d}{H} = 0.868 + 1.335 * K_T - 5.782 * K_T^2 + 3.721 * K_T^3 \tag{9}$$

For $K_T \geqslant 0.8$

$$\frac{H_d}{H} = 0.141 \tag{10}$$

The daily amount of solar radiation on a tilted angle (H_t) using an anisotropic method is due to the sum of three different inputs:

- Direct or beam radiation (H_b)
- Diffuse radiation (H_d)
- Ground reflected radiation (H_r)

so that the total amount of radiation on a tilted surface is calculated as:

$$H_t = H_b + H_d + H_r \tag{11}$$

The daily beam radiation is calculated as:

$$H_b = (H - H_d) * R_b \tag{12}$$

The ground reflected radiation is calculated as:

$$H_r = H * \rho_g * \left(\frac{1-\cos\beta}{2}\right) \tag{13}$$

The total radiation on a tilted surface can be then calculated as:

$$H_t = (H - H_d) * R_b + H * \rho_g * \left(\frac{1-\cos\beta}{2}\right) + H_d \tag{14}$$

The second step in the mathematical modeling is a simulation of the solar field where evacuated tubes are used. The choice of the evacuated tube is made because of the temperature required for the absorption chiller. The model is developed using different required hot water temperature for cooling (90°C) and heating (60°C). That is a lower temperature is used in winter where the efficiency raises and reduces the negative effect of a lower ambient temperature.

The evacuated tube collector consists of heat pipes inside vacuum-sealed glass tubes. To optimize the absorption of the solar radiation some manufacturers install a reflector in their product [12].

The mathematical model follows the standard EN 12975-2 and [10] to specify a reproducible methodology which assesses the panel efficiency so that the results are comparable. Two alternative test methods for the thermal performance characterization of solar collectors are specified, one used for steady-state tests and the other for quasi-dynamic tests [10].

The useful output power of a solar collector for a near normal incidence angle of the solar radiation during steady-state operating conditions, can be written as [10]:

$$Q = F' * A_a * \left((\tau\alpha)_{en} * G - U * (t_m - t_a) \right) \tag{15}$$

The efficiency is then calculated as the ratio of the output energy from the collector and the incident radiation on the area occupied by the collector:

$$\eta = \frac{Q}{G * A_a} = F' * \left((\tau\alpha)_{en} - \frac{U * (t_m - t_a)}{G} \right) \tag{16}$$

Introducing the variable $T_m^* = (t_m - t_a)/G$ indicates the reduced temperature difference as:

$$\eta = F' * \left((\tau\alpha)_{en} - U * T_m^* \right) \tag{17}$$

Heat losses are considered as a function of two terms, the first is a constant and the second dependent on the temperature difference between fluid and ambient $(t_m - t_a)$

The efficiency can be rewritten as:

$$\eta = \eta_o - a_1 * T_m^* * a_2 * G * \left(T_m^* \right)^2 \tag{18}$$

The values of η_o, a_1 and a_2 are usually provided by the manufacturer of the solar collectors. The following collectors have been used for the modeling:

- Company: Thermomax Ltd
- Type: DF 100 30
- Serial number: 08631

Table 1 shows the modeling results for the average daily monthly solar radiation on three different sloped surfaces: tilt angle variable with the month, tilt angle flat with the horizontal and tilted with an inclination equal to the latitude.

Table 1 – Average daily energy per square metre collected by solar panels at different inclination angles

Month	Angle (°)	Daily monthly average energy (kWh)	Angle (°)	Daily monthly average energy (kWh)	Angle (°)	Daily monthly average energy (kWh)
January	0.3	6.550	0.0	6.560	-27.47	5.94
February	5.4	6.237	0.0	6.220	-27.47	5.94
March	20.1	5.700	0.0	5.470	-27.47	5.69
April	38.1	5.842	0.0	4.890	-27.47	5.80
May	50.1	5.478	0.0	3.920	-27.47	5.16
June	55.5	5.473	0.0	3.530	-27.47	4.94
July	53.7	5.674	0.0	3.780	-27.47	5.16
August	43.5	5.642	0.0	4.440	-27.47	5.48
September	28.8	6.207	0.0	5.640	-27.47	6.21
October	10.2	6.093	0.0	6.030	-27.47	5.92
November	0.3	6.940	0.0	6.940	-27.47	6.33
December	0.3	6.610	0.0	6.610	-27.47	5.91

A solar array covering approximately 24 m^2 has been used to calculate the amount of energy collected by the solar collectors with the different tilt angle.

5. Results

The cooling/heating capacity is maximized when the angle is varied monthly to follow the solar elevation. However, the optimization of a solar cooling/heating system also needs to take into account the amount of cooling/heating required as a function of the seasonal weather conditions and the cost associated with the system implementation.

As the solar cooling system in this study requires a peak cooling capacity of 12.2 kW during summer and 5 kW peak heating capacity during winter the proposed system needs a dedicated area of 24 m^2 for the solar panels in order to collect this energy.

Figure 1 and 2 show the maximum cooling capacity obtained by the proposed system in summer and the maximum heating capacity in winter using three different inclinations. The efficiency of the absorption chiller has been assumed to be 0.7 [13] whereas the efficiency of the heating system is assumed as 0.9. The blue line in Figure 1 marks the maximum required cooling in summer and the red line in Figure 2 marks the maximum required heating in winter. Spring and autumn requirements are well below these lines.

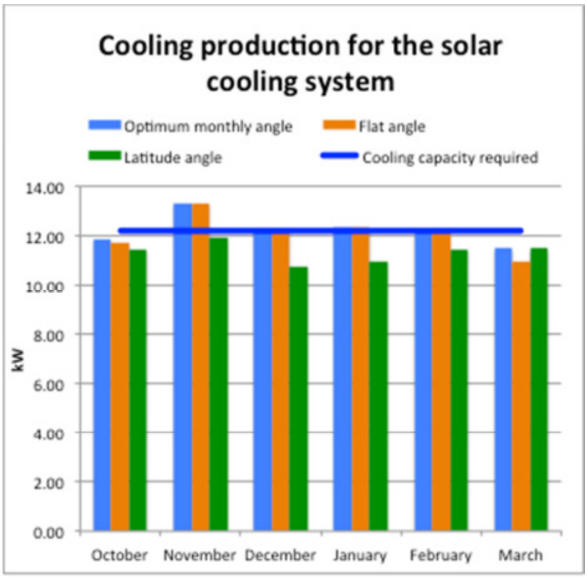

Figure 1 Cooling production during summer

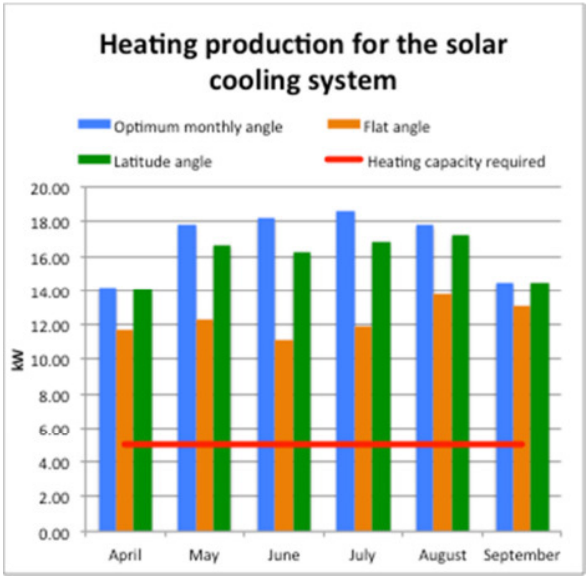

Figure 2 Heating production during winter

The results show that the proposed system can produce the cooling required during summer only by adopting either a monthly variable angle or a fixed horizontal inclination. The calculations show that the solar energy collected during the summer season by the variable or flat angle configuration exceeds the one based on the latitude angle by approximately 10%. Consequently, the number of panels needed for the system can be reduced by 10% with an equal saving in terms of installation cost. It should also be noted that the optimization of the angle by month achieves its best results in winter, when reduced heat is required. In fact the heating required across the winter months is less than half that produced by our system.

6. Conclusion

The cost of implementing a solar cooling system can be compensated by using the solar field of the system not only for a limited time for cooling purpose but also for heating during winter. This is possible by optimizing the number of panels and their tilt angle to achieve the required cooling in summer, as the winter requirement for heating is largely satisfied with the same number of panels used to match the cooling demand.

The results of the calculation suggest that the flat panel configuration is the best solution for a solar cooling and heating installation in the SEQ region considering the cost involved in the installation and maintenance of a variable angle system.

References

[1] Y. Strengers, "Air-conditioning Australian households: The impact of dynamic peak pricing," *Energy Policy*, vol. 38, pp. 7312-7322, 2010.
[2] A. Demirbas, "Global Renewable Energy Projections," *Energy Sources, Part B: Economics, Planning, and Policy*, vol. 4, pp. 212-224, 2009/10/30 2009.
[3] V. Boopathi Raja and V. Shanmugam, "A review and new approach to minimize the cost of solar assisted absorption cooling system," *Renewable and Sustainable Energy Reviews*, vol. 16, pp. 6725-6731, 2012.
[4] K. Sumathy, Z. C. Huang, and Z. F. Li, "Solar absorption cooling with low grade heat source - A strategy of development in South China," *Solar Energy*, vol. 72, pp. 155-165, 2002.
[5] Trane. (2010). *Trace* 700 v6.2.6.5 Available: http://www.trane.com/Commercial/Dna/View.aspx?i=901
[6] K. Bakirci, "General models for optimum tilt angles of solar panels: Turkey case study," *Renewable and Sustainable Energy Reviews*, vol. 16, pp. 6149-6159, 2012.
[7] BOM. (2013). *Boreau of Meteorology*. Available: http://www.bom.gov.au
[8] P. I. Cooper, "The absorption of radiation in solar stills," *Solar Energy*, vol. 12, pp. 333-346, 1969.
[9] B. Y. H. Liu and R. C. Jordan, "The interrelationship and characteristic distribution of direct, diffuse and total solar radiation," *Solar Energy*, vol. 4, pp. 1-19, 1960.
[10] J. A. Duffie, William A. Beckman., *Solar engineering of thermal processes.*, 3rd ed. ed. New York: Wiley, 1991.
[11] A. De Miguel, J. Bilbao, R. Aguiar, H. Kambezidis, and E. Negro, "Diffuse solar irradiation model evaluation in the North Mediterranean Belt area," *Solar Energy*, vol. 70, pp. 143-153, 2001.
[12] E. Zambolin and D. Del Col, "Experimental analysis of thermal performance of flat plate and evacuated tube solar collectors in stationary standard and daily conditions," *Solar Energy*, vol. 84, pp. 1382-1396, 2010.
[13] S. A. Kalogirou, "Recent Patents in Absorption Cooling Systems," *Cyprus Patent*, 2007.