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Solar-Powered Air Conditioning for Buildings in Hot Climates: Desiccant Evaporative Cooling vs. Absorption Chiller-based Systems

Giovanni Brumana*, Giuseppe Franchini

Departement of Engineering and Applied Sciences, University of Bergamo, Viale Marconi 5, Dalmine 24044 (BG), Italy

Abstract

In many countries, solar cooling systems are one of the best candidates to tackling global warming and summer peak loads of building air conditioning systems. In this work, based on the collaboration with the Saudi research institute "King Abdullah City for Atomic and Renewable Energy", two types of solar driven cooling systems are investigated and compared: the open-circuit Desiccant Evaporative Cooling technology and the system based on single-stage LiBr absorption chillers. A computer code has been developed in Trnsys® to simulate a well-insulated single-family residential building, starting from a 3D model of the building architecture, and the solar cooling systems. The simulations have been carried out for two different locations: one in a dry desert area (Riyadh, KSA), the other one on the seaside (Abu Dhabi, UAE). The results show that absorption chillers need a very effective heat rejection system to work properly, whilst DEC systems exhibit a dramatic performance reduction in wet climates.

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Keywords: Solar Cooling; Renewable Energy; Building Simulation

* Corresponding author. Tel.: +39-035-2052300; fax: +39-035-2052077.
E-mail address: giovanni.brumana@unibg.it

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1. Introduction

In recent years, the installation of cooling systems for all kinds of buildings has strongly increased. Unfortunately, this additional energy request accelerated the global warming and the greenhouse effect. Today, for Arabian Peninsula's countries, the electricity request for residential buildings is nearly 40% of the global demand, and approximately 65% of the power consumption in buildings is for air conditioning [1].

Nowadays, the scientific community is addressing many efforts to face this increasing energy request; the focus is on the development of cooling technologies driven by renewable energy sources. Among them, solar cooling systems are the most promising way to reduce the fossil fuel consumption and the related environmental impact [2].

Solar cooling technologies include open-cycle systems, like Desiccant Evaporative Cooling units, and closed-cycle systems, based on absorption or adsorption chillers. The systems with absorption chillers represent the majority of installed units, due to the commercial availability of the chillers for a wide range of cooling capacity (from 15-35 kW up to hundreds of kW). In the open literature, a large number of papers investigates the performance of both solar cooling systems. Many works discuss the influence of the temperature levels in the external circuits [3], and the fundamental role of the hot water storage tank between the solar field and the chiller [4]. Other authors focused the analysis on the control strategy, which can strongly affects the efficiency of the whole system: Shirazi et al. [5] analyzed the performance improvement due to the mass flow rate regulation thanks to a variable speed pump. In the best configuration, the overall performance increases by 11%.

The influence of the ambient conditions is the subject of many papers, mainly devoted to the analysis of DEC systems, which produce the cooling effect by processing the ambient air, without a chiller contribution. In [6] some DEC configurations are tested in the sub-tropical climate of Honk Kong and Muzaffar et al. [7] developed a model to simulate DEC systems for five different climate zones worldwide.

Whilst most works focus on the evaluation of the plant performance as such, only few papers deal with the interaction between the building cooling load and the solar cooling system behavior. Ma and Guan [8] investigated a DEC system installed in a mall for different Australian sites. Dayao et al. [9] discussed the behavior of renewable energy applications in buildings for different climate conditions in China.

The present work, starting from the results of previous researches [10, 11], investigates the performance of two solar cooling technologies (absorption chiller vs. DEC system) for two locations of the Arabian Peninsula, Riyadh and Abu Dhabi. The cooling loads are calculated starting from a 3D model of a residential building for the two sites. The work aims to discuss the performance of solar cooling systems in very hot climates, where high levels of cooling demand and solar radiation take place, and cooling systems undergo critical operating conditions.

Nomenclature

ABS	absorption chiller	Q_{sens}, E_{sens}	sensible cooling load (kW, kWh)
a_1	first order loss coefficient ($W/m^2/K$)	r	latent heat of vaporization (kJ/kg)
a_2	second order loss coefficient ($W/m^2/K^2$)	SF	solar fraction (%/100)
COP	coefficient of performance	T_{chill}	chilled water temperature (°C)
c_p	specific heat (kJ/kg/K)	T_{coll}	outlet collector temperature (°C)
DEC	desiccant evaporative cooling	T_{cool}	cooling water temperature (°C)
ETC	evacuated tube collector	T_{db}, T_{wb}	dry bulb / wet bulb temperature (°C)
$G_{-value,w}$	windows solar factor (%/100)	$T_{ea,d}$	design exhaust air temperature (°C)
$\dot{m}$	mass flow rate (kg/s)	$T_{fa,d}$	design fresh air temperature (°C)
Q_{abs}, E_{abs}	absorption chiller cooling production (kW, kWh)	U_{roof}	roof transmittance ($W/m^2/K$)
Q_{aux}, E_{aux}	auxiliary chiller cooling production (kW, kWh)	$U_{-value,w}$	windows transmittance ($W/m^2/K$)
Q_{coll}, E_{coll}	collected heat (kW, kWh)	U_{wall}	wall transmittance ($W/m^2/K$)
Q_{dec}, E_{dec}	DEC cooling production (kW, kWh)	V_{tank}	tank volume (m^3)
Q_{lat}, E_{lat}	latent cooling load (kW, kWh)	ΔT	temperature difference (°C)
Q_{load}, E_{load}	total cooling load (kW, kWh)	ΔX	absolute humidity difference (g/kg)

2. Case Study

The models developed for simulating solar cooling systems are based on Trnsys® v.17. Hourly weather data are derived from Meteonorm database. To compare the two different solar cooling technologies, the same solar input was considered, i.e. the same solar field (120 m^2) based on Evacuated Tube Collector.

2.1. Building model

The solar cooling systems were designed to meet the cooling demand of a single-family residential building. A two-floor villa with 1000 m^2 total floor area and 3000 m^3 global volume has been considered (Fig. 1).

Fig. 1 – Application for solar cooling systems: single-family detached home

The building geometry was modeled using the common 3D cad software Google Sketch Up®, with the plug-in Trnsys3D. The detailed architectural drawing allows Trnsys® software to accurately predict the solar irradiation and the shading effects on every wall and window. Window orientation and position avoid energy gains related to the direct irradiation. The building design is based on low-energy house references; the aim is to evaluate the performance of innovative cooling systems on a high performing building. The wall layers are designed for hot climates: the external insulation (0.12 m) is coupled with a concrete mass layer (0.20 m). The mass layer smooths the peak of internal energy gains and improves the comfort. The cooling load was calculated on hourly basis in a Trnsys deck based on the Multizone Building model (Type56). The building model includes 20 homogeneous zones, and the internal loads (due to appliances, lights and occupancy) were computed for each room. All main building parameters are reported in Table 1.

Table 1 – Building model parameters

Comfort & Gains			Wall layers & Windows		
	unit	value		unit	value
set point temperature	°C	24	U_{wall}	W/m²/K	0.276
set point relative humidity	%	50	wall thickness	m	0.32
ventilation	Vol/hr	0.60	wall solar absorptance	%/100	0.3
HX efficiency	%	80	U_{roof}	W/m²/K	0.276
infiltration	Vol/hr	0.06	roof thickness	m	0.32
Lighting (peak)	W/m²	5	roof solar absorptance	%/100	0.2
internal gains (peak)	kW	6	$U_{-value,w}$	W/m²/K	0.7
Occupancy	Nr.	20	$G_{-value,w}$	%/100	0.294

2.2. Model of Desiccant Evaporative Cooling system

In a solar desiccant evaporative cooling system, the ambient air flow rate crosses all components from outside to the building. Firstly, the dehumidification occurs in the lower part of the desiccant wheel. Then, the temperature is lowered by crossing an air-to-air heat exchanger and by evaporative cooling. The exhaust air exiting the building is firstly saturated by humidification process; then, it is used to cool the entering fresh air and for the desiccant wheel regeneration. Solar contribution allows exhaust air to increase the temperature level up to 70°C before entering the rotor. An auxiliary chiller provides cooling effect when the DEC system is not able to keep temperature or humidity at the set points. The Trnsys deck of the considered DEC system is reported in Fig. 2.

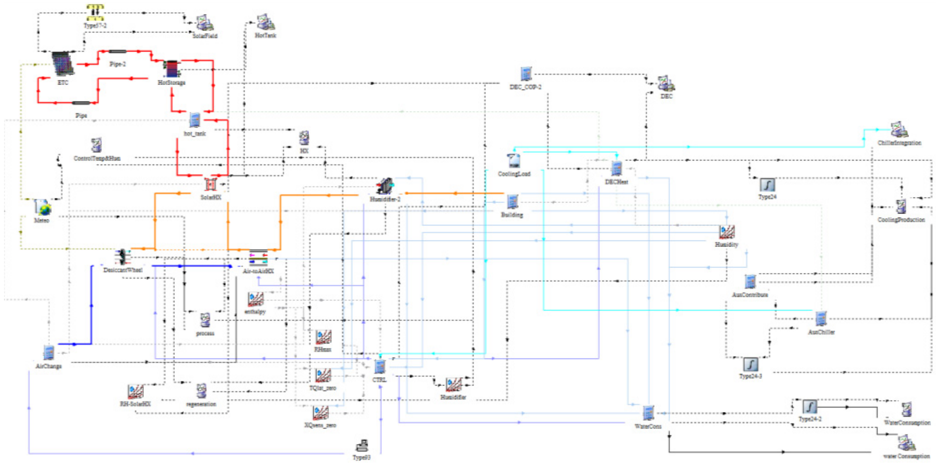

Fig. 2 – Trnsys deck of Desiccant Evaporative Cooling system

The component responsible for the evaporative cooling effect is the humidifier (on the fresh air side) after the air-to-air HX. A user-defined Trnsys 'type' models this component. The algorithm reads the sensible and latent loads from the building model; then, it solves the equation (1) and (2) to calculate the air-flow rate and the entering conditions (temperature and humidity) to meet simultaneously the sensible and latent cooling demand. Figure 3 shows the temperature and humidity set point, and the evaporative cooling effect on the entering air flow. The humidifier on the exhaust flow is set to reach the saturation point.

$$Q_{sens} = \dot{m} \cdot c_p \cdot (\Delta T) \tag{1}$$

$$Q_{lat} = \dot{m} \cdot r \cdot (\Delta X) \tag{2}$$

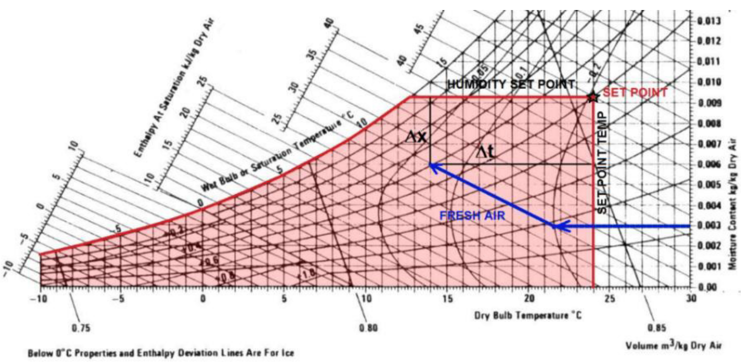

Fig. 3 – Psychrometric chart: set point and evaporative cooling

Table 2 summarizes the design parameters related to the solar field (left part) and the humidification/dehumidification processes taking place in the rotor (central part). The considered air changes for ventilation are reported as well.

Table 2 - Design parameters for the solar field, DEC system and absorption chiller

Solar field (ETC)			Desiccant rotor			Absorption chiller		
Aperture area	m^2	120	$T_{fa,d}$ inlet	°C	30	Rated cooling capacity	kW	35
Optical efficiency	-	0.718	$T_{ea,d}$ inlet	°C	72	Rated COP		0.72
a_1	$W/m^2/K$	0.974	$T_{fa,d}$ outlet	°C	50	T_{chill} inlet	°C	12.5
a_2	$W/m^2/K$	0.005	Humidifier efficiency		0.99	T_{cool} inlet	°C	30
T_{coll} outlet ETC - DEC	°C	80	Air changes	m^3/h	2200	V_{tank} (hot water)	m^3	15
T_{coll} outlet ETC - ABS	°C	90	V_{tank} (hot water)	m^3	15	V_{tank} (chilled water)	m^3	15

2.3. Model of absorption chiller-based solar cooling system

Absorption chiller driven by Evacuated Tube Collectors is the most common solar cooling configuration. The solar field provides heat to the hot storage tank, and a variable speed pump regulates the flow rate to keep the temperature level at the set point. Figure 4 shows the operative Trnsys deck. The hot water tank drives the chiller, which is assumed to operate in On/Off mode. A control system switches on the chiller when the temperature in the cold tank rises up to 10° C, whilst the chiller turns off at 5°C. An auxiliary chiller provides additional cooling when the absorption chiller is not able to keep the chilled water temperature under 11°C. Table 2-right part reports the design parameters related to the absorption chiller. An efficiency map of a commercial LiBr single-stage absorption chiller provides performance data for variable operating conditions. The control system switches off the absorption chiller to avoid crystallization problems when hot water from the solar field and cooling circuit reach the lower (70°C) and upper (32°C) temperature limits respectively.

The heat rejection system strongly affects the absorption chiller performance. In the present work, three different heat rejection modes have been considered: dry air cooler, cooling tower and water. Dry cooler is the most common heat rejection system for residential applications: in hot climates, air-cooled chillers exhibit low efficiency because of the high ambient air temperature. Cooling towers perform well with low wet bulb temperatures, but they require water make-up, and this could be critical in countries with water scarcity. If available, shallow groundwater or seawater can be used as heat sink, with average temperature typically lower than air temperature: this has a beneficial impact on the water-cooled chiller efficiency.

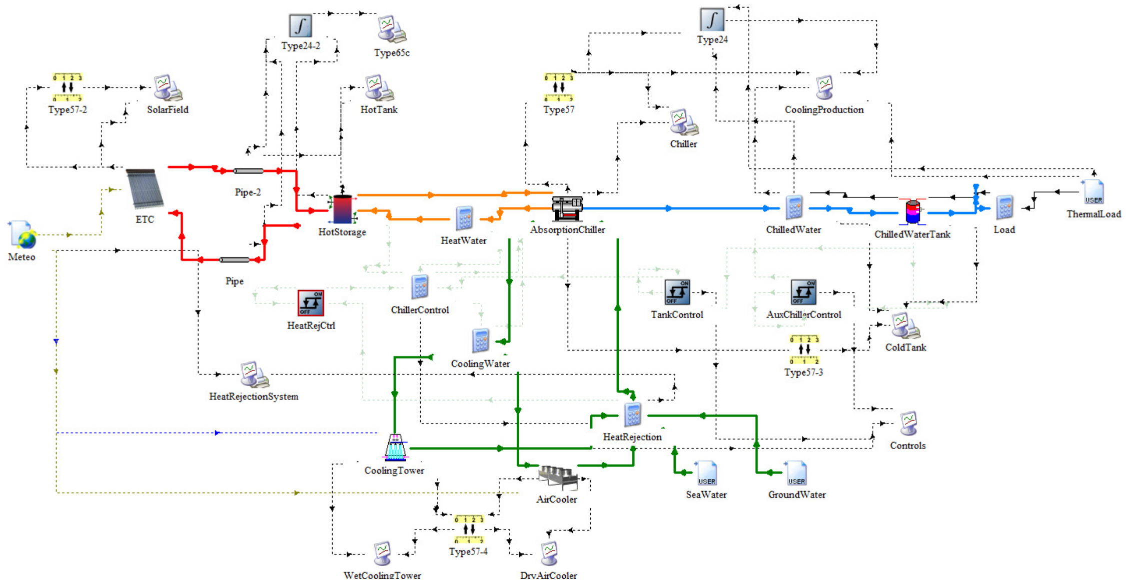

Fig. 4 – Trnsys deck of the absorption chiller based system

3. Simulations Results and Discussion

All simulations have been carried out over a 1-year period with a time step of 0.125 hour (7.5 min). With regard to the building envelop, cooling loads have been calculated for two different locations: Riyadh and Abu Dhabi. Figure 5 shows the cooling demand with the monthly average ambient dry-bulb and wet-bulb temperatures on the left, and the duration curves on the right. Table 3 reports the peak and annual values. Cooling loads for the building located close to the sea (Abu Dhabi) are much higher, because of the huge amount of the latent cooling demand related to the dehumidification process, which is negligible in the dry climate of Riyadh.

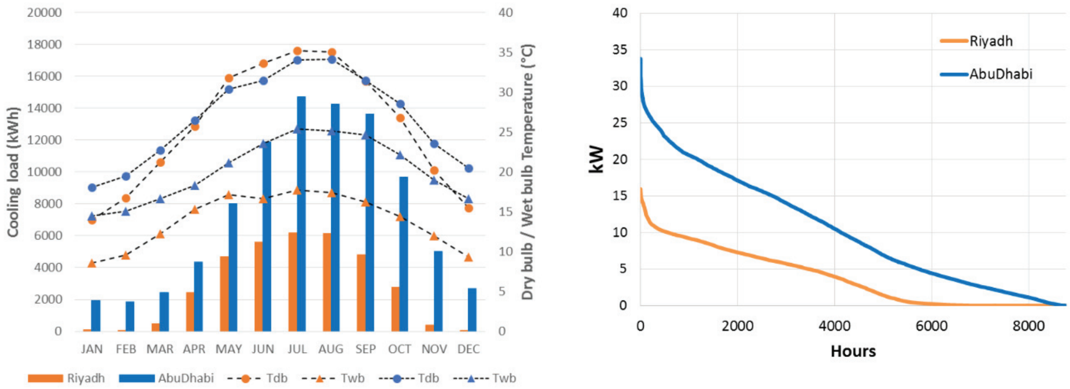

Fig. 5 – Monthly cooling loads and duration curve: Riyadh vs. Abu Dhabi

Table 3 – Cooling loads

	Riyadh			Abu Dhabi		
	sensible	latent	**total**	sensible	latent	**total**
Peak load (kW)	15.94	3.81	**15.94**	16.31	18.56	**33.77**
Annual load (kWh)	33285	450	**33735**	38607	51898	**90504**

With regard to the solar cooling systems, Figure 6 refers to the DEC monthly yield for the two considered locations. For each month, two bar series are reported: the former shows the energy partitioning between sensible and latent load, the latter the cooling production of DEC unit and auxiliary chiller. In the dry climate of Riyadh,

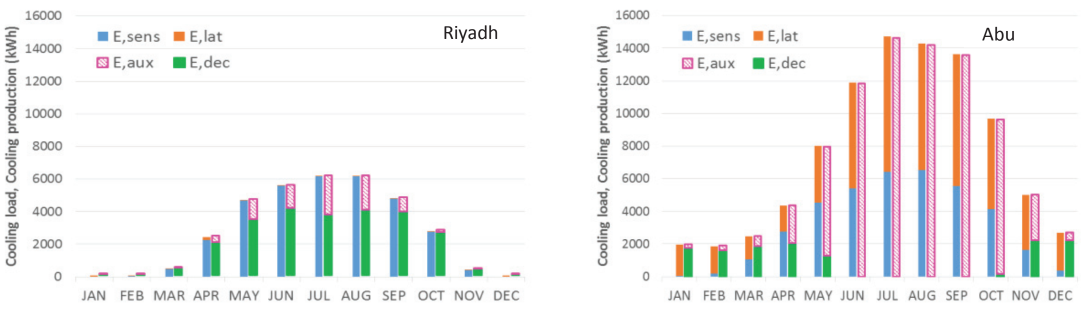

Fig. 6 – Sensible and latent cooling loads; DEC and auxiliary chiller production (Riyadh vs. Abu Dhabi)

where the latent load is minimal, the desiccant-evaporative cooling system performs well: the integration of the electric chiller is needed only for the summer peak loads. Moving to Abu Dhabi, the performance of the DEC system dramatically decays. The sensible cooling demand is similar to the Riyadh case (because the average dry-bulb temperatures are comparable, as documented in Fig. 5-left), whilst the latent load is extremely high. The cooling production by desiccant-evaporative process is limited to the months from October to May. In the summer months, the high levels
of relative humidity inhibit the plant operation.
The solar cooling system based on absorption chiller exhibits a different behavior. Figure 7 shows the simulation results for the case with cooling tower as heat rejection mode. It has to be reminded that the solar input is the same for all configurations. Looking at the performance for Riyadh climate conditions (Fig.7-left), the cooling load is almost completely met by the solar driven chiller: the auxiliary chiller covers only the peak demand in summer. The same plant configuration at Abu Dhabi appears undersized with respect to the increased cooling load. Nevertheless,

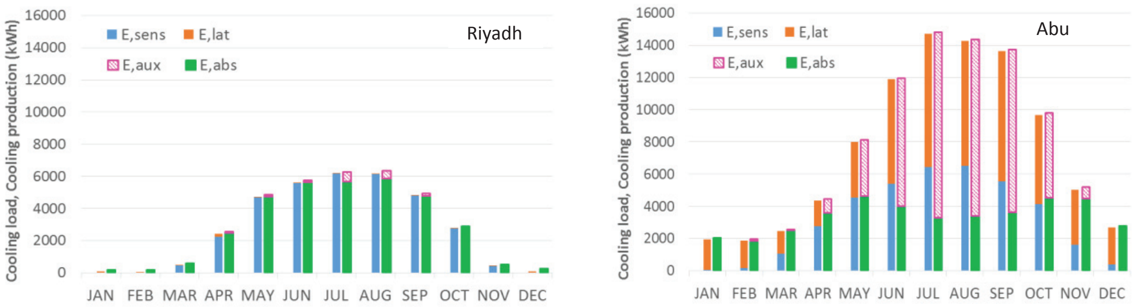

Fig. 7 – Sensible and latent cooling loads; ABS and auxiliary chiller production (Riyadh vs. Abu Dhabi)

the absorption chiller can operate all year long, even if the cooling production decreases in the hottest months. This is due to the high wet bulb temperatures, which affect the cooling tower performance and, consequently, the chiller efficiency. In order to evaluate the global performance of the two investigated configurations, the annual energy balance has been evaluated. Table 4 reports the primary (solar) energy and the cooling production, as well as the solar fraction, defined as in (3).

$$SF = \frac{E_{dec}}{E_{dec}+E_{aux}}, \quad SF = \frac{E_{abs}}{E_{abs}+E_{aux}} \qquad (3)$$

Table 4 – Solar cooling system annual performance

		DEC		ABS	
		Riyadh	Abu Dhabi	Riyadh	Abu Dhabi
E_{coll}	kWh	188393	163802	250714	237708
E_{dec}, E_{abs}	kWh	26011	14037	54167	66041
E_{aux}	kWh	7901	76697	1522	51251
SF	-	0.77	0.15	0.96	0.44

The values of the solar collected energy (E_{coll}) for the DEC system appear significantly lower than the ABS case: this is due to the long periods of non-operation of the DEC unit in summer, leading to the solar field stagnation. As regard to the solar fraction, for Abu Dhabi climate conditions the values are much lower than those of the Riyadh case, because of the much higher cooling load and the negative effect of the high humidity levels.

For the solar cooling system based on absorption chiller, further annual simulations have been carried out in order to investigate the effect of different heat rejection modes. Table 6 summarizes the results for the air-cooled absorption chiller case and for the water-cooled configuration; in the second case, a suitable mass flow rate of groundwater (at Riyadh) and sea water (at Abu Dhabi) was supposed to be available for heat rejection purpose. A constant water temperature level of 29°C has been considered. In Table 5 the results of the reference case (based on cooling tower) are reported for comparison. It can be seen that in the hot dry climate of Riyadh the performance of the air-cooled solar cooling system dramatically decays, because of the high air temperature levels, which negatively affect the chiller efficiency. On the opposite, at Abu Dhabi, where the cooling tower can not perform well due to the high humidity, the solar fraction is similar (46% vs. 44%). The simulation results show that the best performance (SF 100% at Riyadh, 82% at Abu Dhabi) can be achieved by using a water flow rate in an open circuit. A constant temperature heat sink allows the absorption chiller to operate very close to the conditions of full capacity and rated COP.

Table 5 – Annual performance with different heat rejection systems

		Air cooler		Groundwater/Seawater		Cooling tower	
		Riyadh	Abu Dhabi	Riyadh	Abu Dhabi	Riyadh	Abu Dhabi
E_{coll}	kWh	246702	199641	250746	198206	250714	237708
E_{abs}	kWh	22100	42523	34883	75388	33751	40802
E_{aux}	kWh	12918	49252	0	16317	1522	51251
SF	-	0.63	0.46	1.00	0.82	0.96	0.44

4. Conclusions

The model of two solar cooling systems (DEC vs. ABS), including the cooling load calculation of a residential building, was developed to predict the performance under variable operating conditions. Simulations were performed over a one-year period for two locations (Riyadh and Abu Dhabi). The results prove that all solar cooling systems are strongly affected by ambient conditions and cooling load characteristic. It has been shown that a solar cooling system based on absorption chiller with cooling capacity 35 kW and solar aperture area 120 m^2 can meet the cooling demand of a well insulated detached home with 1000 m^2 floor area at Riyadh. Moving to Abu Dhabi, the cooling load strongly increases and the solar fraction is halved. The DEC system exhibits moderate performance in dry climates, whilst it can not operate with high humidity levels. With regard to the heat rejection mode for absorption chillers, the use of groundwater or seawater as heat sink has a beneficial effect on the chiller efficiency, and it is the best option to maximize the overall efficiency.

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