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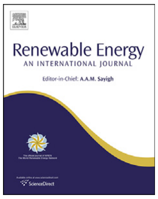

Review

Systematic design and analysis of solar thermal cooling systems in different climates

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ABSTRACT

About 1000 solar thermal cooling systems have been installed worldwide, so experience with system sizing and design is limited. To counter the lack of experience and to evaluate the potential of energy and cost efficient solar cooling systems, a systematic system design study has been carried out covering most climatic regions worldwide. For each technology investigated, an energy optimized control strategy was developed which maximizes the primary energy efficiency.

It could be shown that a reduction of nominal chiller power by 30%–40% or more hardly affects the solar cooling fraction for most climates, but significantly increases the machine operating hours and thus improves the economics. Single effect absorption cooling systems easily reach 80% solar cooling fraction for all but very humid climates. Primary energy ratios can be over 3.0 and primary energy savings between 30 and 79%, depending on system design and cooling load data.

The economic analysis shows that solar thermal cooling and heating is more viable in hot climates than in moderate European climates. To achieve payback times of 10 years with today's energy prices, the investment costs have to be reduced by 30–70% depending on the location and dimensioning.

1. Introduction

Worldwide office buildings are increasingly air-conditioned due to higher comfort standards and increasing financial capabilities. The conventional technology for air-conditioning are electric compression chillers with peak loads during the midday [1]. To reduce the stress on the electrical networks, it is advisable to introduce thermally driven absorption chillers and power them with solar energy or waste heat [4]. In order to achieve significant primary energy savings, it is necessary that high solar fractions are obtained and the lowest possible auxiliary power supply is needed [3].

Today there are about 1000 solar thermal cooling systems installed worldwide. Often hybrid systems with free cooling support are installed and evaluated [5–9]. Heat rejection is an important issue for low auxiliary energy consumption and the use of latent heat stores can reduce heat rejection temperatures and increase efficiency [10]. Many papers analyze the performance of single effect absorption chillers and compare them to conventional cooling equipment. For example, an absorption chiller with 35 kW cooling power had a COP between 0.35 and 0.7, with savings in CO_2 emissions of 36% and energy cost savings of 62% [11]. The performance of a solar assisted 70 kW single effect H_2O/LiBr water chiller also located in Spain was evaluated and achieved a maximum COP of 0.6 [12]. The general agreement is that H_2O/LiBr absorption chiller systems are a mature technology and have a good perspective for energy efficient cooling in the building sector [13] and for industrial applications [2].

Of critical importance for an economical operation are the annual full costs of solar systems. The European funded program ROCOCO found that the installation costs are between 3500 USD and 7000 USD per kilowatt of cooling power in Europe [14]. Otanicar et al. [15] has given a broad technological overview and shows that the COP has a decisive influence on the economics due to the high investment cost of collectors and chiller. The IEA projects a drop of 35–45% reduction in total system cost for solar thermal cooling by 2030 [16].

An economic comparison between a conventional system and a solar thermal system (below 50 kW) in Freiburg and Madrid showed that the annual cost of the solar thermal system were 128% (Freiburg) and 134% (Madrid) higher than those of the conventional system [17]. A study of a hybrid system with an electrical chiller and

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a desiccant wheel in different climatic locations worldwide also showed that the solar system is not yet economically viable [18]. For being economically competitive initial costs for solar thermal collectors and absorption chillers have to be significantly reduced [19].

In summary the current literature either focuses on detailed analyses of individual systems in given climatic conditions or in rather general economic assessments of solar cooling systems, mainly focusing on investment costs. However, as significant primary energy savings at reasonable costs are only possible in very optimized solar cooling installations with minimum auxiliary energy and long operational hours, there is still a know how gap under which conditions solar thermal cooling can be economically and environmentally interesting today.

2. Methodology

To systematically analyze the primary energy performance and cooling costs of solar thermal cooling systems extensive simulations of solar cooling systems in office buildings were carried out for many climatic regions worldwide. The analysis includes different solar collector surfaces areas, chiller nominal powers, storage tank sizes and also three building envelope and internal load specifications. The operating experience has shown that often primary energy savings are less than expected due to high auxiliary energy consumption or to low solar fractions of the cooling demand. Based on previous experimental work by the authors [20], an energy optimized control strategy was developed and implemented in a simulation model, which maximizes the primary energy efficiency. This control strategy was implemented in the renewable energy simulation environment INSEL (Integrated Simulation Environment Language) and system models were developed for a range of thermal cooling technologies, such as single and triple effect absorption chillers as well as adiabatic and desiccant cooling.

The detailed dynamic simulation model of the installed system also considers the auxiliary electricity consumption of all installed components (fans, pumps, etc.). The component models used include dynamic models for the solar collectors and the hot and cold storage tanks. No inertia is considered for the absorption chiller, the piping, the wet cooling tower and the dry heat rejection. The models were validated in an office building installation at the SolarNext company in Germany. Thermal performance data of the solar driven absorption chiller system and auxiliary energy consumption were recorded in summer 2007 and used to validate the developed simulation model of the installed system. The simulation error in thermal energy flows is less than 5%, in auxiliary electrical energy consumption less than 10% [20].

For the single effect machine an economic analysis was carried out on the basis of an annual full cost accounting. The economic analysis was compared with the results of a reference system, consisting of an electrical compression chiller and a gas condensing boiler, described in section 3. Finally, the primary energy and CO_2 saving potentials were analyzed. This paper focuses on the performance of single effect absorption chillers only.

2.1. Cooling load scenarios

The main factors determining the cooling load of buildings is the use, i.e. the internal loads per square meter, the external gains, especially if no sun shading systems are available and finally the insulation standard and ventilation strategy used. To produce a range of load files and analyze the influence of the cooling load time series on system design and performance a three storey office building typology was chosen with a total floor area of 5040 m^2 ([21–23]). The West and East facade have 60% glazing fraction, the North and South facade have 65% glazing fraction. The net air volume is 12,500 m^3. To make results comparable between different climatic zones, the same building was placed in all locations, although local building standards might differ significantly. However, as both loads and insulation standards were varied, the load profiles generated should cover the main influence factors relevant for solar cooling system design.

For each climate three different internal load scenarios and two insulation standards were considered and simulated: Case A with high internal loads, well insulated, Case B with low internal loads, well insulated and Case C with average internal loads, poorly insulated. As the internal loads are extremely important for the cooling load calculation, detailed schedules for each load type were defined with a distinction between weekdays with the main building use from 8am to 5pm, reduced use on Saturdays and no use on Sundays. The details of the building envelope and internal loads scenarios are described in Table 1.

2.2. Climatic boundary conditions

The cooling and heating energy demand of such a middle size office building was dynamically simulated in six different climatic conditions using the EnergyPlus software (Riyadh, Jakarta, Madrid, Barcelona, Stuttgart and Cologne). Global horizontal irradiance and ambient temperature data in hourly resolutions were taken from the EnergyPlus data set [26]. Table 2 summarizes the annual mean temperature and global horizontal irradiance for all locations investigated:

2.3. Heating and cooling demand

For the three scenarios Case A, B and C the heating, cooling and electricity demand was calculated. The electricity demand is caused by appliances and electrical lighting and depends on the internal load scenarios described before. With different internal loads and different building envelope design values, annual cooling demands are changing in each scenario. The building cooling loads were calculated with internal loads (persons, lighting and equipment) as well as with external loads (mainly solar gains and some ventilation gains). The internal loads dominate the cooling loads, especially in the European locations. In addition to the internal loads, the solar

Table 1
Building envelope specifications and maximum internal loads of each scenario.

Case	Façade		Roof		Window		Solar protection	Internal loads		
	Insulation	U-value	Insulation	U-value	U-value	g-Value	b-Value	Lighting	Equipment	People
	cm	W/m^2 K	cm	W/m^2 K	W/m^2 K			W/m^2	W/m^2	W/m^2
A	14	0.319	20	0.235	1.1	60%	40%	18	15	8
B	14	0.319	20	0.235	1.1	60%	40%	9	5	5
C	5	1365	5	1544	2.6	80%	40%	13	10	7

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