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Approaches for the optimized control of solar thermally driven cooling systems

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HIGHLIGHTS

- Strategies for the capacity modulation of thermally driven chillers have been developed.
- The impact of the strategies was evaluated in an extensive parametric study in TRNSYS.
- Adaption of the chilling capacity to varying cooling load functions very well.
- Significant electricity savings can be observed under certain boundary conditions.

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ABSTRACT

Small scale (solar-) thermally driven cooling systems suffer from two important drawbacks: firstly, the systems usually offer no means of adapting the chilling capacity to the actual load; secondly constantly running pumps and fans lead to high auxiliary electricity consumption even when the available driving and cooling water temperatures only allow a reduced chilling capacity. To solve these problems a generic approach for controlling the main parasitic electrical devices – the cooling water pump and the heat rejection fan - as a function of the actual boundary conditions was developed. Different variants of control strategies are analyzed in different system configurations under a variety of climates and load conditions by means of dynamic system simulations in TRNSYS. The most typical combinations of ab- and adsorption chillers with dry cooler and wet cooling tower are covered. The results show that capacity modulation can be realized well by this approach. Additionally electricity savings of up to 25% can be achieved for reasonably sized systems compared to a reference control strategy with fixed pump speed and fixed cooling water set temperature. Yet it becomes obvious that the concrete savings depend strongly on the system configuration and boundary conditions.

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1. Introduction

1.1. Motivation

Small scale (solar) thermally driven cooling systems (STCS) usually feature two drawbacks which lead to a reduced electrical efficiency: Firstly systems with absorption chillers provide no means of adapting the chilling capacity to the actual cooling loads. This leads to cycling and thus inefficient system operation when the cooling load is below the actual chilling capacity [1]. Secondly the auxiliary electricity consumption of the circulating pumps (and frequently also the heat rejection fan) is kept constant, even when the available boundary conditions only require/allow a fraction of the nominal chilling capacity. Since the theoretical maximum EER – determined by the hydraulic power to overcome the internal pressure drops of the three fluid loops at nominal flow, an assumed pump efficiency of 40% and the own consumption of the thermally driven chiller (TDC) – of small scale STCS frequently is already only in the order of 10–20 [2], a reduction of the chilling capacity lead to even lower values. As a consequence, the detailed monitoring of different STCS has shown that the average EER of STCS over an entire cooling season is seldom substantially higher than that of conventional compression cooling systems [3,4].

Therefore the objective of this work is to develop generic control algorithms which tackle both issues. Since the heat rejection unit (either a dry cooler or a wet cooling tower) and the cooling water pump are responsible for 50–80% of the auxiliary electricity

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Nomenclature

Symbols	Description Unit
AEER	average energy efficiency ratio (kW h_{th}/kW h_{el})
COP	coefficient of performance (kW_{th}/kW_{th})
EER	energy efficiency ratio (kW_{th}/kW_{el})
f	relative frequency/speed (%)
I2CL	ratio of daily irradiation on the collector plane to daily cooling load (kW h/kW h_{th})
$\dot{m}$	mass flow rate (kg/h)
P_{el}	electric power (W)
Q	thermal energy (typically daily values) (kW h_{th})
$\dot{Q}$	thermal power (kW_{th})
SF	solar fraction (%)
T	temperature (°C)
t	time (s)
$\dot{V}$	volume flow rate (m^3/s)
Δp	pressure drop (Pa)
ε	efficiency (%)

Abbreviations and subscripts

amb	ambient
avg	average
CC	compression (backup) chiller
CL	cooling load
CT	cooling tower
el	electric
fan	fan
HT	high temperature (driving circuit)
in	inlet
inst	instantaneous
irr	irradiation
LT	low temperature (chilling circuit)
max	maximum/peak
MT	middle temperature (cooling circuit)
nom	nominal
out	outlet
pump	pump
ret	return flow
set	set value
SpcC	space cooling
STCS	solar thermal cooling system
TCD	thermally driven chiller
th	thermal
wb	wet bulb

consumption of STCS according to [2,5], the focus is set on these two components. The chosen approach and the obtainable benefits for systems using both ab- and adsorption chillers are presented in the following.

1.2. State of the art

In this work, the generic term cooling systems refers to chilled water cooling systems, i.e. systems that use chilled water for the cold distribution in the building (with e.g. fan coils, activated ceilings or floor, etc.). Numerous simulation studies on different system concepts have been carried out. Reviews of existing systems can be found e.g. in [6,7]. Conventional systems that use electrically driven vapor compression chillers are distinguished from thermally driven sorption chillers. Both types of systems are commonly operated with constant flow rates and temperature set-points. This work focuses on more advanced control approaches that allow variable flow rates and/or temperature set-points in order to ensure an improved or optimal operation of the chiller.

1.2.1. Control strategies in conventional cooling

Braun developed two methodologies for determining optimal control points of conventional chilled water systems [8,9]. The use of the optimal control leads to significant energy savings at part load conditions. The overall savings depend very much on the time variation of the load. For typical building loads with significant daily and seasonal variation, the penalty for using a fixed set-point control strategy is typically in the range of 5–20% [10].

Lu et al. presented a solution for the global optimization of HVAC systems using a modified genetic algorithm [11,12]. The whole implementation procedure of the proposed optimal method is provided. Simulation studies for a pilot scale centralized HVAC plant show that energy savings of 3–13% compared to conventional strategies were attained with such control.

Similarly, an optimal control strategy for complex building central chilled water systems has been developed for real time applications [13,14]. This optimal control consists of a model based performance predictor based on simplified models, optimization algorithm, supervisory strategy and number of local control strategies. The results obtained in a simulated virtual environment show that 12–25% of the pumping energy and 1–2.5% of the total electricity demand can be saved.

[15] demonstrated that feedback control for cooling tower fans could be eliminated by using an open loop near optimal control strategy. This strategy requires only measuring chiller loading to specify the control and has the advantage to be very stable. The tower fan control is separated into two parts: tower sequencing and optimal airflow. Once the tower sequencing is specified, then the optimal airflow can be determined by analyzing the trade-offs between the costs of operating the chiller and the fan. The authors showed that a linear relationship between airflow and load is valid for loads between 25 and 100% of the design load.

More recently, Li et al. presented an extremum seeking control (ESC) scheme that takes the total power consumption of the compressor chiller and tower fan as feedback, and uses the fan speed setting as control input [16]. The strategy is tested successfully on a dynamic simulation model of the chiller-tower system developed in Dymola using Modelica. Also, a back-calculation based anti-windup issue ESC scheme that can handle the problem of actuator saturation (fan speed limitation) is proposed and validated with simulation. Without using optimization algorithms, the electricity consumption of the cooling tower fans can be significantly reduced if the cooling water set point is controlled according to the wet bulb temperature. A simulation study shows that a simple linear relationship between the set point and the wet bulb temperature allows saving up to 20% of the total electricity demand of a large chilled water system [17].

Similarly to cooling tower fans, the power consumption of the chiller and the chilled water pump can be minimized by controlling optimally the chilled water pump. Braun et al. demonstrated that the optimal chilled water set point varies as a near linear function of both load and wet bulb temperature over a wide range of conditions [8,9].

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