Journal of Process Control 24 (2014) 836–845

Contents lists available at ScienceDirect

Journal of Process Control

journal homepage: www.elsevier.com/locate/jprocont

Predictive and interactive controllers for solar absorption cooling systems in buildings

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ARTICLE INFO

Article history:
Received 15 March 2013
Received in revised form 4 March 2014
Accepted 21 March 2014
Available online 13 April 2014

Keywords:
Absorption system
Model predictive control
Interacting controllers
Modeling

ABSTRACT

A predictive control approach is proposed for a solar powered hot water storage (SHWS) system which interacts with a simple thermal building control. The primary objective of this first controller is to optimize the use of the solar energy in order to ensure the cooling requirement of the building. The main difficulties are related to the presence of safety constraints and the nonlinearity as well as the hybrid nature of the system. The resulting optimization problem is simplified using various relaxations. The second controller is dedicated to the control of the building temperature. Using a model of the building thermal behavior, it sends its predicted operating profile to the SHWS controller. The performances of these two interacting controllers are illustrated by various simulations on a TRNSYS model of the building and its subsystems.

1. Introduction

Conventional air conditioning systems in buildings are a major energy consumer during summer. Therefore, to reduce electrical energy use, the development of an environmentally-friendly, renewable based cooling system is important [12]. A solar absorption refrigeration system is an alternative to reduce the global electricity demand and is particularly attractive because of the near coincidence of peak cooling loads with the available solar power [5]. However, absorption cooling systems have some disadvantages compared to the conventional refrigeration systems, such as the high initial cost and the low efficiency when auxiliary energy is needed. In addition, to improve energy efficiency, it needs a thermodynamic analysis as well as subsequent optimization [9]. Several studies have been performed concerning the performance of absorption cooling systems. In [8] the authors investigated the performance of a solar powered absorption installation with various enhancements and a model of the system was developed for its simulation in the thermal modeling tool TRNSYS [3]. Two driving energy sources are considered in [12] for an absorption cooling system. A biomass boiler works as the auxiliary source when there is not enough solar energy and works as the main heat source when the solar radiation is not available. An experimental study was carried out in [5] to compare the performance of an absorption cooling system with a partitioned hot water storage as well as its performance considering a conventional whole-tank mode. Another cooling system is presented in [15] where the air supplied to the building is produced by both electric and solar energy. Electric energy is saved in the air dehumidification process because of the precooling of the solar system. In [14] a solar-powered air conditioning system for heating and cooling houses in Spain has been experimentally studied. Auxiliary energy is not used to drive the system, thermal energy was supplied entirely by collectors. The authors in [4] and [7] reported the use of TRNSYS to evaluate the energetic and economic performance of the solar cooling system and to carry out statistical studies about the influence of the design parameters in the performance of the entire cooling system. These studies are mainly concerned with technological aspects of the process, whereas the aim of this proposal is to evaluate how the use of predictive control for the solar part of the cooling absorption system which interacts with the chilled water consumption, can improve its efficiency and safety.

Model predictive control (MPC) (see e.g. [2]) is proven to be a useful framework to tackle the problem of energy cost reduction in buildings. For example, the study in [11] focuses on an individual building zone regulated via stochastic MPC. Other studies related to thermal comfort control via MPC for multi zones buildings are presented in [1,10]. However these studies mainly focus on the control of the emission part, while the problem here also concern production. It is then close to the study presented in [13] where the authors consider the optimization of a solar domestic hot water system with a stratified storage tank including a segmented auxiliary heater. However, for the present application of solar hot water system, the load is specific and it is useful to take advantage of this particularity to improve the control efficiency.

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http://dx.doi.org/10.1016/j.jprocont.2014.03.008
0959-1524/

Nomenclature

A	Total collector array aperture or gross area [m^2]
a_0	Solar collector intercept efficiency
a_1	Solar collector efficiency slope [kJ/(h m^2 K]
a_2	Solar collector efficiency curvature [kJ/(h m^2 K)]
c	Specific heat of the fluid [kJ/(kg K)]
C_{min}	Minimum capacity rate of the fluids entering the heat exchanger [kJ/(K h)]
$g_{,max}$	Maximum value of the g variable
$g_{,min}$	Minimum value of the g variable
$g_{,nominal}$	Nominal value of the g variable
I_T	Total radiation on collector tilted surface [kJ/(h m^2)]
I_{Ts}	Total radiation on building's wall oriented to the south [kJ/(h m^2)]
$\dot{m}_1$	Diverter outlet fluid mass flow rate to the tank cold side [kg/h]
$\dot{m}_2$	Diverter outlet fluid mass flow rate to the mixing valve [kg/h]
$\dot{m}_{ch}$	Fluid mass flow rate in the chiller evaporator circuit [kg/h]
$\dot{m}_h$	Fluid mass flow rate to the tank hot side [kg/h]
$\dot{m}_l$	Fluid mass flow rate in the chiller generator circuit [kg/h]
$\dot{m}_s$	Fluid mass flow rate to the collector [kg/h]
N_h	Prediction horizon
o_c	Human occupancy profile
On	Switch control variable of the building cooling system
Q	Positive definite weighting matrix
$\dot{Q}_{aux}$	Rate of energy input by the heating element [kJ/h]
$\dot{Q}_s$	Rate of energy transfer in the collector [kJ/h]
T_{chr}	Temperature of the fluid entering the chiller evaporator circuit [°C]
T_{chs}	Temperature of the fluid entering the cooling ceiling of the building [°C]
T_{ext}	Ambient (air) temperature [°C]
T_h	Temperature of the fluid entering the storage tank from the heat source [°C]
T_i	Collector inlet temperature [°C]
T_k	Temperature of the kth tank segment [°C]
T_l	Temperature of the fluid replacing that extracted to supply the load [°C]
T_o	Mixing valve outlet temperature [°C]
T_s	Collector outlet temperature [°C]
T_{sbg}	Set-point temperature of the building [°C]
T_{set}	Set-point temperature demanded by the chiller generator circuit [°C]
T_{wbp}	Water boiling point temperature [°C]
t_s	Solar cooling plant sample time [h]
U	Input vector of the SHWS system model
u	Input vector of the building state-space model
V	Volume of the stratified storage tank [m^3]
W	Non-controlled vector input of the SHWS system model
X	state vector of the SHWS system model
x	State vector of the building state-space model
$\hat{x}$	Estimated vector of the building state-space model
Y	Output vector of the SHWS system model [°C]
y	Output of the building state-space model [°C]
α	Optimized variable associated with the additional flow rate
γ	Diverter control function
$\Delta\dot{m}_l$	Additional flow rate sent to the chiller [kJ/h]
Δt	SHWS prediction model sample time [h]
ε	Heat exchanger effectiveness
η	Solar collector efficiency
ρ	Water density [kg/m^3]

Moreover, in this application, the solar system is allowed to request for consumption: it induces changes in the control structure. Finally, in [6] a model predictive control has been proposed for building temperature regulation using a compressor-based chiller for cooling production. The predictive control system has been divided into two levels. The high level MPC is related to the cooling/heating system production and the low-level MPC represents the building system regulation. The main difference with this study is the thermal emission regulation that it kept basic to remain compatible with the existing control.

This paper proposes a predictive control approach for an energy production system that interacts with a simple thermal building control. The energy production system controller receives an energy demand profile from the thermal building controller and optimizes the set of control signals to ensure the energy demand. In order to fulfill the constraints, the proposed predictive control approach can request an additional consumption to the thermal building controller. The interactive controllers are conceived in an independent way: the predictive controller design does not depend on the building controller design and vice versa. Moreover, the control structure can be extended when needed for more consumers. A solar powered hot water storage (SHWS) system is chosen as the production system. The paper is organized as follows. A description of the system as well as a basic control scheme and performance indexes are introduced in Section 2. The proposed control structure is presented in Section 3. The control model is described first, then the MPC problem formulation is stated and the global control structure is defined. Finally, in Section 4, the results of experiments performed with a TRNSYS model of the building and its systems are presented. This makes it possible to assess the proposed control structure and to propose further ideas to enhance the approach.

2. The cooling system and its control

2.1. System description

Fig. 1 depicts a solar cooling system which is divided into two parts: the production and the consumption system. The production system corresponds to a solar powered hot water storage (SHWS) and the consumption part is composed of a building and an absorption chiller.

The building is well insulated but with a large window to the south. It is located in Chihuahua (Mexico). The cooling of the building is achieved by a stream of chilled water supplied to a radiant ceiling. This cooling system is controlled by a logical signal that controls the flow rates in the circulation pumps P3 and P4 and the chiller. When operating, the latter imposes that the temperature of the inlet hot water T_o is constant (T_{set}) and delivers cold water at a constant value T_{chs}. A control abstraction of this system is given in Fig. 2 where the meteorological data that influence the thermal comfort inside the building are considered as disturbances.

The hot water generator system is composed of flat-plate collector panels where the global collector area is 11.8 m^2, a constant effectiveness heat exchanger and a stratified storage tank of a 1.8 m^3 with an electric auxiliary heater at the top. A flow diverter and a mixing valve ensure that the temperature of the outgoing flow is set to the correct temperature. The flow rates of circulation pumps P1 and P2, as well as the auxiliary energy of the heater, can