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Energy efficient control of HVAC systems with ice cold thermal energy storage

Alessandro Beghi [a], Luca Cecchinato [b], Mirco Rampazzo [a,*], Francesco Simmini [a]

[a] Dipartimento di Ingegneria dell'Informazione, Università di Padova, via Gradenigo 6/B, I-35131 Padova, Italy
[b] Everest s.r.l., via Roveredo 20, I-33170 Pordenone, Italy

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ABSTRACT

In heating, ventilation and air conditioning (HVAC) systems of medium/high cooling capacity, energy demands can be matched with the help of thermal energy storage (TES) systems. If properly designed, TES systems can reduce energy costs and consumption, equipment size and pollutant emissions. In order to design efficient control strategies for TES systems, we present a model-based approach with the aim of increasing the performance of HVAC systems with ice cold thermal energy storage (CTES). A simulation environment based on Matlab/Simulink® is developed, where thermal behaviour of the plant is analysed by a lumped formulation of the conservation equations. In particular, the ice CTES is modelled as a hybrid system, where the water phase transitions (solid–melting–liquid and liquid–freezing–solid) are described by combining continuous and discrete dynamics, thus considering both latent and sensible heat. Standard control strategies are compared with a non-linear model predictive control (NLMPC) approach. In the simulation examples model predictive control proves to be the best control solution for the efficient management of ice CTES systems.

1. Introduction

Heating, ventilation, and air-conditioning (HVAC) systems in residential, commercial, and industrial sectors are responsible for a major portion of energy utilisation. Energy demands vary with daily, weekly, and seasonal trends. These demands can be matched with the help of thermal energy storage (TES) systems that, if properly designed, installed, operated, and maintained, can be effectively used to shift peak loads to off-peak periods. The use of TES systems often results in significant benefits, such as: reduced energy costs and energy consumption, increased flexibility of operation, decreased initial and maintenance costs, reduced equipment size, more efficient and effective utilization of equipment, conservation of fossil fuels (by facilitating more efficient energy use) and reduced pollutant emissions (e.g. CO_2) [1,2]. In particular, in HVAC cooling systems, a popular thermal storage medium is ice: the cooling capacity of an ice Cold TES (CTES) system under total freezing is 18 times as high as that of a water CTES system operating between 12 °C and 7 °C [3]. An ice CTES has operating phases, namely, a charging phase where (typically at night) heat is removed from water to produce ice, and a discharging phase, where, when the building requires cooling, heat is removed from the building and added to the ice. The melted ice is reused during the next charging period. The advantage of this cooling scheme is that the main electrically driven device in cooling systems, namely, the compressor, is operated during low-electrical cost periods, i.e. at night [3]. However, experience with operating TES systems demonstrates that poor design and operation of the control systems can lead to bad energy efficiency [4]. It is worthwhile noting that a cooling plant with TES is a complex system. Highly non-linear behaviour and strong cross coupling of inputs and outputs make its modeling and control a non-trivial task. Classical control design methods seem not to be able to achieve the right trade-off between energy efficiency and demand satisfaction: they cannot provide reasonable comfort at minimum energy use and financial costs. Different approaches have been proposed in the literature in order to find suitable controls for TES systems. In [5] a simulation environment for the analysis of ice storage controls is presented. In [6] Henze et al. provide some guidelines to obtain an improvement of TES system energy performances; these guidelines are derived from the analysis of optimal control and its comparison to TES system standard control strategies. In [7] predictive control design for a three-story office building equipped with two chillers with constant coefficient of performance and a thermal energy storage system is illustrated.

In this paper, a model-based approach is developed to design efficient control strategies for HVAC systems equipped with ice CTES. The thermal behaviour of the HVAC plant is analysed by

* Corresponding author. Tel.: +39 0498277746.
E-mail addresses: beghi@dei.unipd.it (A. Beghi), lcecchinato@energyeverest.com (L. Cecchinato), mirco.rampazzo@dei.unipd.it (M. Rampazzo), simminif@dei.unipd.it (F. Simmini).

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Nomenclature

$\mathcal{C}$	price of electricity [€ W^{-1} min^{-1}]
ChN	nighttime-chiller
ChD	daytime-chiller
c_{pl}	water specific heat [J kg^{-1} K^{-1}]
c_{ps}	ice specific heat [J kg^{-1} K^{-1}]
h	tank well-mixed section fraction [–]
HS	CTES hybrid system
$\dot{m}$	massflow rate [kg s^{-1}]
N	moving window size [–]
PLR	part load ratio [–]
Q	energy [J]
T	water temperature [°C]
T_{air}	air temperature [°C]
$\mathfrak{T}_c$	control horizon [min]
$\mathfrak{T}_p$	prediction horizon [min]
V	volume [m^3]
VA-CD	charging/discharging valve
VA-TES	modulating control valve
Z	part load factor [–]
α	tuning coefficient [€ K^{-2}]
β	moving window weight factor [–]
Δ	difference operator [–]
ϵ	efficiency [–]
λ	specific latent heat [J kg^{-1}]
ν	VA-TES valve opening [–]
ρ	water density [kg m^{-3}]
σ	loss coefficient [K^{-1} s^{-1}]
τ	time [min]

Subscripts

ch	chiller
e	electrical
f	water tank or piping
g	generation
i	inlet
k	block index
l	load
n	nominal
o	outlet
s	accumulation or storage
TES	thermal energy storage
tran	transition
v	VA-TES valve
w	wastage

resorting to a lumped formulation of the conservation equations and a simulation environment based on Matlab/Simulink® is designed accordingly. The contribution of the paper is twofold. The first contribution regards modeling of the ice CTES. Differently from what has been proposed so far in the literature, the ice CTES is modelled as a hybrid system, where the water phase transitions (solid–melting–liquid and liquid–freezing–solid) are described by combining continuous and discrete dynamics, so that both latent and sensible heats are considered. It is worth noting that the ice latent heat represents a large portion of the total storage energy (e.g. 90%). However it is appropriate to consider also the sensible heat portion in order to adequately evaluate the energy efficiency of the HVAC system when operated with different control strategies. The second contribution in the paper is the comparison, in the developed simulation environment, of three standard control strategies (constant-proportion control, chiller-priority control and storage-priority control) and an advanced control strategy based on model predictive control (MPC), which has been successfully used in building cooling systems with water TES [8,9]. MPC refers to a class of algorithms that compute a sequence of manipulated variable adjustment in order to optimise the future behaviour of a controlled process. In this study, the future outputs of the plant are predicted by using a white-box model fed by future control variables together with disturbances forecasting. The optimisation step is developed by using a stochastic technique, the particle swarm optimisation (PSO) algorithm, that has already been proved to be a practical solution in energy-related industrial applications [10]. In the provided examples two typical commercial building cooling load profiles are taken into account. Furthermore, the case where the predicted disturbances and actual ones do not match is considered. The simulations show that model predictive control provides the best control solution for the efficient management of ice CTES systems.

The paper is organised as follows. In Section 2 the structure of the cooling plant with ice CTES and its model are presented. In Section 3, a TES charging simulation example is provided. In Section 4 extensive simulation results for TES discharging are given: conventional control strategies and the MPC approach are detailed and compared through dynamic simulation examples. Conclusions are drawn in Section 5.

2. Plant description and model

In Fig. 1 a typical HVAC system of a commercial building with ice storage, in chiller upstream configuration, is shown. The system is composed of two parallel air-condensed chillers, an ice storage, a temperature-modulating control valve, a diverting valve that allows charging/discharging operations, and an air-conditioning system that can be a conventional central system. One chiller is used during the night in order to charge the TES; during the day the other one and the ice CTES are used together to satisfy cooling demand.

The following scenario is an example of a partial-storage system at nominal conditions. During off-peak nighttime hours the nighttime-chiller (ChN) works as ice maker: a glycol solution (e.g. 25% ethylene glycol) is pumped through the chiller coils and the CTES in the chilled-water loop (VA-CD = 0, Fig. 1). The −5 °C ethylene glycol produced by the chiller freezes the water contained inside the CTES and charges it for use during the next day's cooling. Ice-making has the effect of de-rating the nominal chiller capacity by approximately 30–35%. Compressor efficiency, however, varies only slightly because lower nighttime temperatures result in cooler condensation temperatures and help to keep the unit operating efficiently (reducing the compressor pressure ratio). A full charging cycle of an ice tank requires approximately 6–12 h, depending on its size. During the discharge cycle in the following day (VA-CD = 1, Fig. 1), the glycol solution pre-cooled by the daytime-chiller (ChD) is further cooled by the ice CTES. The temperature-modulating valve, in the bypass loop around the TES, permits a sufficient quantity of glycol solution to bypass the storage, mixed with solution arriving from the CTES, and allows us to achieve the desired temperature of the supplied glycol solution that is distributed to the cooling devices (e.g. air-handler coils). The solution leaving the building re-enters the chiller and is cooled again.

The thermal behaviour of the plant can be usefully analysed by a lumped formulation of the conservation equations. The elements of the plant are simulated in Matlab/Simulink® through blocks (chiller, piping, storage, valves, tank and thermal load). At each time τ, the mass and energy balance equations for the k-th block are:

$$\dot{m}_{i,k} - \dot{m}_{o,k} = 0, \quad \dot{m}_k := \dot{m}_{i,k} = \dot{m}_{o,k}, \tag{1a}$$

$$\dot{Q}_{g,k} + \dot{m}_{i,k} c_{p_l} T_{i,k} - \dot{m}_{o,k} c_{p_l} T_{o,k} - \dot{Q}_{w,k} - \dot{Q}_{s,k} = 0. \tag{1b}$$