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Model predictive control strategy applied to different types of building for space heating

Gohar Gholamibozanjani[a], Joan Tarragona[b,c], Alvaro de Gracia[b,d], Cèsar Fernández[b], Luisa F. Cabeza[b], Mohammed M. Farid[a,*]

[a] Department of Chemical and Materials Engineering, University of Auckland, Private Bag 92019, Auckland, New Zealand
[b] GREiA Innovació Concurrent, INSPIRES Research Centre, University of Lleida, Pere de Cabrera s/n, 25001 Lleida, Spain
[c] CIRIAF – Interuniversity Research Centre on Pollution and Environment Mauro Felli, Via G. Duranti 63, 06125 Perugia, Italy
[d] CIRIAF - Interuniversity Research Centre, University of Perugia, Via G. Duranti 67, 06125 Perugia, Italy

HIGHLIGHTS

- Model predictive control was applied to study the thermal efficiency of buildings.
- Latent heat thermal energy storage was charging with solar energy.
- The heating demand of buildings was estimated using EnergyPlus software.
- Smart control was effective for domestic, office and service buildings, respectively.
- Through a 7-day simulation, cost savings of about 12–57% was achieved for different buildings.

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ABSTRACT

In recent years, the concept of energy-efficient buildings has attracted widespread attention due to growing energy consumption in different types of buildings. The application of thermal energy storage (TES) systems, especially latent heat energy storage (LHES), has become a promising approach to improve thermal efficiency of buildings and hence reduce CO_2 emissions. One way to achieve this, could be by implementing a model predictive control (MPC) strategy, using weather and electricity cost predictions. To this end, a heat exchanger unit containing a phase change material (PCM) as a LHES medium, thermally charged by solar energy was incorporated into three versions of a standard building. This paper reports on the use of EnergyPlus software to simulate the heating demand profile of these buildings, with Solving Constraint Integer Programs (SCIP) as the optimization tool. After applying MPC strategy, the energy costs of different building types were evaluated. Furthermore, the effect of prediction horizon and decision time step of MPC strategy, and PCM mass capacity on the performance of the MPC were all investigated in 1 and 7-day simulations. Results showed that by increasing the prediction horizon and PCM mass, more cost saving could be obtained. However, in terms of decision time step, although the study revealed that increasing it led to a higher energy saving, it made the system more sensitive to sharp changes as it failed to provide an accurate reading of the parameters and variables.

1. Introduction

About 36% of global energy used worldwide is attributed to buildings [1], which also contribute to about 17% of total direct energy-related CO_2 emissions to the environment [2]. Heating, ventilation, and air conditioning (HVAC) make a major contribution to energy consumption in buildings [3].

Design professionals, especially architects and engineers, are experiencing an unprecedented level of demand to apply novel approaches to buildings in order to improve their thermal performance. The integration of thermal energy storage (TES) systems into buildings can satisfy their growing demand for energy, as well as reduce environmental pollution caused by the excessive use of energy. Among different energy storage systems, latent heat energy storage (LHES) using phase change materials (PCMs) can greatly enhance the energy efficiency of buildings owing to their large energy storage capacity,

* Corresponding author.
E-mail address: m.farid@auckland.ac.nz (M.M. Farid).

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Nomenclature

Δp	overall pressure drop (kPa)
Δt	decision time step (s)
ΔT	temperature difference (°C)
C_p	specific heat capacity (kJ/kg·K)
I	intensity of solar radiation (W/m^2)
k	simulation time step
l	cost function (NZD)
M	mass (kg)
$\dot{m}$	mass flow rate
N	number of prediction horizon
Q	volume flow rate (m^3/s)
$\dot{Q}$	thermal power (kJ/s)
T	temperature (°C)
u	control input
U	Constraint of input value
x	control input
x_0	initial state of the control input
X	Constraint of input value

Greek symbols

η	efficiency
ε	conversion coefficient to estimate the outlet temperature of heat exchanger as a function of PCM temperature

Subscripts

f	fan
amb	ambient
HE-Room	directing from heat exchanger to room
in, SAC	inlet of solar air collector
l	liquid
m	melting point
out, SAC	outlet of solar air collector
out, HE	outlet of heat exchanger
s	solid
SAC-HE	directing from solar air collector to heat exchanger
SAC-Room	directing from solar air collector to room

which is available within a narrow temperature range [4]. However, the incorporation of TES in buildings to minimize energy consumption and energy costs, while maintaining a comfortable thermal environment, requires comprehensive pre-analysis and thorough mathematical study.

The development of computer technologies and modeling techniques has enabled the prediction of energy consumption levels in buildings [5]. By means of design control methods using dynamic models, prediction of the thermal performance of building systems is now more cost-effective and less time-consuming. Indeed, dynamic models have become crucial for the development of control programs to optimize energy consumption and provide a comfort zone for the occupants of buildings [6]. In this regard, smart control of TES would maximize its energy and economic benefits and hence justify its initial high investment costs.

Model predictive control (MPC) through the well-established strategy of classical control has attracted research attention in the area of energy-efficient buildings. Although MPC strategies have been used in process control for several decades, they have not been applied to building automation until recently. Basic criteria that MPC strategies need to meet are simplicity, well-estimated system dynamics, steady-state properties, and suitable prediction properties [7]. For instance, Ebrahimpour and Santro [8] used the moving horizon estimation of lumped load and occupancy in order to improve the accuracy of the dynamic model and MPC performance, subsequently. The advantage of MPC strategy over conventional building control methods is that it considers the future prediction of ambient temperature, solar radiation and occupancy, as well as system operating constraints, in the design of the control system [9]. However, in conventional methods, the control system is based on occupancy status of the building only, so the heating system is switched off if there is no one in the building. Further, TES is not used to cut down the operating cost of the building [10].

By taking into account internal gains, equipment, weather, and cost, an MPC can provide the required level of thermal comfort [11]. Ma et al. [12] conducted a numerical study to control the cooling system of a building. The building was equipped with a water tank and a series of chillers to provide the cold water. A cost saving of about 24% was achieved through the implementation of an MPC strategy and using weather profile prediction. Morosan et al. [13] also studied thermal regulation using an MPC strategy and weather profile prediction. The control design in their study was based on available control strategies, which have centralized and decentralized structures. In the centralized structure, a single controller is used to provide a comfortable indoor temperature for a multi-zone building. However, in the decentralized structure, each zone has its own controller. As the centralized structure has computational complexity, and the decentralized one ignores heat transfer between zones, they proposed a distributed control strategy to take advantage of both control structures. Their findings showed that by implementing the distributed structure, in which case the local controllers of different zones share their future behavior, the performance of system was improved.

MPC strategy is being used in HVAC systems for optimal heating and cooling [14], and reduction of peak energy demand in buildings [15]. In the study of energy efficient heating, Siroky et al. [16] carried out an experimental analysis of an MPC strategy using weather prediction approach. Over a two-month experiment modeled on a building in Prague, the Czech Republic, an energy saving of about 15–28% was achieved. Differences found in energy saving were due to the effect of various parameters, such as insulation level and variation in outside temperature. The results revealed a good consistency with the results of a large-scale simulation carried out in another study [17]. It is clear that MPC not only minimizes energy consumption, but also contributes to reduction in peak energy demand, which in turn can lower the operating costs of a building. Ma et al. [18] studied the effect of MPC strategy on reduction of peak electricity demand for cooling in a commercial building. Owing to the automatic off-peak pre-cooling effect and shifting of energy demand from peak to off-peak hours, the analysis using MPC resulted in a significant cost saving.

Other research has studied the role of MPC strategies in buildings using TES. For example, Zhao et al. [19] conducted an economic MPC-based study to optimize the energy demand of a Hong Kong zero-carbon building. A stratified chilled water storage tank was integrated into the model as TES. The results showed reductions of 6–22% in energy consumption, 23–29% in operating costs, and 12–48% in CO_2 emissions, depending on the connection to grid and season of the year.

In fact, a considerable number of studies have applied MPC strategies to the HVAC systems of buildings to make them more energy-efficient [20]. The majority of this work has taken advantage of sensible thermal energy storage [21] to further improve energy savings. Much less work has been done on the incorporation of LHES into systems. In one example, Papachristou et al. [22] incorporated PCM into the fabrics of a building in Canada. The PCM was charged through forced air circulation in room. Their objective was to develop a low-order thermal network model for the design of MPC strategy as well as optimization of PCM performance. Finally, the comparison of the modeling results with experimental data showed a great match in predicting the peak power