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Hybrid model predictive control of a residential HVAC system with PVT energy generation and PCM thermal storage

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Hybrid model predictive control of a residential HVAC system with PVT energy generation and PCM thermal storage

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Abstract

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Keywords: Hybrid; Model Predictive Control; Residential; Building; Modelling; PVT; Energy Storage.

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1. Introduction

Buildings account for approximately 40% of the world's energy demand [1]. Energy efficiency improvements in buildings are therefore essential to reduce global energy usage and greenhouse gas emissions. Over the last several decades, many methods have been proposed and used to promote building energy efficiency and sustainability, which include, but not limited to, optimal design [2, 3], advanced optimal control [4], existing building refurbishment [5], and integration of renewable energy technologies and energy storage [1]. Among these different approaches, optimisation of the control of buildings and building HVAC systems is receiving increasing interest and attention because of the relatively low marginal cost of improving control systems.

Model predictive control (MPC) is an advanced control methodology and has been used in recent times for real-time control of buildings and building HVAC systems in a limited range of situations. MPC uses a 'system model' to predict the future states of the system and identify optimal control settings to minimise a prescribed 'cost function' over the prediction horizon in the presence of disturbances and operating constraints [4]. Demand management of building energy systems using an economic MPC analysis was studied by Ma *et al.* [6] where the economic objective function used in the MPC included the daily time-of-use energy charge and demand charge. An experimental investigation of an MPC controller applied to an heating system was presented by Široký *et al.* [7]. The results showed that the energy saving potential of using MPC with weather predictions for the heating system was in the order of 15% to 28%. West *et al.* [8] presented trial results for the use of MPC to optimise a commercial building HVAC system. An average energy reduction of 19% and 32% was achieved in two case study office buildings during two winter test months. MPC has also been recently applied in the simulated control of a simple residential energy system [9] and HMPC has found application in many other diverse areas, including control of solar systems [14]. More details on the application of MPC to building HVAC control may be found in two review articles [4, 10].

The results from the studies summarized above show that MPC is an effective tool for reducing building energy consumption, while maintaining satisfactory system performance and indoor thermal comfort. In the following sections the application of a Hybrid Model Predictive Control (HMPC) controller to optimally control the operation of a residential HVAC system in the Team UOW Solar Decathlon House is described. This residential HVAC system consists of an air-based solar photovoltaic thermal (PVT) collector and a phase change material (PCM) thermal storage unit integrated with a conventional ducted reverse-cycle heat pump system. The overall system was designed for operation during both winter and summer, using daytime solar radiation and night sky radiative cooling to enhance the energy efficiency of the air-conditioning system. The PVT system can exchange heat with the PCM thermal storage unit, and the stored heat can then be used to condition the space or precondition the air entering the air handling unit (AHU). Preliminary simulations and experimental results on the thermal performance of the system without HMPC implemented have been presented in [11, 12].

Given the nature of the system and the desire to forecast weather-constrained thermal energy generation from the PVT and the long time lag introduced by the thermally activated building [13] and PCM thermal storage, a Hybrid Model Predictive Control (HMPC) approach was therefore used. In this study, the HMPC strategy was developed using the HMPC toolbox in MATLAB, previously developed by Bemporad [14, 15].

2. HVAC Description and System Operating Modes

2.1. HVAC Description

The Team UOW Solar Decathlon house and a schematic of the HVAC system therein are shown in Fig. 1. The HVAC system integrates a number of energy components including the PVT system, PCM thermal store and conventional air conditioning system, with an outdoor condenser unit and an indoor air handling unit (AHU). The PVT is used to generate electricity and low grade thermal energy, and the PCM store is used to store the low grade thermal energy, which may then be used later for space heating or cooling. The thermal store is 'charged' by warm or cool air generated either by winter daytime solar radiation or summer night-time sky radiative cooling, respectively.

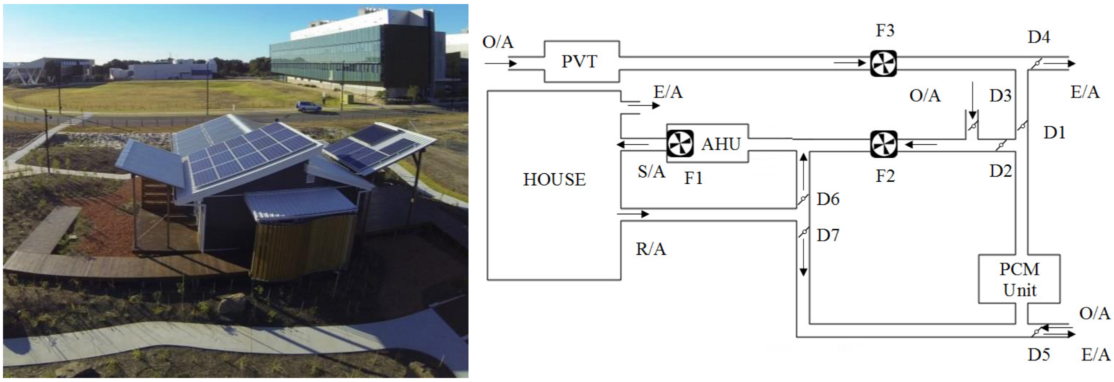

Fig. 1. (a) The Team UOW Solar Decathlon house; (b) HVAC system schematic (where S/A, O/A and E/A are the supply, outside and exhaust air, respectively, and Fn and Dn represent fans and dampers).

The HVAC system in the Team UOW Solar Decathlon house is managed by a sophisticated control system that oversees the operation and interaction of the PVT, PCM storage unit and conventional AHU, and also controls or utilizes all the other key functions and features of the building, including weather station, lighting, etc. This system was developed using off-the-shelf products and an entirely customized logic (see Fig. 2).

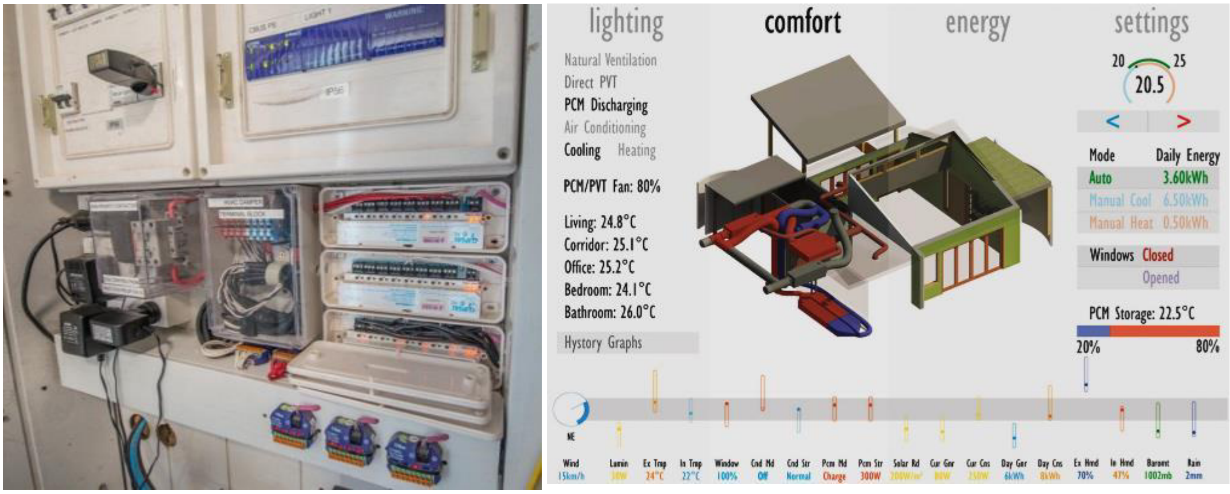

Fig. 2. (a) Team UOW Solar Decathlon House BMS; (b) Control System User Interface.

2.2. System Operating Modes

In this HVAC system, there are a total of five operating modes, including three conditioning modes and two PVT modes, which are controlled through the BMS system specifically designed for this project.

Conditioning modes

Selection of the most appropriate of the three HVAC operational modes is determined from the measured indoor and outdoor conditions (Fig. 3). Depending on the indoor conditions, the system can either work in a 'natural ventilation' mode, automatically controlling the opening of high-level windows, or work in mechanical heating or cooling modes.

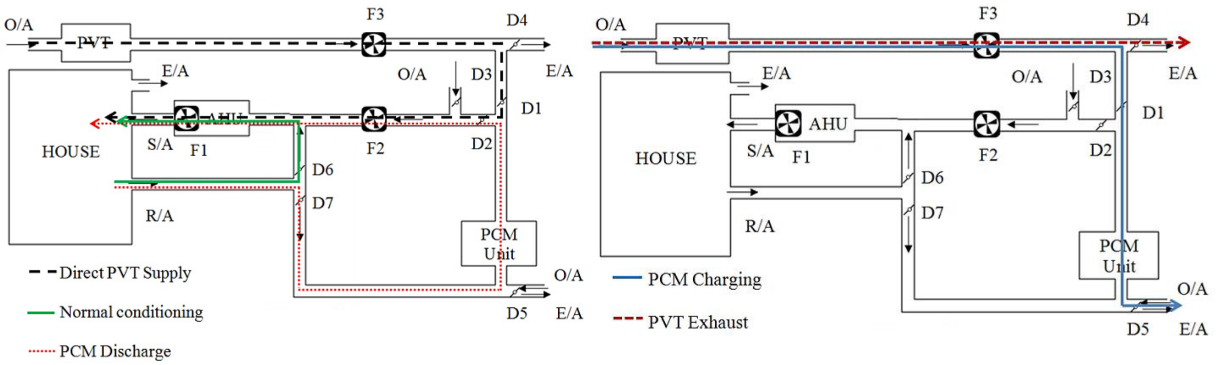

Fig. 3. Schematic of: (a) HVAC system conditioning operating modes; and (b) HVAC system PVT modes.

In the mechanical heating and cooling modes, the system can operate in three different sub-modes (see Fig. 3(a)):

- *Direct PVT Supply Mode*. If the generation of heating during daytime or cooling during night time (night sky radiative cooling) occurs at the same time as the demand, then heated air or cooled air from the PVT collector is directed into the house until demand is satisfied. If the demand is greater than the energy extracted from the PVT system, then the AHU provides the remaining heating/cooling requirement.
- *PCM Discharge Mode*. In this case, if thermal energy is available in the PCM store the mixture of return air and fresh air will be preconditioned by the PCM store, increasing or decreasing the supply air temperature. If the demand is higher than the energy extracted from the PCM storage unit, then the AHU provides the remaining heating/cooling requirement.
- *Normal Conditioning Mode*. If there is no PVT thermal generation and no thermal energy available in the PCM store, then the AHU will supply heating or cooling as required.

PVT modes

The system can operate in two further modes (providing there is no conflict with other modes) as shown in Fig. 3(b).

- *PCM Charging*. If there is no demand from the house, and the PCM unit is not fully charged and it is convenient to charge it, then the PVT collector will charge the PCM unit.
- *PVT Exhaust*. If it is worthwhile at a given point in time to cool the PV panels so as to increase their electrical efficiency, i.e. if the energy used by the fan is less than the increase in PV generation, then air will be drawn underneath the PV panels and exhausted directly to ambient (if insufficient heating or cooling is available or required).

3. BMCS Description and System Integration

A Clipsal C-Bus Domestic Building Management and Control System (BMCS) is used to control the operation of the HVAC system. The HVAC system control is implemented on two levels, i.e. low-level control and high-level control, as shown schematically in Fig. 4. The low-level C-Bus control system is used to monitor HVAC temperatures, air flow rates, current indoor and outdoor conditions, electrical energy consumption (12 sub-circuits) and renewable energy generation (2 sub-circuits), light levels and occupancy. It also controls the on/off dampers, variable position dampers, variable speed drives (VSDs) for the fans, operable windows and lights, relays and dimmers.

The BMCS also provides an interface to the user through a touch-screen. The high-level controller (Tridium JACE-6) that is integrated with the C-Bus system makes decisions on which mode the system should operate in. It also logs all data points with a 5-minute sampling period.

The JACE controller also communicates with the local controller of the reverse-cycle air conditioning unit using a Modbus gateway that allows the control system logic to dynamically change the air conditioning mode, temperature set-point and fan speed.

The JACE controller data points also act as inputs and outputs to the MATLAB code using an oBIX (Open Building Information Exchange) Network that allows a MATLAB controller to override the logic embedded in the JACE. This facilitates the implementation of virtually any desired control strategy in the house, including Hybrid Model Predictive Control which the present authors have implemented using the MATLAB HMPC toolbox [15].

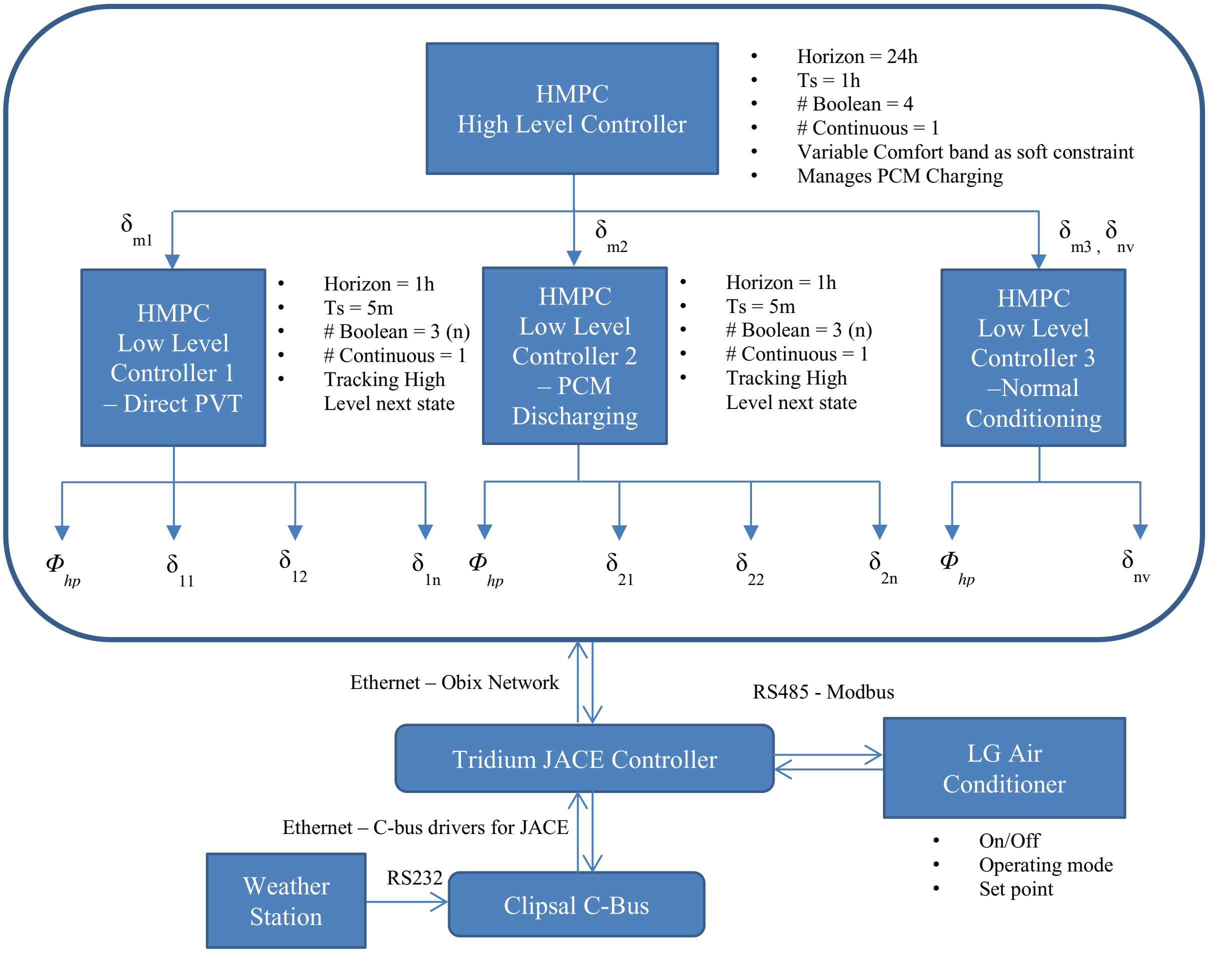

Fig. 4. Schematic of the control system architecture developed in the present project.

3.1. Control Chain Structure

Given the complexity of the problem to be solved, the HMPC control strategy has been divided into a high-level HMPC controller and multiple low-level HMPC controllers. The high-level HMPC computes the optimal solution with a control step of 1 hour and a prediction horizon of 24 hours. The objective of the high-level HMPC is to compute the optimal sequence of operating modes using an object cost function.

Once the high-level HMPC has selected the operating modes for the next hour, the corresponding low-level HMPC controller is then activated. The objective of each low-level HMPC controller is to optimize the particular operating mode for the time it is selected, considering the range of fan speeds to be utilized for the PVT and PCM store, for example. The low-level HMPC computes the optimal solution with a control step of 5 minutes and a prediction horizon of 1 hour. Once the optimal sequence of control actions has been computed, the first set of actions is then sent to the JACE controller and applied to control of the operation of the HVAC system (Fig. 4).

The key objectives of the high-level controller are implemented through the HMPC cost function, and for the present project these were in general terms: a) to maintain the average indoor temperature within a time-varying comfort band; and b) to minimize the energy consumption of the HVAC system by optimizing the use of the available energy sources. Detailed weighting functions of various parameters were used within the cost function.

The objectives of the low-level controllers were essentially: i) to track the reference temperature provided by the high-level controller; and ii) to optimize fan speeds so as to minimize the overall energy consumption of the HVAC system under the chosen operating mode.

4. Building and Solar-Assisted HVAC Modelling and Weather Forecasting

4.1. Building Model

The Team UOW Solar Decathlon House case study building had a floor area of approximately 100 m^2. The whole building was treated as a single zone for simplicity and efficiency of on-board BMCS calculations. The HMPC control strategy used was based on a ‘grey-box’ model of the building, i.e. the building was modelled as a second order system, and represented, in principle, by the RC network shown in Fig. 5. The parameters of this model were quantified using a ‘system identification’ methodology, whereby experimental datasets of system performance over several weeks duration and covering the various operational modes, were analysed using a state space model with a nonlinear, least squares best-fit method. The operation of the building also included stepwise forcing of the building with intermittent heating and cooling using the average temperature of the building as the thermal response. This model was then expanded to include the dynamics of the system relevant to each HMPC controller, including the resources that each can utilise to meet its objectives.

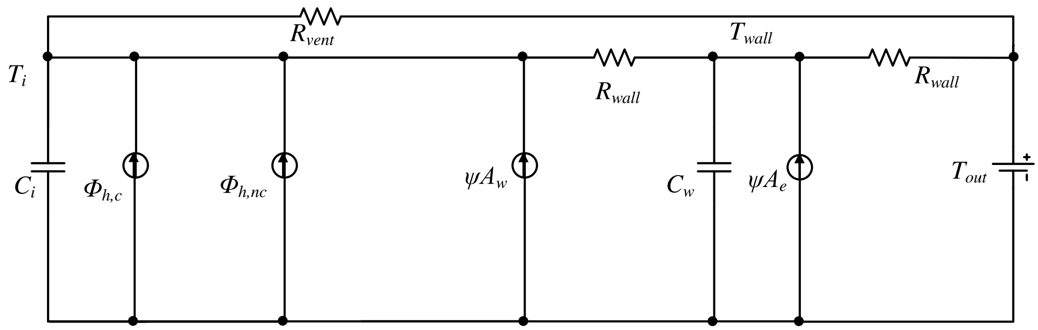

Fig. 5. Simplified thermodynamic model of the building.

4.2. PVT System Model

The Building Integrated PVT collector mounted on the roof was comprised of a number of thin-film PV panels mounted on steel flashings in turn fixed to the top of a TrimDeck™ sheet metal roof profile. This system creates a cavity underneath the steel flashing through which the working fluid (air) can flow and exchange heat with the PV panel. When winter heating is required during the daytime, for example, solar thermal radiation incident on the PV panels undergoes a number of processes including: part is reflected; some is absorbed by the PV modules to generate electricity; a portion is lost to ambient via convection and radiation; and the remainder is transferred to the heat transfer fluid. The air mass flow rate is a key parameter that allows the BMCS to control the air temperature at the outlet of the PVT collector and consequently the quantity of thermal energy harvested. Under favourable climatic conditions during summer, when the house may require cooling, the PVT collector may generate cooling during the night time, whereby the solar panels extract heat from the air flowing through the PVT collector by emitting radiation to the sky providing the sky is at a lower temperature than that of the panel. To describe the heat transfer in the PVT collector a steady-state model has been employed, in order to derive an analytical solution and to minimize the computational cost in determining the PVT output by varying the total airflow rate in the system. The equation used is of the form:

$$T_{pvt,o} = \left(T_{in} - \frac{B}{A}\right) e^{-Ax} + \frac{B}{A} \quad (1)$$

where $T_{pvt,o}$ is the outlet air temperature of the PVT collector, T_{in} is the inlet (ambient) temperature, and A and B are coefficients that are determined from the system identification process described in [16].

4.3. PCM Thermal Storage Unit

The PCM thermal store in the Solar Decathlon house was designed to exchange heat between the PCM and HVAC duct system. The PCM thermal storage unit consists of PlusIce™ PCM bricks, which were placed in a matrix with channels for the air to flow between. The phase change temperature of the material used was nominally 22˚C, the heat transfer channels were 3.0 m long and the latent heat capacity of the whole unit was 24 kWh, roughly two days of heating or cooling demand for the house. The heat exchange rate from the PCM to the air was modelled as [16]:

$$T_{pcm,o} = T_{pcm} - \left(T_{pcm} - T_{pcm,i}\right) e^{\left(-\frac{P\bar{h}\,L}{\dot{V}\cdot\rho\cdot c_p}\right)} \quad (2)$$

where $T_{pcm,o}$ is the air outlet temperature, T_{pcm} is the surface temperature of the channel (assumed to be approximately equal to the PCM temperature), $T_{pcm,i}$ is the inlet air temperature, P is the perimeter of the channel, L is the length of the channel, $\bar{h}$ is the average internal convective heat transfer coefficient, ρ, c_p and $\dot{V}$ are density and specific heat capacity at 20°C and actual volumetric flowrate of the air, respectively.

4.4. Weather Forecast

A wide range of methods for implementing weather forecasts are potentially available, including access to on-line data from regional/national meteorological services. However, in the present project the initial approach has been to use an on-board adaptive weather prediction model that can be used for on-line control of HVAC and thermal storage systems. The model can predict external dry-bulb temperature and solar radiation over the approaching 24 hours. The method applied to this research uses a combination of a deterministic and a stochastic approach. It utilizes the previous two weeks of measured temperature and global horizontal radiation to compute the forecast of future conditions [17].

5. HMPC Experimental Results

Long term experimental testing of the HVAC system installed in the Team UOW Solar Decathlon House located at the University of Wollongong Innovation Campus, Australia has been undertaken since mid-2014 following return of the house to UOW from the Solar Decathlon China 2013 competition in Datong, and rebuilding and re-commissioning. Preliminary results of performance of the HMPC system were collected throughout January-February 2015. Results and operational modes for a specific two-day period are presented in Fig.s 6 and 7. The test period presented started with the average indoor temperature of the house being outside the comfort band (the house was left free running the day before, and the average indoor temperature was approximately 27°C).

The HMPC controller was activated at t = 0, corresponding to a time of 3:00pm in the afternoon on 16th February 2015. It can be seen that following activation of the controller (at t = 0) indoor conditions were quickly brought to be within inside the thermal comfort band. The controller used the PCM Discharge Mode at the start of the test period since the PCM thermal store had sufficient cooling capacity at that time. After sunset (at t = 4 h, corresponding to 7:00pm) the controller selected the Direct PVT Supply Mode to pre-cool the building using the PVT collector. The controller was also able to utilize known future changes to temperature set point and cooling requirements to optimize system performance and carried out pre-cooling of the house as soon as the Direct PVT Supply Mode became available, since this was the most efficient source of cooling. As soon as the sun rose (at t = 15 h, corresponding to 6:00am), the controller switched to a combination of Normal Conditioning Mode and subsequently in combination with PCM Discharge Mode. At the beginning of the second evening (at t~28 h), given that the outside temperature was greater than or approximately equal to the indoor temperature of the building, Direct PVT Supply could not be used since the PVT system was unable to reduce the outdoor temperature sufficiently for space conditioning. When the outdoor temperature dropped towards the end of the night (at t = 35 h), the Direct PVT Supply mode was selected again for pre-cooling.

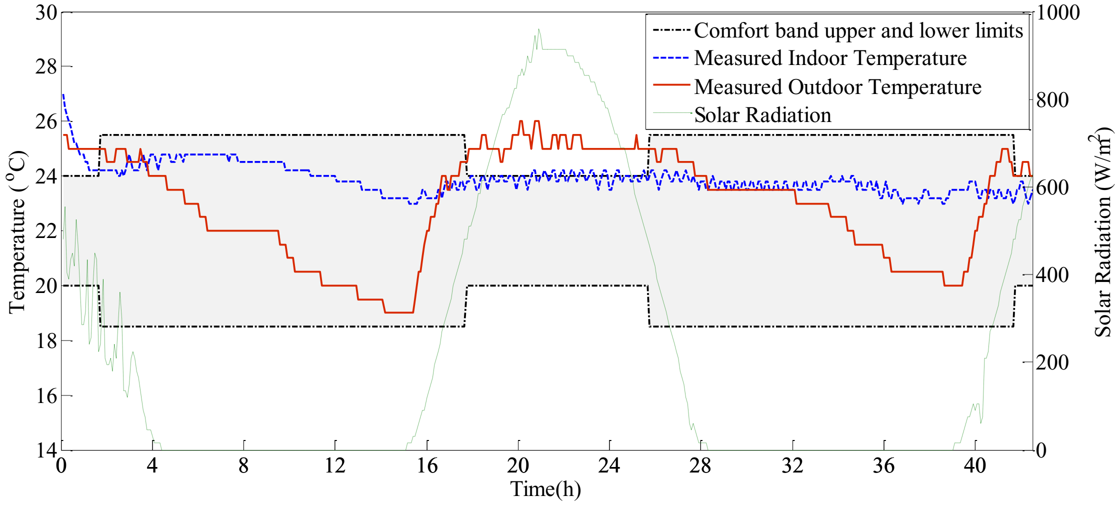

Fig. 6. Temperatures and solar radiation of HMPC experimental results for the Team UOW Solar Decathlon house in Wollongong, Australia, (t = 0 is equivalent to 3:20pm 16th February 2015).

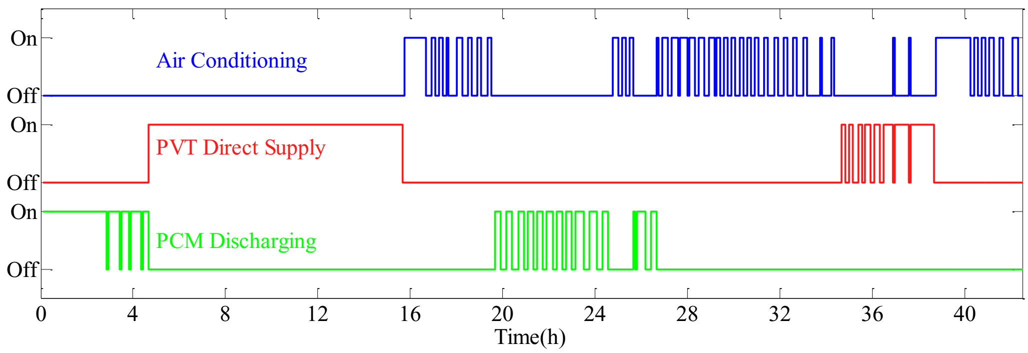

Fig. 7. Operating modes of HMPC system corresponding to Fig. 6.

The cooling supplied to the house P_{th} at each control time step k was calculated using the house BMCS temperature and duct air velocity sensors data as follows:

$$P_{th,k} = \rho \dot{V}_k c_p (T_{supply,k} - T_{avg,k}) \quad (3)$$

Where T_{supply} is the supply air temperature from either the PVT system or the PCM storage, and T_{avg} is the average indoor temperature of the house. The COP of the system, calculated at each time step, is defined as:

$$COP_k = P_{th,k}/P_{el,k} \tag{4}$$

where $P_{el,k}$ is the electrical power consumption of the fan.

The cooling rate delivered to the house and instantaneous COP during the test are shown in Fig. 8. The low-level HMPC controllers could control the airflow rate in four discrete levels to optimise the performance of the system. The 'identified' COP of the conventional heat pump air conditioning system was 2.1, and this value was used as a reference for the HMPC controller, i.e. the other modes have to operate more efficiently than the heat pump to be considered beneficial to the overall efficiency of the system. This set up led to peak cooling rates using the Direct PVT Mode supply of 3.0 kW, and 2.0 kW when using PCM Discharge Mode (see Fig. 8). The performance of both these operating modes was highly dependent on weather conditions and states of the system, and it can be seen that there was a noticeable scatter in the instantaneous COP of both these operating modes.

During the test period, the PVT system supplied a total of 30.7 kWh of cooling with an average COP of 6.2 and the PCM Discharge Mode supplied 5.6 kWh of cooling at an average COP of 2.7. The air conditioning system when in the Normal Conditioning Mode or when providing extra cooling to the Direct PVT Supply or PCM Discharging Modes, supplied 29.1 kWh of cooling during the test period.

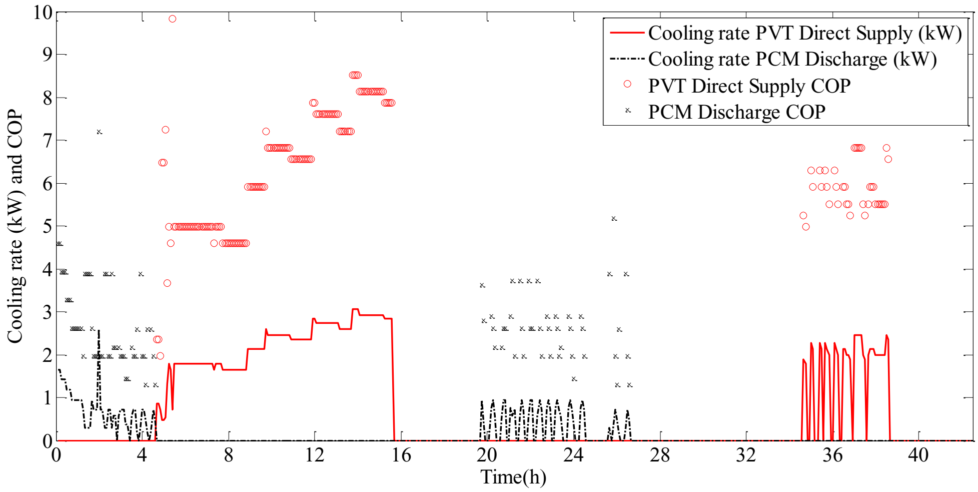

Fig. 8. Instantaneous cooling rates and COP of case study system corresponding to Fig. 6.

The results presented here represent the first phase of work by the authors in optimizing the system via the implementation of the HMPC strategy, and this optimization work is ongoing. Our preliminary results are however encouraging, and demonstrate that the HMPC controller is taking effective decisions under the range of conditions reported here. It should be emphasised that further work is required to ensure that the control strategy is robust and capable of dealing with the full range of weather and operational conditions over the course of a year.

6. Conclusions

This paper has outlined the development of a Hybrid Model Predictive Control system for application to residential buildings that have on-site renewable energy generation, energy storage and/or conventional HVAC systems available. The HMPC strategy developed in the present project utilized a new high-level/low-level approach to the overall predictive control of the system, whereby the high-level controller selects the overall operating mode of the system over the future 24-hour horizon and then feeds target information to several low-level HMPC controllers that optimize the performance of key building and energy sub-systems over a 1-hour horizon.

This HMPC strategy has been used successfully to control the solar-assisted HVAC system of the Team UOW Solar Decathlon house, which incorporates thermal energy generation and storage systems. Preliminary results show that the controller is able to select the appropriate operating mode to achieve multiple objectives such as maintaining indoor conditions within the defined temporally-variable comfort band, while optimizing the overall energy efficiency of the system using the available energy resources. The high-level controller used future comfort band and equipment schedules and relatively simple on-board weather forecasting to determine the most efficient use of resources over the 24-hour prediction horizon. The low-level controllers were demonstrated to be capable of optimizing the flow rates in the system to achieve the targeted comfort temperatures set by the high-level controller.

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