ENERGYPLUS MODEL OF NOVEL PCM COOLING SYSTEM VALIDATED WITH INSTALLED SYSTEM DATA

Chao Yang\textsuperscript{1}, Gideon Susman\textsuperscript{1}, and Mark Dowson\textsuperscript{2}

\textsuperscript{1}BuroHappold Engineering, Los Angeles, CA
\textsuperscript{2}BuroHappold Engineering, London, UK

\textbf{ABSTRACT}

An innovative hybrid application of Phase Change Material (PCM) has been modelled in EnergyPlus, with DesignBuilder, and validated with results from a fully-functioning installation in a London school. The model was used to evaluate performance, test alternative control strategies and quantify energy savings. The modelling method, utilizing a modified chilled ceiling with integrated PCM, effectively mimicked actual system operation and was validated to have an acceptable error rate. Energy savings in passive and active discharge modes were found to be 36\% and 21\%, depending on different control schemes and seasons. Greater energy savings may be possible with a refined control logic.

\textbf{INTRODUCTION}

Phase change materials have been widely used in buildings as a passive way to stabilize indoor temperature and save cooling and heating. Many studies have been done to prove the integration of PCM in building envelope is beneficial for energy reduction on room conditioning, with and without regular system operation. The characteristics of cooling and heating energy savings has been discussed (Kim et al. 2013) by applying PCM under local regular conditioning system types through EnergyPlus modelling. The installation location of PCM in building envelope (wall, ceiling etc.) and the climate influence have been evaluated by experiment (Lee 2014).

Beyond installing PCM in the building fabric, other PCM positioning strategies have been studied. A free cooling system with individual PCM units (Kamali 2014) showed that diurnal temperature range from 54°F to 59°F and PCM melting point within 68°F to 79°F are demonstrated to be the most effective to reduce the cooling and ventilation loads in summer. A PCM container with aluminum fins is used as ‘free cooling’ (Stritih & Butala 2007). This PCM cold storage with night ventilation method mainly depends on the selection of PCM melting point and the measurement showed less temperature fluctuation in the room and higher thermal comfort. A new floor supply air conditioning system incorporated granular PCM with a large heat capacity as heat storage material (Nagano et al. 2006). It indicated that 89\% of daily cooling load can be stored during the night. A PCM unit with heat pipe on the ceiling proved that the system provided sufficient cooling to protect room from overheating (Turnpenny et al. 2000). A fan has been installed with the “active” system to augment the air flow and the cooling effect in the space.

\textbf{Model Inputs}

In this paper, the NewMass system (patent pending) is a novel phase change material (PCM) cooling system composed of an array of finned tubes which are installed below the ceiling in a conditioned space. The tubes are filled with a composite phase change material (melt temperature of 70°C and heat capacity of 69 Btu/lb). It is capable of absorbing excess heat passively and actively from the space when the tube surface temperature is below the room temperature. While the absorbed heat could be either discharged into the space passively during unoccupied hours or rejected to a chilled water circuit using free cooling or a vapor compression chiller. To model the PCM, 16 points defined the temperature-enthalpy curve of the NewMass units. Two NewMass unit arrays were installed in 2 classrooms and fed by a single central plant consisting of a 4.5 ton air-cooled chiller and a 4 ton dry air cooler. The arrays were represented in the model by internal ceilings containing with two layers of PCM and a chilled water loop. The thermophysical properties of the ceiling were input to mimic the behavior of the installed arrays. In this study, the NewMass system has been both monitored and...
modeled to evaluate performance, test alternative control strategies and quantify energy savings.

CONCEPT

The NewMass system was installed temporarily in a primary school in North-West London. The building fabric includes brick wall with insulation, double glazing and light weight roof construction. Two rooms were selected for the system test. Prior to the installation, the IT Suite had a 2 ton air conditioner installed and the Red Classroom had no cooling system. The air conditioning was disconnected during the NewMass test period. The monitored data include room air temperature, radiant temperature and PCM temperature. These data have been used to validate simulation models, which are able to predict energy use and savings for comparison.

![Figure 1 Installed NewMass units and DesignBuilder geometry in Red Classroom](image)

EnergyPlus was used to model PCM performance and system energy use. It incorporated a one-dimensional conduction finite difference (CondFD) solution algorithm in the version 7 (Tabares-Velasco et al. 2012) which enable the software to model transient heat transfer especially with phase change features. Specific material inputs are needed to initiate the calculation (Lee 2014). DesignBuilder is the graphical user interface that facilitated the use of EnergyPlus engine. In this study, DesignBuilder was used as the energy modelling software to model the NewMass system.

The methodology is illustrated in Figure 2 below. To represent the NewMass unit location in each room, two stacked zones were developed: an occupied zone and a ceiling zone. This feature allowed for the NewMass arrays to be represented as ceiling elements located at the boundary of the two zones. These ceiling elements consist of two layers of PCM, containing chilled ceiling pipework, bordered on both sides by holes. DesignBuilder allows for the thermo-physical properties of the PCM to be entered. The array’s thermal behavior is thus mimicked by representing the conductivity, thermal capacity and surface heat transfer coefficient as modified values in the model. The holes that surround the ceiling element allow for the heat conduction between upper and lower spaces. The fact that the chilled water pipes are fully encased by the PCM means that heat must flow through the PCM from the space, as is the case in the installed system.

Construction parameters were selected to match those of the school’s envelope elements. Internal gains including lighting power density (LPD), equipment power density (EPD) and occupant numbers are intended to match real configuration in both rooms. CO₂ concentration has been used to give an indicator of occupants density. In this study, the maximum students number and CO₂ concentration have been cross referenced to make an assumption of real occupants density and create a corresponding occupancy profile. It assumed when CO₂ density is the hightest the room is fully occupied and the maximum occupant number equals to the maximum seat number.

*Table 1 Model construction and internal gains*

<table>
<thead>
<tr>
<th>INPUTS</th>
<th>IT SUITE</th>
<th>RED CLASS</th>
</tr>
</thead>
</table>

© 2016 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.
Roof U (Btu/(h*ft²*°F)) | 0.023 | 0.023
Wall U (Btu/(h*ft²*°F)) | 0.13 | 0.13
Floor U (Btu/(h*ft²*°F)) | 0.14 | 0.14
Glazing U (Btu/(h*ft²*°F)) | 0.62 | 0.62
LPD (W/ft²) | 0.29 | 0.40
EPD (W/ft²) | 0.15 | 3.32
People (p/ft²) | 0.05 | 0.06

### PCM Properties

NewMass unit properties were determined from the schedule of weights, known from design, combined with the properties of the SP21e PCM, obtained from the manufacturer. The key input is a temperature enthalpy curve which is used to define the latent properties of the PCM. It indicates the ability of the material to absorb and reject heat in both melting and solidifying process. A 16 point temperature-enthalpy curve from the PCM manufacturer has been defined in the model PCM layer, which is showed in Figure 3. In addition, thermal conductivity, specific heat capacity, density and heat transfer coefficient of the material are taken from the material specification.

**Figure 3 PCM temperature and enthalpy curve**

### VALIDATION

#### Validation Method

To validate the model, two indices were used to assess simulation accuracy: The normalised mean bias error (NMBE) and coefficient of variation of the root mean square error (CVRMSE), which are outlined in ASHRAE Guideline 14 (ASHRAE 2002) to quantify the variation between predicted and observed values.

\[
NMBE = \frac{\sum_{t=1}^{n}(y_{\text{simulated},t} - y_{\text{measured},t})}{y_{\text{measured}} \times (n - p)}
\]

(1)

\[
CV(RMSE) = \frac{1}{\bar{y}_{\text{meas}}} \times \sqrt{\frac{\sum_{t=1}^{n}(y_{\text{sim},t} - y_{\text{meas},t})^2}{(n - p - 1)}}
\]

(2)

Where:

- \( y \) = Hourly simulated or measured temperature;
- \( \bar{y} \) = Mean of hourly measured temperature;
- \( n \) = Number of data points;
- \( p \) = number of predictor variables (p=1).

#### Passive Operation

Passive operation indicates the system is running passively without an active chilled water loop picking up the excessive heat gain from the space. In order to validate the passive operation of the NewMass system, the modelled and monitored air temperature, mean radiant temperature and PCM temperature, were compared over the period 14th to 20th July 2014. Figure 4 to Figure 9 show the comparison of the three temperature measurement in each room. Outdoor air temperature has been used as a context.

The Red Classroom has comparatively more consistent pattern of daily temperature change since the occupancy is more consistent and it has lower internal gains in classroom than IT room. On the other hand, The IT Suite experienced a more chaotic temperature profile as it is used less consistently and has much higher equipment gains. To achieve good correspondence in profiles, the internal gain profiles were adjusted, as was the heat transfer coefficient of the ceiling. The heat transfer coefficient determines the rate of heat transfer to the NewMass array and thus affects performance and energy savings.

Graphs indicated a good correspondence between monitored data and modelling results. The simulation yielded close correlation of air temperature, mean radiant temperature profiles and PCM temperature.

**Figure 4 Validation of air temperature in IT suite in passive mode**
Active Operation

Active operation occurs when chilled water is circulated in the system to boost the cooling capacity of the passive NewMass system. One week between September 15th and September 21st was selected when the system operated in active mode within the IT Suite. Figure 10 to 12 show the validation of indoor air temperature during active cooling mode in IT Suite. In September, the outdoor air temperature decreased and the indoor air temperature was more tempered, which resulted in a higher possibility that PCM temperature falls into the optimal range (64°F to 72°F). A similar pattern in air temperature variation showed a close representation of real indoor air temperature, however, the NewMass model has greater temperature swings. The measured air temperature and PCM temperature have more fluctuation because the chaotic occupancy profile. However, to discuss the annual energy savings by the NewMass system, a typical occupancy profile still could be used in both baseline and proposed models.
Validation Summary

ASHRAE Guideline 14 recommends achieving a NMBE of +/- 10% and a CVRMSE of +/- 30% for hourly energy modelling calibration. In this research, the two metrics are used as reference when validating the hourly air temperature change. Table 2 summarizes the NMBE and CV(RMSE) for both cases. Both metrics are lower than 5% in passive mode in two rooms. In IT suite the NMBE is 1.89% and the CV(RMSE) is 5.36%. It proves the model has a good accuracy in predicting indoor air temperature in both passive and active operation in NewMass system.

<table>
<thead>
<tr>
<th>INDEX</th>
<th>IT SUITE</th>
<th>RED CLASSROOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation</td>
<td>Passive</td>
<td>Active</td>
</tr>
<tr>
<td>Validation Period</td>
<td>Jul 14th – Jul 20th</td>
<td>Sep 15th - Sep. 21th</td>
</tr>
<tr>
<td>NMBE</td>
<td>0.95%</td>
<td>1.89%</td>
</tr>
<tr>
<td>CV(RMSE)</td>
<td>3.10%</td>
<td>5.36%</td>
</tr>
</tbody>
</table>

ACTIVE PERFORMANCE MODELING

The validated model is used to evaluate the NewMass system’s performance, controls and energy saving potential. Using this model, this made it possible to predict the active operation of the system across the entire year for both the IT Suite and Red Classroom. When incorporating the chilled water loop inside the PCM as designed, NewMass entered ‘active performance’ mode. Chilled water could be able to pick up more heat absorbed by PCM material during the daytime. The system is operating from 9:00 am to 20:00 pm and staying off in the night. The excessive heat in the PCM will be released passively during the night. It is called “Passive discharge” operation. This control scheme is the simplest strategy to improve the indoor thermal comfort without wasting energy. On weekends, the system is completely off which is different from the validation case.

From Figure 13 to 15, chiller is on every morning after the space is occupied. The chilled water will cool the PCM first which result in a significant big temperature difference between room air temperature and PCM temperature during the day whenever cooling is required to maintain the setpoint (75°F). Compared to
the passive performance, the room temperature has been decreased to the range around setpoint.

Chiller is designed to supply 55°F chilled water when it’s on. The chilled water flow rates of two different secondary loop and the primary loop are showed in Figure 18.

Case 2: NewMass system is operated only during the day and heat is passively discharged at night after occupancy.

Case 3: In addition to case 2 settings, the chiller actively discharges heat from PCM from 02:00 am to 09:00 am.

Case 4: To further improve the system efficiency, the dry air cooler operates whenever the outdoor temperature is lower than 50°F.

The associated operating parameters are given in the table below:

<table>
<thead>
<tr>
<th>Case 1: Baseline</th>
<th>Case 2: Passive Discharge</th>
<th>Case 3: Active Discharge</th>
<th>Case 4: “Free Cooling”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Night operation</td>
<td>No</td>
<td>No</td>
<td>Chiller</td>
</tr>
<tr>
<td>Daytime operation</td>
<td>Chiller 09:00 am - 20:00 pm</td>
<td>Chiller 09:00 am - 20:00 pm</td>
<td>Dry Cooler + Chiller 02:00 am - 09:00 am</td>
</tr>
<tr>
<td>PCM start temp.</td>
<td>Above Best Range</td>
<td>Within Best Range</td>
<td>Within Best Range</td>
</tr>
</tbody>
</table>

**Passive Discharge**

When comparing the annual cooling energy use of case 1 (baseline) and case 2 (passive discharge), the chilled ceiling has to be operated all year to maintain the room air temperature while NewMass can provide more comfortable room condition and only operates in the summer and part of transition seasons.

A week in summer, the mid-season and winter were selected to evaluate NewMass performance. In summer, the baseline system has to operate constantly while NewMass can operate intermittently. In the transition season, the peak power is about the same in both cases while NewMass is only needed to operate for less hours. In winter, only PCM in NewMass system is enough to moderate room temperature while chilled ceiling is still needed to operate.
Active Discharge and “Free Cooling”

In Figure 19, “66°F” and “68°F” indicate the initial PCM temperature approximately are closer to 66°F and 68°F just before occupancy. In active discharge, chiller is on from 2:00 to 9:00 to discharge PCM temperature ideally into 64°F to 68°F. Active discharge with “free cooling” indicates that in addition to active discharge, whenever the outdoor temperature is below 50°F and space is occupied, a dry cooler is on to supply chilled water either to cool the space during the day if needed or cool the PCM for a better performance of recharging in the next day. This can be seen as “Free Cooling” by taking advantage of high efficiency of dry cooler when outdoor temperature is low enough.

Advantage:

When actively discharging the heat in PCM which absorbed during the occupied hours in the night, PCM temperature could be cooled down to 66°F (or 68°F in another test) in the early morning before occupancy. PCM could perform better to make full use of high heat absorption ability for the next few hours until it needs to be discharged again in the afternoon.

Annual Energy Use and Savings

All cases are compared in terms of total and component energy as a combined function of both the Red Classroom and IT Suite. As discussed, discharging absorbed heat at night with the chiller alone saves 20% energy as compared to passive chilled beam baseline, discharging with the dry air cooler saves 21% energy and discharging passively saves 36% energy.

The passive discharge case saves most energy because while maintaining the room setpoint, the time in which heat can be discharged passively is maximized and any additional discharge can be achieved efficiently during early morning occupancy.
CONCLUSION
This paper presented results from a validated DesignBuilder (EnergyPlus) model of a new PCM cooling system known as NewMass. The system was shown to save energy in both passive and active mode, with the active mode guaranteeing thermal comfort at design conditions.
It was also shown that DesignBuilder (EnergyPlus) has the capacity to model this partially passive and partially active system accurately. The includes the capacity to dynamically model the modified thermophysical properties of the composite PCM, the NewMass array, the mechanical system and the host building. This is important since EnergyPlus is shown to be a viable and practical engine for the modeling of unique/novel PCM systems.
Of particular interest to the modelers, was how well the NewMass array could be represented as a construction element, as well as an active cooling system. The stacking of zones (occupied and above-ceiling zones) allowed the NewMass units to be added as construction elements that contained chilled water pipework but were themselves surrounded by room air. This method proved effective.
Validation of the model, with monitored data from the school installation, was successfully achieved with CV(RMSE) and NMBE metrics, to within a generally accepted range of accuracy.
The results from alternative discharge scenario modeling showed that active discharge was essential during high summer but in shoulder seasons passive discharge can be sufficient. When comparing all control strategies, the largest savings were found to come from passive discharge mode.
Next steps in product development will be to use the model to test the system with further alternative control strategies, system configurations, building types and climates.

ACKNOWLEDGMENT
This paper represents the end of phase 2 submission for the “NewMass PCM” project undertaken for the Innovate UK “Invest in Innovative Refurbishment” programme, funded by the Department for Energy and Climate Change (DECC). The project has been led by BuroHappold Engineering, in collaboration with ICE Architects, HA Marks and Chalfont Energy Investments.
Special acknowledgement should also be given to Brentfield Primary School and Brent Council for providing the opportunity to undertake the testing at a live demonstrator building.

REFERENCES
ASHRAE, 2002. Measurement of Energy and Demand Savings,