A simple method for validating a simulation model of a radiant ceiling panel with thermal energy storage

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Abstract. This paper focuses on validating a simulation model of a radiant ceiling panel (RCP) incorporating phase change materials (PCM) for heating and cooling applications in buildings. The development of an RCP with thermal energy storage capacity aims to encourage high thermal mass radiant systems in existing buildings to replace the traditional all-air HVAC system. First, a heat flow meter (HFM) is used to perform enthalpy measurements at a product scale (macro-encapsulated PCM). Then, a small test chamber is constructed to measure the dynamic thermal performance of an RCP with PCM under well-known and realistic boundary conditions. A known thermal resistance is used to establish a realistic heat transfer coefficient between room air (represented by the temperature of a temperature-controlled metal plate) and ceiling. The results show that HFM enthalpy measurements of products incorporating PCM are within $\pm 2\%$ of manufacturers’ data. Additionally, results indicate that a test chamber can be used for validating a dynamic simulation model of the RCP with PCM installed in a room. The proposed method can be helpful during the system optimization phase, as many conditions and sample configurations can be tested without spending too much time or money on test rooms or real building monitoring.

1. Introduction

Statistics presented by the International Energy Agency (IEA) show that heating systems are currently responsible for around 45\% of building emissions and still rely on fossil fuels for supplying more than half of its final energy consumption [1]. On the other hand, the use of energy for space cooling is growing faster than any other end-use in buildings (more than tripling between 1990 and 2016) and is expected to remain so over the coming decades [2]. These statistics suggest that the most effective way to reduce building’s greenhouse gas emissions globally is to focus on providing energy-efficient heating and cooling services.

To meet future heating and cooling demand without dramatically increasing emissions, a promising and innovative technology is proposed in this study. The principle of the proposed system is based on a known technology such as an embedded water-based surface cooling system, which combines the advantages of radiant cooling with the utilization (activation) of thermal mass. The most common configuration of embedded radiant cooling systems is known as thermally activated building systems (TABS), in which pipes carrying water for cooling are embedded in the central concrete core of a building’s construction [5]. The main disadvantage of TABS is that the system has to be incorporated in the building from the design stage, limiting its application to new buildings. The literature shows that research is still required to encourage TABS applications in existing buildings [3], [4], which account for the largest share of the total building stock. As a potential solution, the proposed system...
considers incorporating macro-encapsulated phase change materials (PCM) in a standard radiant ceiling panel (RCP) for providing thermal energy storage capacity to the system, instead of using the thermal mass of the building structure.

As suggested by Dutil et al. [5], high fidelity and reliable simulation or numerical models are needed to optimize the use of PCM in building applications. Despite the vast amount of work that has been developed in the last years in PCM modeling in buildings, a simple methodology that can be followed to obtain an accurate and reliable model is still required. Most studies do not provide all the information needed for replicating the experiments for model validation purposes or do not include a detailed description of the steps that were implemented to validate the numerical models.

Previous research studies show that the accuracy of simulation models is highly dependent on the proper thermal characterization of PCM products or components and the validation of the model with experimental measurements [5], [6]. A common practice is to use the thermal properties of pure PCM (provided by the manufacturer) for evaluating the energy or thermal performance of buildings with PCM products or components. However, the thermal properties of PCM products/components can be significantly different from pure PCM properties. Thermal properties can be modified by factors such as the heat capacity and thermal conductivity of the PCM container (for micro or macro-encapsulated PCM), the size of the PCM sample, or the presence of additives (fire retardants, conduction inhibitors, adhesives).

It is also common to see many studies that use dynamic scanning calorimetry (DSC) to measure the amount of heat energy that can be stored and the operating temperature range of PCM, which can be another source of error for the model. The main problem with DSC is that it can only test very small specimens (sample sizes of several µl) and requires a specimen with a homogeneous composition, which means that PCM products or components cannot be characterized. To overcome this limitation, Kosny et al. [7] proposed a method for measuring thermal storage properties of PCM products and components (large samples of PCM, PCM composites, or encapsulated PCM) using a heat flow meter (HFM). This method, which was later incorporated in ASTM Standard C1784 [8], is the first step to obtain an accurate and reliable model of a building with PCM.

Another important aspect for making reliable predictions of the energy and thermal performance of buildings incorporating PCM is the validation of simulation or numerical models. Thus, it is generally necessary to perform measurements in test rooms or even perform real building monitoring. However, this approach can be very time-consuming and expensive during the development or design stage of PCM products, systems, or components. Instead, a previously developed experimental measurement setup [9] designed to measure the dynamic thermal behavior of a PCM cooling system was used in this study for model validation. The experimental setup allows reducing the amount of time and costs involved in real building monitoring while accurately predicting the thermal conditions in a room with a PCM product, system, or component.

In this study, a simple methodology that can be followed to obtain an accurate and reliable model of a building incorporating PCM is presented. A model of a room conditioned by a RCP with macro-encapsulated PCM was developed and validated to demonstrate the implementation of the proposed method. At first, the thermal storage properties of macro-encapsulated PCM are determined using ASTM Standard C1784-20 [8]. The obtained properties are then used in a whole-building simulation model that is validated using measurements in a small test chamber that replicates the conditions of a real test room.

2. Methodology

2.1. Calorimetric measurements

2.1.1. Experimental setup. The dynamic test method proposed in ASTM Standard C1784-20 [8] was used to measure the sensible and latent heat storage capacity of a macro-encapsulated PCM incorporated in a radiant ceiling panel (RCP) for building cooling and heating applications. A heat
flow meter (HFM) equipped with one heat flux transducer on each plate of the apparatus was used for performing a series of measurements to determine the thermal energy storage of the test specimen over a temperature range. According to the datasheet provided by the manufacturer, the HFM has a measurement accuracy of ± 1 to 3 %. The thermal storage properties that were obtained using this method include:

- PCM active range – temperature range over which the phase transition occurs (melting and freezing).
- Specific heat of the fully melted $c_{pM}$ (J/kg·℃) and fully frozen $c_{pF}$ (J/kg·℃) macro-encapsulated PCM.
- Enthalpy $h$ (J/kg) as a function of temperature (change in enthalpy associated with incremental temperature changes).

The specimen used in the test is a macro-encapsulated PCM (ice-pack filled with 220.5 grams of pure PCM – RT21HC) with dimensions of 165 mm x 110 mm x 17 mm. Considering that the specimen area is lower than the HFM plate area (300 mm x 300 mm), a frame (constructed from styrofoam) was used to contain the specimen as recommended by the HFM manufacturer.

2.1.2. Measurement procedure.

2.1.2.1. Calibration: Before using the test method proposed in ASTM Standard C1784-20 [8], the HFM output was calibrated with a standard material (NIST1450d fiberglass board) with dimensions of 300 mm x 300 mm x 25 mm. Additionally, a heat storage correction factor was calculated to account for the heat flux transducers’ heat storage. As suggested by Tleoubaev et al. [10], the correction factor was determined by performing measurements with the HFM plates closed and with no sample. The correction factor calibration was conducted over the entire temperature range in which the PCM test specimen was tested (11 ℃ to 31 ℃), using the same incremental step procedure (described below).

2.1.2.2. Measurements and calculations. The first step for measuring the enthalpy stored in the PCM test specimen is to define a series of temperature steps for both plates of the HFM. ASTM Standard C1784-20 [8] recommends temperature steps of 1.5 ± 0.5 ℃, starting and ending at a temperature of at least 10 ℃ below and 10 ℃ above the expected PCM active range, respectively. The thermal properties of the pure PCM (RT21HC) provided by the manufacturer were used to estimate the PCM active range and define the initial and final temperature for the plates. Considering that the peak melting temperature of the pure PCM used in the test (RT21HC) is 21 ℃, the initial and final temperatures of the plates were set to 11 ℃ and 31 ℃, respectively. A temperature step of 1 ℃ was selected to have a good temperature resolution.

At first, the HFM plates were maintained at the same constant initial temperature (11 ℃) until a steady state was achieved. Then, the temperature of both HFM plates was incrementally increased by 1 ℃ until the final temperature was reached (31 ℃), allowing the plates to reach steady-state conditions after each temperature step. The cumulative amount of energy that entered the specimen from the time of a temperature change until reaching a steady state was measured to determine the enthalpy stored in the test specimen for each step change in temperature. This procedure was repeated starting at the final temperature (fully melted temperature condition – 31 ℃) and decreasing the plate temperatures in 1 ℃ steps until the initial temperature was reached (11 ℃). Three heating and three cooling series were performed as indicated in ASTM Standard C1784-20 [8].

The total amount of enthalpy stored $h_A$ (J/kg) in the PCM test specimen for a given temperature interval $T_{begin}$-$T_{end}$ was calculated using Equation 1. The recorded heat flux for both plates, corrected for the residual equilibrium heat flux $q_{equilibrium}$ (due to a small temperature difference between the plates and edge heat losses), was multiplied by the length of time $\Delta t$ for each data point $q_t$ and summed over the total number of data points $N$ for the given temperature interval $\Delta T$. Equation 1 also includes the transducer’s heat storage correction factor $C_{hr}(T_{begin}, T_{end})$ (J/m²·℃) and the
correction factor for heat storage in other materials \( C_{other}(T_{begin}, T_{end}) \) (J/m\(^2\)-\(^\circ\)C) used to surround the test specimen (calculated in the calibration step), subtracted from the sum of the heat flow into the specimen.

\[
h_A = \left[ \sum_{i=1}^{N} (q_i - q_{equilibrium}) \Delta \tau \right] - C_{hft}(T_{begin}, T_{end}) \Delta T - C_{other}(T_{begin}, T_{end}) \Delta T \] upper + \[ \left[ \sum_{i=1}^{N} (q_i - q_{equilibrium}) \Delta \tau \right] - C_{hft}(T_{begin}, T_{end}) \Delta T - C_{other}(T_{begin}, T_{end}) \Delta T \] lower \tag{1}

The calculation of total enthalpy change between the lower temperature limit \( T_L \) and the upper-temperature limit \( T_U \) of the PCM active range includes both sensible and latent heat effects. To define the sensible heat storage over the temperature range, the specific heat of the fully frozen \( c_{PF} \) (J/kg-\(^\circ\)C) and fully melted product \( c_{PM} \) (J/kg-\(^\circ\)C), below and above the mean temperature \( T_{mean} \) of the PCM’s active range, respectively, was obtained as suggested in ASTM Standard C1784-20 [8]. The latent heat \( h_{fs} \) (J/kg) was then obtained by the difference between the total and sensible heat storage, as shown in Equation 2.

\[
h_{fs} = \sum_{T_L}^{T_U} (\Delta h) - c_{PF}(T_{mean} - T_L) - c_{PM}(T_U - T_{mean}) = \sum_{T_L}^{T_U} (\Delta h) - \frac{(c_{PF} + c_{PM})(T_U - T_L)}{2} \tag{2}

2.2. Dynamic thermal performance

2.2.1. Experimental setup. A previously developed experimental measurement setup [9] was constructed to evaluate the dynamic thermal behavior of a radiant ceiling panel (RCP) integrated with the macro-encapsulated PCM (RCP-PCM) that was characterized in the previous step. The measurement setup is a highly insulated box used to replicate the conditions in a real test room in much smaller dimensions. Measurement results are used for validating a building-system model implemented in EnergyPlus v.9.3.

The insulated box is constructed of rock wool insulation with a thickness of 0.1 m. and thermal conductivity of 0.035 W/m·K. At the bottom, the insulated box holds a temperature-controlled metal plate connected to an external thermostat, with a heat flux sensor centered on top of the metal plate. The metal plate is used to establish a fictitious air temperature to which the RCP-PCM is exposed. The next layer is a known thermal resistance used to adjust the heat transfer coefficient between the fictive room air and the RCP-PCM surface. In this case, cellular rubber with a thickness of 8 mm. was used to achieve a heat transfer coefficient of around 10 W/m\(^2\)-K, an expected value for ceiling cooling applications [11]. On top of the cellular rubber, a cooper sheet with two heat flux and temperature sensors is installed (one in the center and one in the corner) to check for differences in heat flow in the horizontal plane. A prototype of the RCP-PCM (0.6 m. x 0.6 m.) is placed on top of the copper sheet with the sensors, which is then covered with an insulation layer to minimize heat gains/losses through the backside of the sample. Temperature sensors were also installed on the top and bottom of the macro-encapsulated PCM (filled with 2 kg. of RT21HC). Temperatures were measured with type-K thermocouples that were calibrated against a reference thermocouple through ice-bath tests. The heat flux sensors used in the test have a sensitivity of 1.18 ± 0.03 µV/(W/m\(^2\)). A cross-section of the measurement setup showing the position of the temperature and heat flux sensors is presented in Figure 1.

2.2.2. Measurement procedure. The measurement setup was used to evaluate the dynamic behavior of the RCP-PCM sample being exposed to a temperature change. The RCP-PCM sample was tested in two operation modes: passive mode or PCM melting/heating cycle (no water flow) and active mode or PCM freezing/cooling cycle (cold water flow). A voltage and thermocouple data logger system was used to record heat flux and temperature measurements every 60 seconds.

For the passive mode measurements, the RCP-PCM sample was first preconditioned at a temperature of 15\(^\circ\)C to ensure that the PCM was entirely in its solid-state. Water at 15\(^\circ\)C was circulated through the RCP-PCM sample for several hours until a steady-state was reached within the
measurement setup. The cold-water flow was stopped for starting the measurements, and the temperature of the metal plate (room temperature) was set to 26℃. The temperature and heat flux measurements lasted until a steady state was reached again.

The measurements in active mode or PCM freezing/cooling started right after the measurements in passive mode when the temperature within the measurement setup was at 26℃, which indicated that the PCM was in its liquid state. The metal plate was then switched off, and water at 15℃ was circulated until steady-state was reached within the measurement setup once again.

Figure 1. Cross-section of the experimental measurement setup showing the position of the temperature and heat flux sensors. From bottom to top, the insulated box is subdivided into the following layers: (1) A temperature-controlled metal plate representing room air temperature, (2) several layers with embedded temperature and heat flux sensors, (3) a known thermal resistance, and (4) a sample of the RCP-PCM.

2.3. Building-system model validation

The measurements obtained from the previous step were used to validate a building-system model implemented in EnergyPlus v.9.3. For the validation, a building-system model of the insulated box containing a RCP-PCM sample with the same amount of PCM (2 kg.) used in the experimental setup was considered.

For modeling the RCP-PCM system in EnergyPlus, the ceiling surface construction was modified using construction of the type Construction:InternalSource, which defines the material makeup of the RCP-PCM and the dimensions of the hydronic tubing (see Figure 2). The internal source object requires at least two material layers (one on either side of the source) between which the hydronic tubing is embedded. A copper pipe with a diameter of 0.0124 m. (½") and a tube spacing S of 0.15 m. were selected for performing the simulations, which are the same dimensions of the RCP-PCM used in the experimental setup. The outside layer is a 20 mm. thickness insulation (thermal conductivity of 0.04 W/m·K), and the inside layer is macro-encapsulated PCM (aluminum cases or panels filled with PCM). However, the thin metal layers of the PCM panels and RCP were not considered in simulations because high conductivity material layers are not well supported by the conduction finite-difference algorithm used to simulate PCMs in EnergyPlus.

Figure 2. Cross-section showing the material makeup of the RCP-PCM that was modelled in EnergyPlus.

The validated parameters are the temperatures at the top and bottom surfaces of the PCM panel and the surface cooling rate. The root mean square error (RMSE) was used as an indicator for the quality of the simulations and was calculated using Equation (3) and Equation (4) as follows:
\[ S_{S_{res}} = (S_i - M_i)^2 \]  
\[ \text{RMSE} = \sqrt{\frac{SS_{res}}{n}} \]  

where, \( S_i \) is the value of the simulation results at the \( i \)-th time step, \( M_i \) is the value of the measurement results at the \( i \)-th time step, and \( n \) is the number of time steps that are evaluated. A low RMSE indicates that the simulated values match the data from the experimental measurements. For reference, in the German standard VDI 6020, a maximum RMSE value of ± 1.5 ℃ for operative temperatures and ± 0.06 kW for cooling power is specified [12].

3. Results

3.1. Calorimetric measurements
The calorimetric measurements were performed on a macro-encapsulated PCM (containing RT21HC), using the test method of ASTM Standard C1784-20 (described in the previous section). Figure 3 shows the enthalpy change for each temperature step of the heating and cooling tests. The results show that the enthalpy change during the cooling test is greater than the enthalpy change during the melting test for most temperature intervals.

![Figure 3. Enthalpy change for each temperature step of the heating and cooling tests (comparison of measurements and datasheet information from the manufacturer).](image)

According to the datasheet of RT21HC provided by the manufacturer, the heat storage capacity for the temperature range between 13 ℃ to 28 ℃ is 190 KJ/kg ± 7.5% (a combination of latent and sensible heat). The measured enthalpy change obtained using the HFM is 193 KJ/kg ± 8.4% for the same temperature range. These results suggest that the total heat storage capacity of the test specimen (macro-encapsulated PCM) is only slightly different than the pure PCM. Additionally, the results show that the macro-encapsulated PCM has the same peak melting and freezing temperature (between 20 ℃ and 21 ℃), which is also in agreement with the information provided by the manufacturer. The main discrepancy between the measured properties and the properties provided by the manufacturer is in the PCM active range. The measurement results show a PCM melting range between 18 ℃ and 22 ℃ and a PCM freezing range between 22 ℃ and 16 ℃. On the other hand, the datasheet provided by the manufacturer indicates a PCM melting/freezing range between 20 ℃ and 23 ℃ and between 21 ℃ and 19 ℃, respectively. This discrepancy might be associated with external factors such as the PCM container's heat capacity and thermal conductivity or by the sample size [13]. The properties of the macro-encapsulated PCM obtained with calorimetric measurements are summarized in Table 1.
Table 1. Thermo-physical properties of the PCM used in the simulations.

| Properties                                           | RT21HC |
|------------------------------------------------------|--------|
| Latent heat during the phase change process (KJ/kg)  | 136    |
| Peak melting temperature (°C)                        | 21     |
| Peak freezing temperature (°C)                       | 21     |
| Liquid-state thermal conductivity (W/m·K)            | 0.15   |
| Solid-state thermal conductivity (W/m·K)             | 0.16   |
| Liquid-state density (kg/m³)                         | 770    |
| Solid-state density (kg/m³)                          | 880    |
| Liquid-state specific heat (kJ/kg·K)                 | 3.0    |
| Solid-state specific heat (kJ/kg·K)                  | 4.3    |
| High temperature difference of melting curve (delta °C) | 0.6    |
| Low temperature difference of melting curve (delta °C) | 5.0    |
| High temperature difference of freezing curve (delta °C) | 0.6    |
| Low temperature difference of freezing curve (delta °C) | 6.0    |

3.2. Dynamic thermal performance and model validation

Figure 4 shows the test results obtained during passive mode operation. As shown in the figure, the temperatures at the top and bottom of the PCM panel and the surface heat flow rate obtained from simulations showed a good agreement with the monitoring data from the experimental setup. The surface temperature at the top of the PCM panel (piping location) showed a slightly lower deviation (RMSE ± 0.28 °C) than the surface temperature at the bottom of the PCM panel (RMSE of ± 0.33 °C) – but still lower than the maximum values of the RMSE provided in the German Standard VDI 6020 (maximum of ± 1.5 °C). For the simulated surface heat flow rate, an RMSE of ± 6.00 W/m² was obtained, which means that the building-system model has good accuracy for predicting the cooling capacity (surface cooling rate) of the RCP-PCM.

Figure 4. Measured and simulated surface temperatures at the top and bottom of the PCM panel and surface heat flow rate. Simulated values are plotted in dashed lines.

Due to the small size of the experimental setup and the relatively high flow rate of the water circulator (0.27 kg/s), the temperatures measured at the inlet and outlet of the radiant panel were the same when the system operated in active mode. For this reason, the dynamic performance of the system during active mode operation could not be validated. Future work will focus on field experiments in a real-size test room for validating the model during active mode operation and to identify any differences in the system’s performance compared to the experimental results presented in this study.
4. Conclusions

To accurately predict and optimize the performance of buildings incorporating PCM products, systems, or components, validated numerical models are needed. The first step for obtaining a validated numerical model is to properly characterize the PCM products or components, as their thermal properties tend to be different than the pure PCM. Unfortunately, only a limited number of studies describe the process of measuring the thermal storage properties of PCM products or components using a different method than the common DSC or T-history methods, which have limitations associated with the size of the test specimen. To address this research gap, the authors demonstrated the use of a relatively new standard such as ASTM C1784-20 [8] for measuring the properties of a macro-encapsulated PCM. The results show that HFM enthalpy measurements of products incorporating PCM are within ± 2% of manufacturers’ data. However, some important discrepancies with literature values were also found, especially in the PCM active range, which should be carefully considered in the validation process.

The study results also show that a simple experimental setup can be used for successfully validating a simulation model of a room with a PCM product, system, or component. The validated parameters (radiant surface temperature and heat transfer rate) showed a good agreement with the monitoring data from the experimental setup. The radiant surface temperatures (at the top and bottom of the macro-encapsulated PCM) showed an RMSE of around ± 0.33 °C, which are lower than the maximum values of RMSE provided in the German Standard VDI 6020 (maximum of ± 1.5 °C). For the simulated surface heat flow rate, an RMSE of ± 6.00 W/m² was obtained.

References
[1] International Energy Agency (IEA) 2020 “Is cooling the future of heating?,” https://www.iea.org/commentaries/is-cooling-the-future-of-heating (accessed Jan. 15, 2021).
[2] International Energy Agency (IEA) 2018 “The Future of Cooling”.
[3] Romani J, De Gracia A and Cabeza L 2016 Energy Build. 127 22.
[4] Jobli M, Yao R, Luo Z, Shahrestani M, Li N and Liu H 2019 Appl. Therm. Eng. 148 466.
[5] Dutil Y et al. 2014 Renew. Energy 61 132–5.
[6] Dutil Y, Rousse D, Ben Salah N, Lassue S and Zalewski L 2011 Renew. Sustain. Energy Rev. 15 112.
[7] Kosny J, Kossecka E, Brzezinski A, Tleoubaev A and Yarbrough D 2012 Energy Build. 52 122.
[8] ASTM International 2020 “ASTM C1784-20: Standard Test Method for Using a Heat Flow Meter Apparatus for Measuring Thermal Storage Properties of Phase Change Materials and Products”.
[9] Klinker F, Mehling H, Konstantinidou C and Weincläder H 2014 “Measurement setup to determine the thermal properties and dynamic thermal behavior of cooling ceilings with PCM” Eutotherm Seminar #99.
[10] Tleoubaev A, Brzezinski A and Braga L 2008 12th Brazilian Rubber Technol. Congr.
[11] Shinoda J, Kazanci O, Tanabe S, and Olesen B 2019 Build. Environ.159 106.
[12] VDI 2002 “VDI 6020 - Requirements to be met by calculation methods for the simulation of thermal-energy efficiency of buildings and building installations”.
[13] Mehling H, Leys J, Glorieux C and Thoen J 2021 SN Appl. Sci.