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Effects of phase change material roof layers on thermal performance of a residential building in Melbourne and Sydney

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ABSTRACT

This paper assesses the effectiveness of Phase Change Materials (PCMs) for the improvement of the thermal performance and the thermal comfort of a residential building in Melbourne. The incorporation of PCMs in buildings with their significant heat storage capacity can delay the heat transfer and reduce the cooling and heating loads. Numerical simulation is a useful tool for comprehensive assessments and optimization of PCM applications in buildings. Thus an available TRNSYS component, PCM Wall: Type1270, was implemented with Type56 (Multi zone component). PCM Wall TRNSYS component has been validated with some experimental data published in the open literature. The validated model was then utilised to simulate the thermal performance of a residential building which has a PCM roof layer. The building is a typical single-storey, three bed room residential building in Melbourne. It was found that the PCM roof layer can reduce the cooling and heating loads whilst providing better thermal comfort for occupants with reduced indoor temperature fluctuations.

1. Introduction

Phase change materials (PCMs) provide thermal mass effect (i.e. delay the heat transfer) and offer a convenient mean for better energy efficiency in buildings. Although sensible storage has been used for centuries as a passive thermal storage, latent storage materials provides more effective storage of heat with comparatively very small amount of phase change material [1]. Building materials incorporated with PCMs can store significant amount of thermal energy in building envelope with less structural mass compared with sensible heat storage [2]. PCMs can be used to stabilize the indoor temperature in a building by reducing the temperature fluctuations due to external weather conditions [3]. Some assessments of thermal performance of buildings with the application of PCM were mainly focused with experimental analysis in the past. However with the recent development of building energy simulation software tools, thermal performance investigations have become a reality with wide variety of PCMs and different methods of placement within a building fabric. Therefore a complete simulation of thermal performance for buildings with PCMs has been utilised to evaluate the benefits.

EnergyPlus and TRNSYS have been the most widely used building energy simulation software tools for researchers. They are capable of handling thermal performance evaluation for buildings with PCM layers [4]. EnergyPlus building simulation is based on one dimensional conduction finite difference (CondFD) solution algorithm which is capable of solving varying thermophysical properties with respect to temperature [4]. A single room cubical modelled by Tardieu et al. [5] emphasis the accuracy of simulation results with the use of actual weather data rather than using historical data for simulation. Honeycombed PCM panels installed in an existing office building simulated with EnergyPlus by Evola [6] showed that incompetence in solving effect of hysteresis in heat capacity is a limitation of EnergyPlus when simulating PCMs. Indicators for evaluation of effectiveness with PCM were discussed which includes intensity of thermal discomfort, number of hours which meets thermal comfort criteria and frequency of activation of PCM. In the work of Tabares-Velasco et al. [7] a PCM model (CondFD coupled with enthalpy-temperature function) in EnergyPlus was verified and validated. They have identified a few key limitations and guidelines when using the EnergyPlus PCM model. Time steps should be less than or equal to 3 min and for sub-hourly analysis a Space Discretization Constant should be about 0.3–0.5.

TRNSYS is an abbreviation for TRaNsient System Simulation program and it is a modular simulation software where components (TYPES) can be linked together. Thus for simulations of buildings and its complex environments either available type can be used or

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new modules can be developed and easily integrated [4]. Ibanez et al. [8] developed a simple model with TRNSYS to simulate the thermal behaviour of building including elements with PCMs using active layers with proper external controls. Since the standard TRNSYS components do not include wall components with PCM, add-on PCM models have been developed for coupling with Type56 Multizone building model. The models includes Type260 [9], Type101 [10] and Type260 [11]. Most of them are research modules while quite a few are available commercially and some of them have limitations in simulation time and lack of validation. Kuznik et al. [11] has developed PCM Type260 which was linked with Type56 "Multi zone Building" to model test-cells with PCM wallboard. A similar approach in modelling of PCM wall layers was used by Schranzhofer et al.[12] by integrating a novel PCM wall type (Type241) and multi zone building model in TRNSYS. Finite difference method was used to calculate thermal conductivity and heat storage inside the PCM layer. Poulad et al. [13] used Type204 to evaluate the effect of heat transfer coefficient on heating and cooling energy demand. Type204 component simulates heat transfer of a 3D PCM composite wall system with a total of 729 nodes where material properties and concentration can be easily defined by the user. The high number of nodes increases the computing time with Type204 which makes quite difficult to run a year around simulation of a PCM integrated building.

In this paper, a commercially available PCM computation module "Type1270" by Thermal Energy System Specialists [14] has been validated with published experimental results and subsequently used for evaluation of thermal performance of an existing residential building. TRNSYS was selected for the investigation because it is a modular simulation software with the possibility of including other system components (such as HVAC and renewable energy) in buildings. Moreover the computing time for Type1270 is relatively short compared to other available Types, thus it can facilitate full year energy simulation of buildings with PCM. In the following sections the modelling with PCM component Type1270 is discussed and then experimental data reported in the literature was used to validate Type1270. Then the validated PCM component was applied to evaluate the thermal comfort, heating and cooling loads of a typical single-storey residential building in Melbourne and Sydney.

2. Method

2.1. Type1270

The building energy simulations were carried out using TRNSYS version 16.01.003 and Type1270 was used to simulate a layer of PCM completely confined within a wall of Type56 Multi zone building [14]. It uses the boundary wall concept to define the energy inputs to the PCM layer. Standard wall components of the building are modelled with Type56 and the PCM layer is modelled externally. The wall containing PCM is divided into two parts, where each part acts as a boundary wall to the PCM layer. Type56 output "QCOMO" (NTYPE20) for each of the two boundary walls which gives the heat flux energy to the outside surface of the boundary wall is given as the input to the PCM layer. Type1270 computes the PCM layer temperature (T_PCM shown in Fig. 1) which is then fed back to Type56.

Type1270 models a pure PCM where it assumes PCM undergoes its face transition at a constant temperature and the specific heat capacity of solid and liquid phases is constant. The temperature at the end of time step is calculated as follows;

Solid Phase;

$$T_{final} = T_{initial} + \frac{q_1 + q_2}{m_{PCM} Cp_{solid}} \quad (1)$$

Liquid Phase;

$$T_{final} = T_{initial} + \frac{q_1 + q_2}{m_{PCM} Cp_{liquid}} \quad (2)$$

where q_1 and q_2 are the quantity of energy (W) entering the PCM from the adjacent wall layers, $C_{p_{solid}}$ is the heat capacity of solid state of PCM ($Jkg^{-1}K^{-1}$) and $C_{p_{liquid}}$ is the heat capacity of liquid state of PCM ($Jkg^{-1}K^{-1}$).

2.2. Validation of Type1270

The validation of TRNSYS Type1270 was done by comparing simulation results with experimental data reported by Ahmad et al. [10]. The experimental data based on two test-cells which consist of one glazed surface and five opaque surfaces insulated with vacuum insulation panels (VIPs) as shown in Fig. 2. One of the test-cells comprised of five PCM panels. Quite a few PCMs were tested based on their availability, cost and thermal performance and polyethylene glycol (PEG) 600 was selected for experiments. A brief description of the experiment is presented here and the reader may find more information in the cited reference.

The test-cell without PCM consists of VIP which is sandwiched between two panel of fibre cement and plywood. The test-cell with PCM comprises with a PVC panel which was filled with 20 kg of PCM and the test-cell constitutes of VIP and PCM panels sandwiched between fibre cement panel and plywood panel. The test-cells consist of double glazing windows with solar radiation transmission coefficient of 0.8. The windows were oriented south for the maximum collection of sunlight during winter in Grenoble, France. The test-cells were equipped with thermo couples and heat flux sensors and heat fluxes between outside and wall, and between wall and inside were measured. The experimental results show that the indoor temperature of the test-cell without PCM reaches 60 °C during hottest period of the day while test-cell with PCM reaches around 40 °C. Conversely during night the drop in temperature in the test-cell with PCM is lower than the test-cell without PCM. The diurnal temperature amplitude of the two test-cells is approximately 20 °C for the test-cell with PCM and 50 °C for the test-cell without PCM. It shows the ability of PCM to store energy and it acts as a heat absorber.

The test-cell was modelled using Type56 and the external boundary conditions which includes the ambient temperature and solar irradiation values for the period was obtained from the experimental results reported by Ahmad et al. [10]. The paper published by Ahmad et al. [10] does not provide exact details on material properties other than the PCM, thus other material properties were obtained from available literature and material databases [15,16] as presented in Table 1.

PCM layer was applied to five surfaces of the test-cell which excludes south oriented surface with the window. For each surface, Type1270 component was used to model the PCM. The two walls which were set as boundary walls were given back side convection coefficient of 0.0001 indicating a direct contact (see Fig. 1). Type1270 calculates the surface temperature of each PCM layer and this is fed back to Type56 multi zone building to calculate the indoor air temperature of the test-cell.

2.3. Simulations

The validated TRNSYS Type1270 was used to simulate a typical single-storey residential building in Melbourne and Sydney to verify its application in real-world conditions. The dimensions and materials for the single-storey residential building were obtained from published data by Aguilar et al. [17] and only some of the relevant details of the residential building is reported. EnergyPlus simulation was carried out by the cited reference which