Energy Conversion and Management 106 (2015) 1409–1417

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

A reference device for evaluating the thermal behavior of installed multilayered wall containing a phase change material

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ARTICLE INFO

Article history:
Received 17 July 2015
Accepted 23 October 2015
Available online 11 November 2015

Keywords:
Multi-layered wallboard
Phase change material
Thermal characterization
Modeling
Uncertainty

ABSTRACT

Thermal inertia of lightweight building envelopes can be improved including phase change materials in multilayered wallboards. The thermal modeling of buildings for design purposes needs a robust description of the thermal properties of installed phase change materials. A standard method would improve the thermal characterization of commercial products. The aim of the study is to develop a simple methodology to obtain reliable thermal data for phase change materials integrated in multilayered wallboards. The methodology modifies differential scanning calorimetry measurements on phase change material by installation factors to obtain the apparent specific heat vs. temperature for the wallboard layer embedding phase change material. Simple cubic cells were realized as reference devices to simulate a confined environment. A dynamic model of heat transfer was developed to simulate the thermal behavior of devices. Installation factors were calculated by regression of the monitored temperatures inside and outside the devices operating under real environmental conditions. The apparent specific heat of phase change material, measured by differential scanning calorimetry at different rates, resulted in a spread of curves vs. temperature. Mean curves were used as initial condition for regression. The mean calculation method did not significantly affect the installed resulted curve. A unique curve of apparent specific heat vs. temperature best fit data measured over a wide range of experimental devices and conditions. Good regression performances were observed for solid liquid and biphasic states with different thickness of the phase change material layer. The modification of differential scanning calorimetry measurements through installation factors improved the robustness of description. The proposed methodology could be a starting point for the definition of a reference standard for the characterization and comparison of wallboards embedding phase change materials.

1. Introduction

Building sector is the dominant energy consumer in modern cities. In order to achieve the environmental thermal comfort passively and to reduce the energy demand, different constructive components have been designed [1], in particular lightweight engineered envelopes provided with resistive and capacitive layers [2]. PCM composite wallboard can reduce the energy consumption of buildings in summer and winter, can shift the peak electricity load in the summer [3,4] and can improve the indoor thermal comfort [5,6]. For design purpose a robust modeling of building is required and accurate measurements of the properties of construction material are necessary [7,8]. Macdonald and Strachan [9] reviewed the sources of uncertainty in the predictions from thermal simulation programs. The potential impact of uncertainty analysis on design decisions in building performance evaluations has been analyzed by de Wit et al. [7]. Hopfe et al. [8] carried out an uncertainty analysis with respect to several building performance parameters evaluating energy consumption and thermal comfort. Palomo del Barrio et al. [10] showed how model parameters space analysis is an effective tool for empirical validation of the thermal analysis of a building. Domínguez-Munoz et al. [11] analyzed the propagation through the building model of the input data uncertainties in order to determine their impact on the peak cooling load. Spitz et al. [12] evaluated the uncertainty of the simulation results during the design process for determining the influential parameters in the building's energy performance. As a result, heat capacity of the system is one of the most effective parameters.

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http://dx.doi.org/10.1016/j.enconman.2015.10.061
0196-8904/

Nomenclature

c_p	apparent specific heat (kJ kg^{-1} K^{-1})
$c_{p,installed}$	apparent specific heat of PCM layer modified by installation factors (kJ kg^{-1} K^{-1})
$c_{p,liq}$	liquid apparent specific heat of PCM layer (kJ kg^{-1} K^{-1})
$c_{p,mean\_all}$	apparent specific heat of free PCM as the mean of all DSC curves (kJ kg^{-1} K^{-1})
$c_{p,mean\_C}$	apparent specific heat of free PCM as the mean of cooling DSC curves (kJ kg^{-1} K^{-1})
$c_{p,sol}$	solid apparent specific heat of PCM layer (kJ kg^{-1} K^{-1})
$c_{v,a}$	air specific heat at constant volume (kJ kg^{-1} K^{-1})
dV	elemental solid volume wallboard faces of devices (cm^3)
IF_P	peak scaling factor (–)
$IF_{S,H}$	shaping factors, high temperature side of the peak (–)
$IF_{S,L}$	shaping factors, low temperature side of the peak (–)
IF_T	temperature shifting factor (°C)
k	coverage factor (–)
l_0	edge size of faces of devices (cm)
RMAE	Relative Mean Absolute Error%
RMBE	Relative Mean Bias Error%
RMSE	Relative Mean Squared Error%
RRMSE	Relative Root Mean Squared Error%
q_c	heat flow rate transferred between air and one inner face of the cell (kJ min^{-1})
q_s	heat flow rate coming from the fan mixer motor installed inside the cell (kJ min^{-1})
R^2	correlation coefficient (–)
s	thickness of PCM layer (cm)
t	monitoring time (d)
T	temperature (°C)
T_a	temperature of air inside the device (°C)
T_{ew}	temperature of the external face of devices (°C)
$T_{installed}$	temperature of curve modified by installation factors (°C)
T_{iw}	temperature of the internal face of devices (°C)
$T_{iw,meas}$	temperature of the internal face measured (°C)
$T_{iw,sim}$	temperature of the internal face simulated (°C)
ΔT_{iw}	internal temperature simulation error $\Delta T_{iw} = T_{iw,meas} - T_{iw,sim}$ (°C)
T_{DSC}	temperature of DSC curve (°C)
$T_{melting}$	starting melting temperature, DSC or installed curve (°C)
T_{peak}	temperatures of peak, DSC or installed curve (°C)
$T_{solidification}$	starting solidification temperature, mean DSC or installed curve (°C)
V_a	air volume inside the device (cm^3)

Greek letters

x	position along wallboard thickness (cm)
λ	thermal conductivity of each layer of wallboard (kW m K^{-1})
α	thermal diffusivity of each layer of wallboard $\alpha = \lambda/(\rho c_p)$ (m^2 s^{-1})
β	slant angle of faces of devices (°)
ε	convergence criterion (–)
ε_{target}	target value for convergence criterion (–)
ρ	average density of each layer of wallboard (kg m^{-3})
ρ_a	air density inside the device (kg m^{-3})

Acronyms

DSC	differential scanning calorimetry
EMT	effective medium theory
IFs	installation factors
PCM	phase change materials
PCM Free	PCM not embedded in the layer
PCM layer	layer of wallboard embedding PCM
PCM Installed	PCM embedded in a layer of wallboard
PU	polyurethane
SEM	scanning electron microscopy

Phase change materials (PCMs) are used as high efficiency thermal energy storage layers in the form of latent heat. The choice of proper measurement techniques is still an open discussion in literature and many efforts have been made by researchers in this field to improve the accuracy of thermal data [13]. Analysis of the transient heat process inside a wallboard containing PCM needs measurement of: thermal conductivities; heat capacities of the solid and liquid phases; transition temperatures; the enthalpy change of the free PCM undergoing phase transformation as a function of temperature. The accurate knowledge of the thermal properties of PCM is crucial for the correct design of commercial products [14]. Differential scanning calorimetry (DSC) is the main reference technique because of its accuracy and simplicity [15]. Main limitations of DSC methods are the small quantities of sample analyzed that are not representative of larger sample sizes, and a sort of hysteresis effect dependent on the rates of heat/cooling ramp [16,17]. The equivalent heat capacity calculated using the DSC curves is influenced by the sample mass and heating rate [18,19] because of the convection phenomena in the sample, the non-uniformity of the temperature in the sample [20], the time needed to heat or cool the sample [21]. Lazaro et al. [22] asserted that the temperature uncertainty could be reduced by using, instead of DSC steady temperature ramps, a steps program. In this case the temperature gradients in the sample are minimized and the temperature uncertainty is lower and known. Castellon et al. [14] found that using a paraffin sample and the DSC step mode, the accuracy can be increased to a satisfactory level, and that the step method is far less sensitive to a variation in the measurement parameters. Barreneche et al. [20] found that a slow dynamic mode is recommended when analyzing salt hydrates with DSC and that no significant differences between DSC isothermal step mode and dynamic mode were observed for paraffin. The T-history method for the analysis of larger samples (20 ml) was proposed by Yinping in 1999 [16], and successively verified [22] and improved [15,13,23,24]. Gunther et al. [18] evaluated the accuracy of enthalpy vs. temperature measurements by using DSC analysis and the T-history methods and proposed an air flow chamber for calorimetric measurements of PCM components for air-based storages. However, this method allowed a verification of overall storage capacity only, because a loss in temperature precision occurs as a trade-off of the increased sample size at a realistic measurement time [18].

The thermal characterization of wallboard containing PCM should be aimed to describe the layer embedding PCM by a unique c_p vs. temperature curve to be inserted in a simulation tool [25], e.g., Energy Plus [26] and ISOLAB [27]. Properties of installed PCM in multilayered wallboard are considerably different from those measured for free PCM by laboratory analysis techniques. The sample size analyzed with the above described methods is much smaller than the PCM amount used in real scale installation (at least of the order of kilograms). Moreover the real conditions at which PCM operates are different than the laboratory testing conditions, it is mainly due to the embedding matrix effects and local heat exchange rates.