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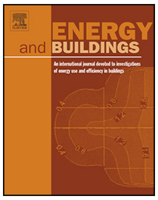

Use of a latent heat thermal energy storage system for cooling a light-weight building: Experimentation and co-simulation

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ABSTRACT

Air cooling systems that make use of the energy storage potential of the latent heat of Phase Change Materials (PCMs) are alternatives to conventional air-conditioning units for maintaining indoor comfort in summer in light-weight buildings. However, the functioning of such systems is closely linked to the ambient climatic conditions and to the spatial and energy specifications of the buildings to be cooled. For a better understanding of their performance in situ, a thermal co-simulation of a Latent Heat Thermal Energy Storage (LHTES) system and of an existing wooden building is proposed. The performance of this co-simulation is demonstrated by comparing results with experimental results from tests on a building which incorporates an LHTES system. This performance analysis, conducted using Normalised Mean Bias Error (NMBE) and Coefficient of Variation of the Root Mean Square Error (CV(RMSE)), demonstrates the viability of integrating co-simulation to facilitate the LHTES system design process.

1. Introduction

Ensuring indoor comfort in summer has become an increasing problem in the residential sector and the service industries, where buildings have become increasingly insulated and airtight, and therefore sensitive to internal and external energy supplies. Experimental studies in the literature have shown that Latent Heat Thermal Energy Storage Systems (LHTES) are able to cool air for several hours under controlled conditions [1–7], i.e. with constant incoming air flow and temperature. Air-cooling systems based on LHTES, which are composed of Phase Change Materials (PCMs), should now be tested in terms of their adaptability to different spatial layouts of buildings as well as in terms of their capacity to respond to the cooling problem in summer, to see if they can offer a reasonable technological solution with potentially interesting performance coefficients. The thermal co-simulation of the building with the LHTES system that it contains is a possible alternative to tests in situ; under ideal circumstances, it is a suitable way to develop decision support tools for the use and validation of the performance of such phase change systems (Sebastian et al. [8]).

Yanbing et al. [9] present the modelling and experimental study of an LHTES system for maintaining thermal comfort in summer. This system, which contains 150 kg of PCM in the form of flat-plate capsules, is incorporated in a false ceiling. It extracts air from the inside (air cooling mode) or from the outside (regeneration mode) and blows air into the premises. The authors have developed a calculation tool that couples the thermal model of an LHTES system with a simplified thermal model of a mono-zone building. Although the mathematical model they developed disregards perceptible heat compared with latent heat and underestimates transfers within the molten PCM, overall, the behaviour of the simulation and the experimental results are similar. Furthermore, the authors demonstrate the contribution of the system in terms of comfort by comparing results obtained with and without the LHTES system.

In Japan, Takeda et al. [10] studied the appropriateness of using an LHTES system based on PCMs for air cooling. The LHTES system studied was composed of a packed bed of granules with a diameter of 1–3 mm containing 35% paraffin. Contrary to Yanbing et al., the system developed by Takeda et al. was incorporated into a hygienic ventilation system: only air coming from the outside enters the LHTES system. This choice of design means that the LHTES system operates free from all connection with the building, which greatly simplifies the associated modelling. Based on climate data from different towns in Japan and a very simplified LHTES model (the localised temperature of the encapsulated PCM granules was

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Nomenclature

A	Area (m^2)
Cp	Specific heat (J kg^{-1} K^{-1})
CV(RMSE)	Coefficient of variation of the root mean squared error (%)
H	Mass enthalpy (J kg^{-1})
h	Heat transfer coefficient (W m^{-2} K^{-1})
L	Latent heat (J kg^{-1})
n	Number of data points or periods in the baseline period (−)
NMBE	Normalised mean bias error (%)
p	Number of parameters or terms in the baseline model, as developed by a mathematical analysis of the baseline data (−)
PCM	Phase change material
q	Volume air flow (m^3 h^{-1})
S	Cross section (m^2)
T	Temperature (°C)
t	Time (s)
U	Velocity (m s^{-1})
y	Dependent variable of some function of the independent variable(s) (−)
$\bar{y}$	Arithmetic mean of the sample of n observations (−)
$\hat{y}$	Regression model's predicted value of y (−)

Greek letters

ΔT	Temperature difference
κ	Volume variation between solid-liquid during phase change (−)
λ	Thermal conductivity (W m^{-1} K^{-1})
ρ	Bulk density (kg m^{-3})
σ	Volume fraction (−)

Indices

0	Initial condition
a	Air blown into the cooling system
exp	Experimental
ext	Air outside the house
f	Phase change
in	Entering the system
int	Air inside the house
out	Leaving the system
w	PCM container wall

assumed to be uniform and equal to the local air temperature), the authors assessed the cooling potential of the LHTES system by calculating the reduction in need for mechanical ventilation for cooling compared to a conventional ventilation system that carries out the same function. They conclude that it is thus possible to reduce the need for ventilation by 62.8% by using an LHTES system.

The prototype presented by Arkav et al. [11] is composed of two cylindrical LHTES devices, whose encapsulated spheres are filled with paraffin RT21. In order to maintain a comfortable temperature of 26 °C during the day, these authors combined mechanical and/or natural night ventilation cooling with daytime cooling using an LHTES system. With the aid of a building model coupled with an approximate LHTES model (transfers within the PCMs were purely conductive) in a TRNSYS® environment, they assessed numerically the potential of such combinations for different commonly occurring scenarios in terms of energy efficiency.

The use of co-simulation for automated optimisation of air-PCM systems has not been studied very extensively. Chiu et al. [12] used TRNSYS software (the block function TYPE 842 developed by the University of Graz, Austria), adapting it to the case of an LHTES-Air-PCM system (the block function TYPE 842 in its original version, only allows simulation of the behaviour of LHTES of the water-type PCM system). Simulating the LHTES system coupled with a building thus enables them to determine the lack of comfort in the building and the energy use of the fan required to make the system work. By using multi-objective optimisation algorithms, these authors have determined the Pareto front by seeking to minimise the remaining cooling requirements and the cost over the life cycle of the LHTES system.

It is important to note that co-simulation is used for Building Performance Simulation (BPS) in order to assess the performance of various systems that interact with the building. Wetter [13] has developed the BCVTB® (Building Controls Virtual Test Beds) platform, which ensures the exchange of information between different calculation and simulation software packages, thus providing the possibility of testing innovative control systems or algorithms. For example, Novakovic and Cvetkovic [14] propose temperature regulation by way of slatted blinds, where the rising/falling and the angles of the slats depend on the amount of solar input, while Zhao et al. [15] propose a system of predictive technical building management using MATLAB/SIMULINK and EnergyPlus.

The work presented here forms part of a research project to develop a design support tool for buildings from the preliminary design stage by permitting an optimal dimension pre-calculation of air-cooling systems using PCMs. A thermal behaviour simulation approach to the system in its environment has been chosen as a basis for a multi-criteria optimisation tool. First, a dynamic simulation model of an LHTES system was developed on the MATLAB® software platform and subsequently validated by Rouault et al. [7,16]. The objective here is to couple this thermal model of an LHTES system with a BPS software package and to validate this coupling by comparing the simulation results with results from experimental tests in situ. With this aim, a prototype of an individual one-storey house was fitted with an LHTES system (used for maintaining indoor comfort in summer) and a thermal model of this prototype was developed on a BPS software package and considered with the help of experimental results from a period of measurements without the use of the LHTES system. The suitability of a building-LHTES co-simulation was then assessed by comparing the simulation results with experimental results from a measurement period during which the LHTES system was used.

2. Presentation of a case study

2.1. Presentation of the prototype and the house

Napevomo (cf. Fig. 1) is an individual house with a living area of 47 m^2 able to accommodate two people. This house was built within the remit of the international inter-university competition Solar Decathlon Europe 2010 (SDE 2010) [17], and was developed by students of the Arts et Métiers ParisTech engineering school with technical support from a business consortium and scientific support from the Institut de Mécanique et d'Ingénierie de Bordeaux (I2 M). After this competition, which took place in Madrid in June 2010, the Napevomo house was rebuilt on the site of Bordeaux-Talence d'Arts et Métiers ParisTech (France), where it was instrumented and monitored for a duration of two years.

The Napevomo house is light in structure (wooden frame) in order to meet the criterion of being transportable and very lightly tied to the ground, which was a requirement of the SDE 2010 competition rules. The composition of the walls retained for the building model developed in this work, is that described by Bruneau et al. [18] with certain simplifications. In fact, water loss from the roof and from the green wall and the contribution to resistance of the