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Numerical modelling and experimental studies of thermal behaviour of building integrated thermal energy storage unit in a form of a ceiling panel

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HIGHLIGHTS

- A new concept of heat storage in ventilation ducts is described.
- Ceiling panel as a part of ventilation system is made of a composite with PCM.
- A set-up for experimental investigation of heat storage unit was built.
- Numerical model of heat transfer in the storage unit was developed.
- Numerical code was validated on the base of experimental measurements.

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ABSTRACT

Objective: The paper presents a new concept of building integrated thermal energy storage unit and novel mathematical and numerical models of its operation. This building element is made of gypsum based composite with microencapsulated PCM. The proposed heat storage unit has a form of a ceiling panel with internal channels and is, by assumption, incorporated in a ventilation system. Its task is to reduce daily variations of ambient air temperature through the absorption (and subsequent release) of heat in PCM, without additional consumption of energy.
Methods: The operation of the ceiling panel was investigated experimentally on a special set-up equipped with temperature sensors, air flow meter and air temperature control system. Mathematical and numerical models of heat transfer and fluid flow in the panel account for air flow in the panel as well as real thermal properties of the PCM composite, i.e.: thermal conductivity variation with temperature and hysteresis of enthalpy vs. temperature curves for heating and cooling. Proposed novel numerical simulator consists of two strongly coupled sub models: the first one – 1D – which deals with air flowing through the U-shaped channel and the second one – 3D – which deals with heat transfer in the body of the panel.
Results: Spatial and temporal air temperature variations, measured on the experimental set-up, were used to validate numerical model as well as to get knowledge of thermal performance of the panel operating in different conditions.
Conclusion: Preliminary results of experimental tests confirmed the ability of the proposed heat storage unit to effectively control the air temperature inside the building. However, detailed measurement of the temperature of PCM composite have shown some disadvantages of the panel used in the study, e.g. thickness of the walls and distribution of PCM should be optimized. This can be achieved with the aid of the numerical simulator developed in this research.
Practical implications: The proposed ceiling panel, optimised from the point of view of thermal performance in a given environmental conditions, can be used as a part of ventilation systems in residential and office buildings.

1. Introduction

Night ventilation is a low-cost technique that is suitable to provide required indoor conditions in buildings during a summer. During the day, due to heat generation from various sources (such

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as office equipment, personnel and solar radiation) internal temperature steadily increases, and then decreases during the night. At high ambient temperature and high heat loads maximum internal temperature can significantly exceed upper limit of thermal comfort conditions. The range of temperature variations in daily cycle depends, among others, on the rate of building cooling during the night, which in turn depends on the intensity of night ventilation while the amplitude of temperature oscillations depends on the thermal capacity of the building structure. Recently very effective method for an increase of the thermal inertia of buildings was proposed, keeping theirs mass at low level and involving phase change materials (PCM). These materials absorb (and release in a subsequent phase of a cycle) a large amount of heat undergoing nearly isothermal phase change process (melting/solidification). Thus temperature variations of both building elements containing PCMs and interior environment are substantially reduced [1–3].

Efficiency of night ventilation with PCM embedded in building envelope depends on the amount of PCM (its total thermal capacity), air flow rate during night ventilation and heat transfer area between blowing air and absorbing elements. The latter is related to the shape of building elements containing PCM and their distribution in the structure [4]. When PCM is introduced in internal façade (e.g. in gypsum plasterboard) heat transfer rates are limited because of low heat transfer surface area. A major consequence of this approach is the difficulty of full solidification of PCM. In order to improve the process of heat transfer between air and PCM special configurations of building elements located in ventilation ducts are proposed. One group of solutions involves integration of ventilation ducts with elements of the building, usually with the structure of the ceiling. It is especially useful in office buildings, where suspended ceilings provide ample opportunities for packaging both energy storage panels and air ducts. The simplest solution is applying slabs made of composite containing PCM or pure PCM enclosed in flat metallic boxes, which are hidden above ceiling [5]. Susman et al. [6] analyzed performance of PCM based 'sails' board designed to be hanged below ceiling in office space. This approach provides increased heat transfer with interior environment due to higher surface area. In order to enhance heat transfer to and from the PCM, containers with this material are equipped with both internal and external fins [7], or internal heat exchanger made of capillary tubes, which can be supplied by water [8] or by the PCM slurry [9]. Thermal inertia of the other parts of building structure are also considered to be utilized in ventilation systems, e.g. solid walls with internal air ducts were studied in the work of Fraisse et al. [10], while Nagano et al. [11] analyzed air channels arranged in an under-floor PCM packed bed. In another approach specially designed PCM based storage units are arranged in the ventilation system. These units are not parts of the building envelope, however, since they contain much higher amount of PCM, and capsules are optimized from the point of view of heat transfer, their performance characteristics are much better. Different PCM–air/water heat exchangers are studied for example in the works of Arkar et al. [12] and Torres Ledesma et al. [13] – PCM enclosed in spheres, Dolado et al. [14] – heat reservoir made of flat boards filled with PCM, Raj et al. [15] – special disc-shape modules with internal air passage holes, Banaszek et al. [16] – PCM contained in the wall of a spiral heat exchanger. Solutions proposed recently in [17,18] combines the two above approaches. Both are designed for building ventilation system, in the first one active ventilated facade was improved by fins containing PCM, while in the other phase change material is enclosed in cylindrical vessels that are located in the hollow core ceiling slab.

The main aims of the paper are to present a novel structure of a ceiling panel made of PCM-based composite and to develop an advanced and fast numerical model which will help in the future analysis of the operation of proposed solution. Containing substantial amount of PCM, the panel works as a thermal energy storage unit. It is also assumed that the panel is incorporated in building ventilation system between the inlet from the environment and the interior of the building. In the summer time, during the day the panel may accumulate heat from the ambient hot air. As a consequence temperature of the air which enters the interior of the building may be decreased. Stored heat is then released during the night when the ambient air temperature falls below the melting point of PCM.

Subsequently, physical model of the panel was made and experimental studies on its thermal performance were carried out. Preliminary results of experimental tests were used in verification of the proposed simulation code, which is expected to be used in future as a tool for optimization of the ceiling under consideration. The presented novel numerical simulator is composed of two parts. The first one – 3D – accounts for heat transfer in the body of the panel, while the second one – 1D – models heat transfer in the air flowing through the channel. Both parts are coupled through boundary conditions and source terms. The numerical model was implemented with the aid of commercial package ANSYS Fluent 14.0 and its advanced functionalities. It is worth noting that the model developed in this study for the first time takes into account real thermo-physical properties of the PCM, including hysteresis of enthalpy–temperature curve for heating and cooling.

The scheme of ceiling panel under study, with basic dimensions, is shown in Fig. 1. It is a board 6 cm thick, with 3 m long parallel channels of the square cross-section 3×3 cm. It was assumed that ambient air passes through two branches of U shaped channel before it reaches the interior of a building (as shown in the bottom-right part of Fig. 1). So that repetitive element of the ceiling can be distinguished from the whole ceiling board. Based on the geometry of this repetitive element both experimental set-up and numerical model for computational analysis were prepared.

2. Thermal performance of the ceiling panel – preliminary experimental study

Test module with two parallel channels of square cross-sections was built. It was made of a composite consisting of gypsum mortar (produced by Knauf) and micro-encapsulated PCM (Micronal DS-5008X, produced by BASF). PCM content is about 27.6 wt.% (30 wt.% for dry components). Melting point for the PCM used in the composite equals to 22.8 °C (by DSC, Perkin–Elmer). Precise measurement of enthalpy vs. temperature revealed that the curve for cooling is shifted by about 1.5 °C from the heating curve – both curves are shown in Fig. 2 (enthalpy characteristics were determined by DSC for scanning rates 0.5 K/min, sample mass equals to 14.93 mg). Thermal conductivity was also estimated with the use of mini-plate apparatus (Poensgen type) and was found to be temperature dependent. In the range of temperature 15–30 °C its values follow the formula: $k(T(°C)) = 0.5772 - 0.01611T$(W m^{-1} K^{-1}) [19]. Density of the composite equals to $\rho = 1000$ kg/m^3.

The side surfaces of the test module were insulated (Styrofoam plate, 5 cm thick) in order to reduce heat transfer to the ambient air – see Fig. 3. In fact, heat flow in horizontal direction is negligibly small due to the repeatability of these elements in the ceiling panel. Also bottom wall was insulated, this means that experimental model is reversed relative to the actual position in the ceiling (where heat transfer at top side, rather than bottom, can be neglected). However, convective heat transfer on the external surfaces of the panel does not substantially affect the whole process, so that this facilitation can be justified.

The set-up was equipped with several thermocouples (K-type, 0.5 mm diameter): eight sensors were installed inside the channel for measurement of the air temperature, six sensors were glued to