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Influence of internal thermal mass on the indoor thermal dynamics and integration of phase change materials in furniture for building energy storage: A review

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A B S T R A C T

The increasing share of intermittent renewable energy on the grid encourages researchers to develop demand-side management strategies. Passive heat storage in the indoor space is a promising solution to improve the building energy flexibility. It relies on an accurate control of the transient building temperature. However, many of the current numerical models for building energy systems assume empty rooms and do not account entirely for the internal thermal inertia of objects like furniture. This review article points out that such assumption is not valid for dynamic calculations. The furnishing elements and other internal content can have a significant impact on the indoor thermal dynamics and on the occupants' comfort. There is a clear lack of guidance and studies about the thermo-physical properties of this internal mass. Therefore, this paper suggests representative values for the furniture/indoor thermal mass parameters and presents the different available modelling technics. In addition, the large exposed surface area of furniture pieces offers a good potential for the integration of phase change materials. It can highly increase the effective thermal inertia of light frame buildings without any construction work.

1. Introduction

Climate change, pollution and fossil fuel shortage have been designated by many as some of the most important challenges of the 21st century. To prevent major energy crisis and reduce CO_2 emissions, significant efforts are required in increasing the renewable energy production while enhancing the energy efficiency of buildings [1]. With about 40% of the total final energy use in Europe, buildings are indeed the largest end-use energy sector, followed by transportation with 33%. Similar repartitions can be observed in the rest of the world [2]. On the production side, a significant expansion of wind and photovoltaic power is planned in many European countries [3]. In Denmark, for example, the energy mix is characterized by a large share of wind power which is expected to reach 50% on an annual basis in 2020. The energy development strategy of countries like Denmark relies on the implementation of a smart grid with high number of wind turbines coupled with district heating for buildings in cities, heat pumps outside urban areas and extensive use of electric cars [4] and [5].

Studies suggest that flexible technologies and demand-side management can improve the integration of renewable energies and facilitate operation of a smart grid system with high intermittent power penetration [6]. Indoor space heating accounts for 75% of the energy demand of a building in Europe [2]. Analyses showed that individual heat pumps and district heating form the best heat supply solutions in relation to costs, fuel consumption and CO2 emissions [7]. This thermal energy can be stored efficiently in the building indoor environment or in heat accumulation water tanks. It can thereby decouple the energy need from the intermittent availability of renewable energies, reduce excess wind electricity production and allow optimum use of the free internal and solar gains [8].

Low temperature, water-based radiant heating systems can accumulate heat in buildings with noticeable flexibility. They can be controlled according to a price signal and contribute to shaving of load peaks on the grid without affecting indoor comfort. A research indicated that passive heat storage in the indoor space can be more efficient for the reduction of excess electricity production and fuel consumption compared to heat accumulation water tanks [9]. Passive thermal energy storage (TES) aims to accumulate a maximum amount of heat in the building thermal mass and indoor volume. The operative temperature in the building increases when the electricity is available and cheap, and decreases when the power production is too low. However, the temperature must be kept within the limits of occupants'

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thermal comfort.

The study, implementation and optimization of such strategy for energy flexible buildings need accurate dynamic thermal building models. Nevertheless, many of the current numerical models take into account solely the thermal inertia of the envelope, the floors and the internal walls. The indoor thermal zone is considered as an empty space filled with air only. Furniture and additional mass present in a real occupied building are not included. This assumption is reasonable for classic design and energy analysis of buildings based on steady state or simplified long-term calculations. However, it could lead to noticeable errors for short-term transient temperature prediction, especially in residential buildings with light structure and a lot of furnishing, appliances or objects. This model simplification is thus worth investigating to quantify the role of furniture/indoor thermal mass and develop passive TES with optimum predictive control.

The large surface area of the furniture exposed to the indoor environment can be ingeniously used for latent heat thermal energy storage (LHTES) with the integration of phase change materials (PCMs). Their appreciable energy storage density is an interesting asset for increasing the thermal inertia of light structure buildings and for extending the applicability of the TES strategy. PCM furniture could allow integration of LHTES in low thermal inertia dwellings without the need for building renovation.

This paper aims to review the different scientific studies dealing with the influence of the indoor mass on the building thermal dynamics and emphasises the opportunities for coupling with the PCM technology. The article will first define the thermal mass in buildings. This is followed by a review on the interaction between the internal elements and the indoor environment. Representative thermo-physical characteristics for indoor content will be suggested based on published data and a simple building survey in Denmark. The article will then present different internal element modelling technics. The two last parts of this paper will discuss the different kinds of PCMs and the potential for their integration in furniture. The paper closes with conclusions and proposal for further investigations.

2. Definition

From the thermodynamics point of view, a building is usually considered as an assembly of sub-systems or thermal zones. Each of them is composed of elements with specific conductance and thermal inertia [10]. This section suggests distribution of these thermal inertia elements into three categories: thermal zone envelope, indoor air volume and furniture/indoor thermal mass. Construction parts such as external walls, floors, ceilings, roofs or partition walls form the envelope of the thermal zones. They often integrate heavy materials from the building's structure and have a significant thermal inertia [11]. The external thermal mass of the building envelope is exposed to the outdoor and indoor environment. It is not isothermal and its internal energy varies slowly. On another hand, the air volume contained inside a thermal zone is usually considered as one single node with homogenous temperature. The indoor air temperature can vary quickly because of its limited thermal inertia [10].

If many numerical models only account for the indoor air volume and the zones' envelope thermal mass, the real occupied buildings are actually not empty spaces. The additional furniture/indoor thermal mass of a building is defined as all the matter in a room with the following characteristics:

- It is not defined in the construction elements of the building envelope, floor, ceilings or partition walls.
- It is permanent in the thermal zone. It can move inside the same zone, but it does not leave it.
- It does not emit noticeable heat.
- Its temperature is driven by convection heat exchange with the indoor air and long-wave radiation heat exchange with the envelope inner surfaces, plus the internal heat gains (sun, HVAC systems, equipment and people loads).

According to that definition, the furniture/indoor thermal mass is composed of all the furnishing elements (sofa, bed, table, chair, desk, cupboard, closet, shelves and boards), the finishing parts or accessories that are not directly integrated in the envelope or walls and the aggregate of the other objects present in a room (plants, books, clothes, paper and small appliances). It excludes the body of living beings, movable objects, which enter and leave the zone several times a day, HVAC terminals (radiators, air handling units) and all equipment emitting heat energy (computer, ventilator, engines, lighting, lamps).

3. Influence of furniture and internal mass on the indoor environment

The furniture/indoor thermal mass elements present a large surface area for interaction with the indoor environment.

They exchange heat and moisture by convection with the indoor air and by diffusion with direct contact surfaces such as floors or walls. They also exchange heat by long wave radiation with the surrounding surfaces and can cover and hinder heating or cooling radiant systems. They can change air flow pattern in the room and affect ventilation efficiency and convection heat transfer. They can also reflect, diffuse and absorb solar radiation or internal gain and release it quickly to the surrounding air.

The furniture/indoor thermal mass is thus highly activated and coupled to the other elements. It is legitimate to wonder if this additional internal mass can be neglected in numerical models. This simplification could lead to significant errors especially for light structure houses or radiant systems. Some researchers have investigated this question. Most of the building related publications about internal mass and furniture study the chemical compounds emission of the different materials of furnishing parts and its impact on the indoor air quality [12]. Building numerical analysis including details of interior partitions and furniture has pointed out that they have a significant impact on daylight conditions [13]. However, the following discussion will only focus on the indoor thermal comfort and the thermal dynamics issues.

3.1. Micro-climate, indoor humidity and local discomfort

Mortensen et al. [14] investigated the local micro-climate created by furnishing elements close to cold walls. A piece of furniture placed near a poorly insulated external wall can lead to condensation on the inner side of the building envelope. The authors used particle image velocimetry to perform a two-dimensional experimental analysis of the airflow pattern in a small air gap between a chilled wall and a closet placed next to it. Two air gap widths were tested: 25 and 50 mm. Length of legs of the furniture varied from 0 to 200 mm. The study indicated that vertical flow dominates with similar behaviour as in between vertical plates heated asymmetrically. The flow in the air gap was not fully developed and maximum velocities were found near the cold wall. Finally, the flow rate increased when the gap was expanded or if the furniture was elevated from the floor.

The humidity buffering effect of materials located in the thermal zone can reduce humidity variation. It improves thermal comfort and decreases energy consumption of the mechanical systems for humidification or dehumidification. Yang et al. [15] conducted full-scale experiments on moisture buffering capacity of interior surface materials and impact of the presence of furniture in the interior space. The results showed that the indoor humidity variation decreased by up to 12% and the total moisture buffering potential of the room increased by up to 54.6% for a fully furnished case. The authors explained that furnishing elements present much more surface area for moisture exchange and buffering than envelope inner surfaces. Furniture