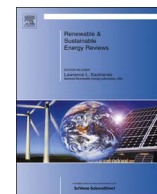




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## Thermal inertia in buildings: A review of impacts across climate and building use

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## ABSTRACT

A building with a great amount of thermal mass is able to time-shift and flatten out heat flow fluctuations; this is referred to as the thermal inertia of a building. This paper presents a literature review focussing on the reported impacts of building thermal inertia on thermal comfort and energy use for space heating and cooling. A wide range in research methods, building types and climatic conditions considered by the respective authors, contributes to a large spread in research outcomes. As a general tendency it can be concluded that for most buildings and climates, higher amounts of thermal mass at the inner side of the thermal insulation appear to be beneficial with regard to improving thermal comfort and reducing the energy demand. The impact on energy demand is however relatively small. With an order of magnitude of a few percent for most cases, other design parameters such as thermal insulation of the building envelope and solar heat gains will be more significant. The paper reviews some practical applications exploiting the effect of thermal inertia in design and operation of HVAC systems, and concludes with a discussion on the apparent discrepancy in simulation outcomes and suggestions for further research.

## 1. Introduction

Energy consumed in residential and commercial buildings increases by an average of 1.5%/year, and accounts for 20.1% of the globally delivered energy in 2016 [1]. The most important share of this energy demand can be attributed to the heating, ventilation and air-conditioning (HVAC) systems which regulate the indoor thermal comfort and indoor air quality (IAQ) [2]. Two main strategies can be distinguished to improve building energy efficiency [3]. Active strategies encompass improvements to heating, ventilation and air conditioning (HVAC) systems and artificial lighting, whereas passive strategies involve improvements to the building envelope such as increasing thermal insulation and optimizing solar gains to lower the energy demand of a building.

Increasing the thermal resistance of the building envelope by applying thermal insulation materials is generally advocated as the

most crucial factor to reduce the building energy demand, especially in heating dominated climates [4]. Consequently, many energy performance rating schemes and code standards set specific requirements to the thermal resistance (R-value) or thermal transmittance (U-value) of building components [5]. These performance indicators relate to the one-dimensional steady state thermal conduction of building envelope components such as walls, roofs and floors. R-values and U-values are simplified representations of the heat transfer of a building envelope component, as these indicators do not factor in any dynamic behaviour. The latter is introduced by exposing a building to variations in usage and environmental conditions such as time-varying outdoor temperature and solar irradiation.

In a transient situation, the thermal mass of a building can absorb, store and progressively release heat depending on the temperature difference with the immediate surroundings. The amount of heat stored

**Abbreviations:** BEPS, Building energy performance simulation; BREEAM, Building Research Establishment Environmental Assessment Method; CTF, Conduction transfer function; DOE, Design of Experiments; DSM, Demand side management; DBMS, Dynamic benefit for massive systems; EPBD, Energy Performance of Buildings Directive; HATS, Hybrid adaptable thermal storage; HQE, Haute Qualité Environnementale; HVAC, Heating, ventilation and air conditioning; IAQ, Indoor air quality; KPI, Key Performance Indicators; LEED, Leadership in Energy and Environmental Design; MPC, Model predictive control; PCM, Phase change material; PV, Photo-voltaic; TABS, Thermally activated building systems; TES, Thermal Energy Storage; TFM, Transfer Function Method; TOU, Time of use; TSBM, Thermal storage in building mass

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**Nomenclature**

A	Surface area [m <sup>2</sup> ]
b	Thermal effusivity [W m <sup>-2</sup> K <sup>-1</sup> s <sup>1/2</sup> ]
c	Specific heat capacity [J kg <sup>-1</sup> K <sup>-1</sup> ]
c <sub>a</sub>	Specific heat capacity of air [J kg <sup>-1</sup> K <sup>-1</sup> ]
C	Volumetric heat capacity [J m <sup>-3</sup> K <sup>-1</sup> ]
C <sub>eff</sub>	Effective thermal capacitance [J m <sup>-3</sup> K <sup>-1</sup> ]
C <sub>v</sub>	Ventilation conductance [W K <sup>-1</sup> ]
d	Thickness of a material slab [m]
f	Decrement factor [dimensionless]
f <sub>r</sub>	Thermal response factor [dimensionless]
M	Thermal mass of a building [kg]
N	Room air change rate per hour [ach]
q <sub>c</sub>	Conductive heat flow [m <sup>3</sup> s <sup>-1</sup> ]
q <sub>v</sub>	Ventilation rate [m <sup>3</sup> s <sup>-1</sup> ]
R	Thermal resistance [m <sup>2</sup> K W <sup>-1</sup> ]
T	Temperature [K]

t	Time [s]
T <sub>i</sub>	Average indoor air temperature [K]
T <sub>D</sub>	Decrement factor [dimensionless]
T <sub>o</sub>	Outdoor air temperature [K]
U	Thermal transmittance [W m <sup>-2</sup> K <sup>-1</sup> ]
V	Room volume [m <sup>3</sup> ]
x	Space-coordinate [m]

**Greek letters**

$\alpha$	Thermal diffusivity [m <sup>2</sup> s <sup>-1</sup> ]
$\delta$	Periodic penetration depth [m]
$\zeta$	Amplitude reduction factor [dimensionless]
$\lambda$	Thermal conductivity [W m <sup>-1</sup> K <sup>-1</sup> ]
$\rho$	Density [kg m <sup>-3</sup> ]
$\tau$	Time constant [s]
$Y$	Thermal admittance [W m <sup>-2</sup> K <sup>-1</sup> ]

depends on the density  $\rho$  and specific heat capacity  $c$  of the material, whereas the rate of heat exchange is influenced by the thermal conductivity  $\lambda$  of the material. Buildings with a large amount of thermal mass within the thermal envelope, will display a reduced and delayed reaction to an initial excitation such as a sudden rise in external ambient temperature. This transient behaviour is referred to as the thermal inertia of a building.

Building thermal inertia is a complex phenomenon, which is not always fully understood by design practitioners. As part of ‘climate responsive architectural design’ or ‘passive solar design’, architects and researchers have often argued that thermal mass is beneficial for maintaining indoor thermal comfort and reducing energy demand [6–10]. Indeed, constructing methods with a high amount of thermal mass - often obtained by using large quantities of concrete or bricks - have proven to be beneficial for reducing overheating risks in numerous case studies [11–16]. This behaviour can be witnessed in buildings with large amounts of exposed thermal mass such as medieval churches, which display very slow fluctuations in indoor temperature, and thus remain cool during a hot week in summer, without the need for active cooling. This effect is also exploited in many instances of vernacular architecture in hot climates, and in ‘rammed earth buildings’ and ‘earthships’ which use large quantities of soil to create a stable indoor climate [17–19].

Thermal mass isn’t always beneficial with regard to comfort and energy consumption. Slee et al. concluded that “the general view that ‘mass is good, therefore more mass must be better’ is erroneous” [20]. An exponential relationship between the quantity of thermal capacity and the internal diurnal temperature fluctuations implies that adding additional thermal mass to a heavy weight building has a negligible effect. Furthermore, buildings with large amount of thermal mass need more time to reach the cooling or heating set point temperature in case of intermittent building use. This might cause thermal discomfort for occupants and result in an increased energy consumption due to longer preheating or precooling periods [21,22].

It can be concluded that estimating the effect of thermal inertia on building energy consumption and thermal comfort is not always self-evident. The subject has been studied widely by many authors, but the research methods and scope of the various studies differ greatly. An early example of an analytical approach is described in the report ‘Thermal mass assessment’ by Childs et al [23]. Many other authors have instead relied on measurements or advanced computer simulations. Thermal inertia is a complex phenomenon, and its relative impact is proven to be influenced by many factors including the climate where the building is located [24], the thermal insulation of the building envelope [25,26], and the type of building usage [15,27]. Thermal inertia is just one of the

many factors to consider in a building design, and many authors have described it as part of a wider analysis. Heier et al. provides an in depth overview of the topic of Thermal Energy Storage (TES) in buildings [28]. A distinction is made between passive storage and active storage, which makes use of pumps or fans to charge or discharge the energy storage. The effects of sensible energy storage in building thermal mass are discussed alongside latent thermal mass effects, sensible and latent storage in HVAC systems and storage in direct vicinity to buildings such as borehole energy storage. Olsthoorn et al. provide a review on the specific topic of using thermal mass for peak shaving and shifting of electrical power consumption [29].

This paper will review the current body of knowledge on the effects of thermal inertia in buildings, and focus on the sensible heat storage and its effects on thermal comfort and energy consumption for heating and cooling. Firstly a description of the qualitative effect and the underlying physical processes is briefly introduced, followed by an overview of the terminology used in literature to describe the effect. The next section describes the modelling methods which are available to analyse dynamic heat transfer, and discusses the modelling approaches of many mandatory energy performance assessments. The main part of the paper focusses on summarising the reported impacts of thermal inertia analysed on the scale of individual construction components and whole buildings. Specific attention is given to the practical application of thermal inertia in building design to enhance its operation. This review paper concludes with a discussion on the factors that can attribute to the large spread in research findings reported in scientific literature and provides suggestions for future study.

## 2. Describing and quantifying building thermal inertia

### 2.1. Qualitative description of thermal inertia effect

Building thermal behaviour and the related energy consumption are defined by a complex interaction of heat gains, losses and storage in building materials and finishing. Four main sources of heat fluxes can be observed when studying the heat balance of a building. For reasons of simplification, a single room with uniform air temperature will be considered in the following qualitative analysis Fig. 1.

The first major heat flux consists of heat generated or extracted internally due to building operations. These thermal loads stem from heat losses from various sources such as artificial lighting, office equipment and metabolic heat gains from building occupants.

Secondly air movement will introduce outside air by ventilation and infiltration through the building skin. If the air pressure remains constant, and equal amount of air is expelled from the building. In case

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