SINTEF REPORT

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TITLE

COIN P5 Energy efficiency and confort of cocnrete structures
SP 5.1 F Energy efficient buildings

Thermal Mass Concepts

State of the art

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CLIENT(S)
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ABSTRACT

Thermal mass (TM) is defined as the mass of the building that can be used to store thermal energy for heating/cooling purposes. TM can be effectively used to reduce the wide outdoor temperature fluctuations and offers the engineers and architects a powerful opportunity to manage energy flows in the building efficiently.
This state-of-the-art review gives a brief overview of concepts for activation of thermal mass for enhancing the energy efficiency of buildings focusing on Passive Thermal Mass Systems, Thermo Active Building Systems (TABS), Ground Coupled Systems, Phase Change Materials (PCM) Systems, and Dynamic insulating walls (DIW).
The review includes a brief description of the concepts, their reported energy performance, and cost data if available. The most promising concepts were identified and it was concluded that different concepts regarding activating thermal mass for enhancing the energy efficiency of buildings have different levels of development. While passive thermal mass is very well developed today some of the new design strategies were developed by combining passive and active techniques together, such as activation of the thermal mass or utilization of phase change materials in building constructions. Further research should focus on optimizing costs, construction time and buildability. Also, improved control strategies should be developed and tested. Design guidelines could be developed focusing on practical applications of integrated thermal mass systems in buildings.
The needs for research for further development of the different concepts are discussed in more detail.

KEYWORDS	ENGLISH	NORWEGIAN
GROUP 1	Energy	Energi
GROUP 2	Concrete	Betong
SELECTED BY AUTHOR	Thermal Mass	Termisk masse
	Energy efficient building	Energi effektive byggninger

Foreword

COIN - Concrete Innovation Centre - is one of presently 14 Centres for Research based Innovation (CRI), which is an initiative by the Research Council of Norway. The main objective for the CRIs is to enhance the capability of the business sector to innovate by focusing on long-term research based on forging close alliances between research-intensive enterprises and prominent research groups.

The vision of COIN is creation of more attractive concrete buildings and constructions. Attractiveness implies aesthetics, functionality, sustainability, energy efficiency, indoor climate, industrialized construction, improved work environment, and cost efficiency during the whole service life. The primary goal is to fulfill this vision by bringing the development a major leap forward by more fundamental understanding of the mechanisms in order to develop advanced materials, efficient construction techniques and new design concepts combined with more environmentally friendly material production.

The corporate partners are leading multinational companies in the cement and building industry and the aim of COIN is to increase their value creation and strengthen their research activities in Norway. Our over-all ambition is to establish COIN as the display window for concrete innovation in Europe.

About 25 researchers from SINTEF (host), the Norwegian University of Science and Technology - NTNU (research partner) and industry partners, 15 - 20 PhD-students, 5 - 10 MSc-students every year and a number of international guest researchers, work on presently 5 projects:

- Advanced cementing materials and admixtures
- Improved construction techniques
- Innovative construction concepts
- Operational service life design
- Energy efficiency and comfort of concrete structures

COIN has presently a budget of NOK 200 mill over 8 years (from 2007), and is financed by the Research Council of Norway (approx. 40 %), industrial partners (approx 45 %) and by SINTEF Building and Infrastructure and NTNU (in all approx 15 %). The present industrial partners are:

Aker Kværner Engineering and Technology, Borregaard LignoTech, maxitGroup, Norcem A.S, Norwegian Public Roads Administration, Rescon Mapei AS, Spenncon AS, Unicon AS and Veidekke ASA.

For more information, see www.sintef.no/coin

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1 Preface

This report is produced within the framework of the COIN – Concrete Innovation Centre, Sub Project 5.1: Energy-Efficient Buildings and Construction. The focus of this state-of-the-art review is to give an overview of concepts for activation of thermal mass for enhancing the energy efficiency of buildings. The review will include a brief description of the concepts, their reported energy performance, and cost data if available. The most promising concepts will be identified, and the needs for research in order to further develop the concepts will be discussed.

Each chapter pursues the following outline

- Description of the concept - classification
- Examples of applications
    - Reported performances- energy, cost, indoor environment (measurements, calculations)
- Design tools
- Barriers and opportunities

2 Introduction

Thermal mass (TM) is defined as the mass of the building that can be used to store thermal energy for heating/cooling purposes. TM can be effectively used to reduce the wide outdoor temperature fluctuations and offers the engineers and architects a powerful opportunity to manage energy flows in the building efficiently.

Components typically adopted when the TM concept is applied include: the building envelope, the interior partition, the furnishing, or even the building structure.

According to its location, there are two basic types of thermal mass:

- external thermal mass
- internal thermal mass

The external thermal mass, such as walls and roofs, is directly exposed to ambient temperature variation. The internal thermal mass, such as furniture and purpose-built internal concrete partitions, is exposed to indoor air temperature.

Furthermore, another classification may be done based on the type of activation:

- direct interaction system – when the thermal mass is directly exposed to the indoor air
- indirect interaction system – where the ambient air passes through floor voids, cores and air paths (such as for example TABS components: walls, ceilings, floors equipped with ducts for circulation of air or embedded pipes for circulation of water).

The thermal mass concepts are applied on residential, commercial (office) and school buildings.

In general the application has been found to be particularly suitable for climates with big diurnal temperature variations. The most of the component applications can be observed in moderate climatic zones. Installations in cold climatic zones are limited mainly by the heating capacity of the system. Using the systems in hot and humid climate may give rise to condensation problems.

3 Passive Thermal Mass Systems

Description of the concept - classification

Thermal mass is defined as the mass that has the ability to store thermal energy (heat or cooling energy). The thermal capacity of building mass is defined by ASHRAE (1999) as the amount of heat needed to increase the temperature of a given mass by one Kelvin. Thermal mass is very effective in reducing the wide outdoor temperature fluctuations and keeping the indoor temperature within a narrow comfortable range (Asan and Sancakta, 1998). Therefore, thermal mass offers the engineers or architects the powerful opportunity to manage the building energy efficiently.

Historically, there have been many successful Direct Interaction Systems used in buildings. These applications include passive cooling systems, such as night flush cooling and earth cooling etc. (Lechner, 2001), thermal storage heating systems and passive solar heating systems.

For storing heat in buildings, two important thermal properties of the materials should be considered, i.e. the heat capacity by volume and the heat-absorption rate. The first property determines the ability of the materials to store and thermal energy, and the second property determines the ability of the element to adsorb the thermal energy. The combined convective and radiant heat transfer coefficient and the surface area of the thermal mass determine the rate of heat transfer between the thermal mass element and the air. Depending on the interaction of these thermal properties, the thermal mass can shift energy demand to off-peak time periods when electricity is cheaper (i.e. nighttime). The time delay between external maximum and minimum temperature, and the internal maximum or minimum temperature is known as the time lag. Higher thermal mass can significantly reduce the daily fluctuations. Comparison of different representative building materials is shown in Table 1.

Table 1: Time lag for 1-foot-thick walls of common building materials (Lechner, 2001).

Material	Time lag (hours)
Adobe	10
Brick (common)	10
Brick (face)	6
Concrete (heavyweight)	8
Wood	20*

*) Wood has such a long time lag because of its relatively low thermal conductivity

For a typical internal thermal mass “structure” (Figure 1), the basic heat transfer processes can be described as follows:

- Conduction
- Convection
- Radiation

When the outdoor air enters the building by either mechanical or natural forces (i.e. mechanical ventilation, natural ventilation or infiltration), the thermal mass in the building absorbs or releases the heat through its surface and interior body. There is a convective heat transfer process at the surface of the heat mass and a radiant heat transfer between them and other surfaces. The conduction heat transfer takes place in the interior body. For an effective thermal storage and release process, the surface heat transfer rate governing by the convective heat transfer coefficient and the surface area need to be sufficiently large. It is well known that the convective heat transfer coefficient depends on the temperature difference between the thermal mass surface and the surrounding air and the air flow speed around the thermal mass. Generally in the building, it is difficult to enhance the convective heat transfer rate significantly without using a mechanical fan. Thus, the surface area of the thermal mass is a crucial design parameter. The heat penetration through the thermal mass body is by the heat conduction, and the penetration depth is limited by the diffusivity of the material during one cycle (Li and Xu, 2006).

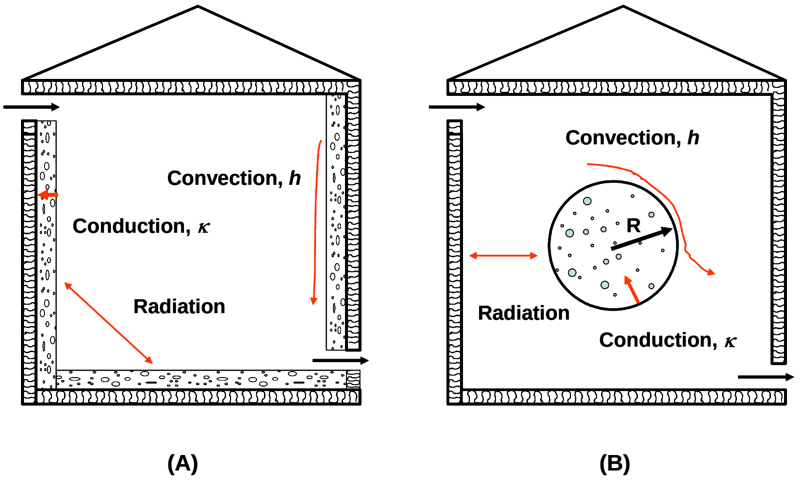


Figure 1: (A) Illustration of use of interior thermal mass in the walls, floor; and (B) Illustrate of the heat transfer process of a thermal mass sphere in a room. (Li and Xu, 2006).

Different locations of thermal mass in buildings can result in distinctively different behaviours. For external thermal mass design, the orientation of the wall elements surface and its desirable time lag are two key factors as different orientation experiences its major heat gain at a different time. However, the general guidelines do not apply to internal thermal mass design. Proper engineering design or simulation is necessary to ensure the proper design of the thermal mass and insulation.

One of the good examples in using thermal mass is the night cooling, which can avoid or minimize the need of mechanical cooling in buildings. During a summer night, the ambient air can circulate in the building and cool the thermal mass. The stored cooling is then released next day to the building.

There are generally two systems (CIBSE, 2001):

- Direct interaction system – the thermal mass directly exposed to the indoor air. Both convection and radiation play roles in heat transfer (see Figure 1a).
- Indirect interaction system – the ambient air passes through floor voids, cores and air paths and there is no direct interaction between the room air and the heat mass surfaces. Convective heat transfer is the main heat transfer mode. Mechanical fans may be used to drive the air flow and increase the heat transfer rate, however, design is needed to ensure the fan energy cost doe not exceed the mechanical cooling energy saved (see Figure 2b).

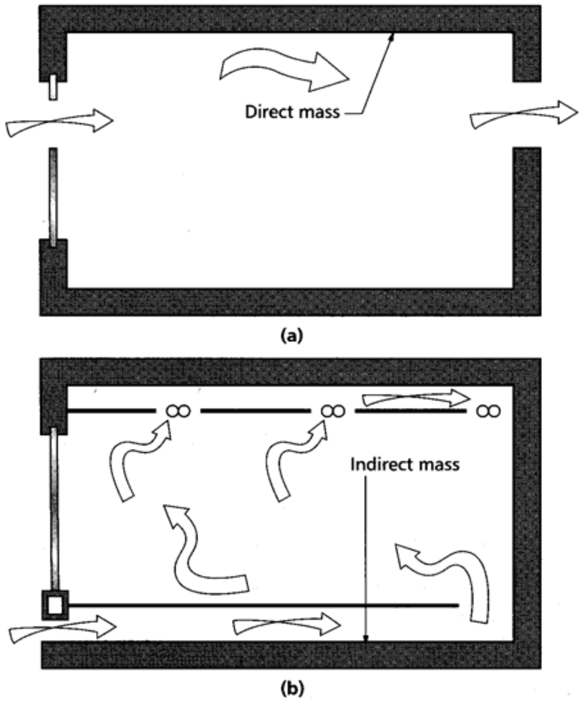


Figure 2: Direct and indirect interaction thermal mass (CIBSE, 2001)

Examples of applications

In general the application has been found to be particularly suitable for climates with big diurnal temperature variation. Cooling by night-time ventilation, one of the most efficient applications of thermal mass can be used if night temperatures are low enough to release heat from the building's thermal mass. For Europe the climatic potential for passive cooling of buildings by night-time ventilation has been analyzed by Artmann et al. (2006) using a degree-hours method. It was shown that in the whole of Northern Europe (including the British Isles) there is very significant potential for cooling by night-time ventilation and this method therefore seems to be applicable in most cases. In Central, Eastern and even in some regions of Southern Europe, the climatic cooling potential is still significant, but due to the inherent stochastic properties of weather patterns, series of warmer nights can occur at some locations, where passive cooling by night-time ventilation might not be sufficient to guarantee thermal comfort. If lower thermal comfort levels are not accepted during short time periods, additional cooling systems are required.

Name of building: BedZED (Beddington Zero Energy Development)
Type of building: Residential / commercial
Location: Hackbridge, Sutton, U.K.
Owner: the Peabody Trust and the Bioregional Development Group
Start of operation: June 2001
Architect: Bill Dunster Architects
Engineering: Ove Arup and Partners
Net conditioned area: 83 dwellings and 3000 m^2 for offices and services
Total energy use: 80% less than standard practice

Figure 3: Example of a building project in the UK (Annex44 2007)

There is no cooling system per say, however, the complex uses thermal mass as well as the heat-exchange system in the wind cowls to keep the temperature steady during hot summer and cool winter periods. The ventilation principle is a natural system with a passive heat- exchange system (wind cowls). The architectural expression and the terrace-houses were inspired by the architectural expression of traditional British housing and the project has a very holistic approach to sustainability, as it considers both urban design and architectural design elements in the solution. The architectural expression has also been under great influence of the technical solutions, e.g. in case of the wind cowls, the double high rooms, the green terraced roofs, the choice of material and the orientation of the different units etc.

The project underlines the need for holistic and integrated planning and design as it considers technical, functional and ecological principles, and these principles are integrated and expressed through the architectural expression of the building complex, while keeping the price of the units down.

The first period of monitoring has already shown that compared with current UK benchmarks:

- Hot water heating is about 45% less.
- Electricity for lighting, cooking, and all appliances is 55% less.
- Water consumption is about 60% less.

Name of building: GSW Headquaters
Type of building: commercial
Location: Berlin, Germany
Owner: GSW company
Year of completion: 1999.
Architect: Sauerbruch Hutton Architects.
HVAC consultant: Arup.
Gross floor area high-rise: 16208m^2.
Number of storeys: 22
Depth of plan: 11.5- 15 meters.
Floor-to-ceiling height: 2.7 meters.
Total energy use: 50% less than standard practice

Figure 4: Example of a building project in Germany (Kleiven 2003)

The GSW high-rise is equipped with a mechanical ventilation system in addition to a natural system. The mechanical system was incorporated for comfort during seasonal weather extremes when, for most normal office uses, the windows need to be closed. The main air-handling plant is located in a two-storey plant-room at the 22nd floor (just below the roof). Mechanical ventilation is initiated by the building management system (BMS), although occupants can select individual zones within a floor in either mechanical or natural ventilation mode by a wall-mounted zone controller. The mechanical ventilation system takes over for the natural system when the external temperature drops below 5ºC. This is to avoid the risk of draughts. Exhaust air is then returned to the central plant-room via risers for heat recovery. The cooling system is designed to provide maximum internal temperatures of about 27ºC at external temperatures of 32ºC (Kleiven 2003).

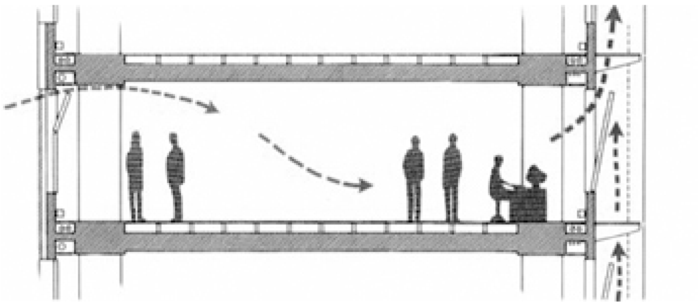


Figure 5: Principle of cross-ventilation

The building is 100% naturally ventilated when the outdoor temperature is between 5ºC and 25ºC. The natural ventilation principle in the high-rise building is stack-ventilation in that the natural driving forces promote an outflow out of the building (through the double facade). This is the case for the building viewed as a whole, but for the individual floor it is more natural to characterise the ventilation principle as cross. Air enters each floor through the east façade and is exhausted through the thermal flue in the west façade. This air-path is valid for a number of possible plan layouts (Figure 5). The upward motion of air in the western double façade (due to thermal buoyancy) creates an under pressure that can suck air out of every storey in the building, and into the double façade (when the windows in the west facades are opened). When windows on the two facades (east and west) are open, fresh air flows accordingly from east to west. Control flaps located at the bottom and at the top of the thermal flue regulate the airflow and make the system less dependent on outside conditions. This system enables air exchange rates comparable to mechanical systems. The natural ventilation concept substitutes the operation of the mechanical ventilation system for 70% of the year (i.e. about five of the week's seven days) according to estimates done by Arup (Kleiven 2003).

Reported performances- energy, cost, indoor environment (measurements, calculations)

Givoni (1998) tested the effectiveness of thermal mass and night ventilation in lowering the indoor air temperature during daytime. It was found that, for building with light construction, night ventilation had only a very small effect on reducing indoor maximum temperatures. However, it was very effective to lower indoor maximum temperatures for the building with high thermal mass (heavy construction). Also a simple predictive formula for indoor air temperature was developed and found to be applicable to a wider range of climatic conditions.

Ogoli (2003) developed four environmental test chambers with different thermal mass levels and monitored the effect of thermal mass in lowering the maximum indoor daytime temperatures in Nairobi, Kenya, during the warm season in 1997. High thermal mass was observed to be very effective in lowering indoor maximum temperatures. Cheng et al. (2005) demonstrated the effect of envelope color and thermal mass on indoor temperatures in hot humid climate. The results revealed that the use of lighter surface color and thermal mass can dramatically reduce maximum indoor air temperature but the practical applications could be different and depend on the circumstances.

Table 2: Studies focusing on Thermal mass

Author(s)	**Building**	**Climate**	**Method**	**Scope**	**Results**
Bellamy and Mackenzie (2003)	Single zone test building	Moderate (NZL)	Measurements and simulations	A timber and a concrete test building monitored for a year. Simulations with BSim2000 and SunCode were compared against measurements.	The concrete building used 7.5 kWh/m^2 (15.7%) less heating energy than the timber building. The simulated savings were 16.2 % and 23.2 % for BSim2000 and Suncode, resp.
Birtles et al (1996)	Office	Moderate (UK)	Simulation	A bioclimatic chart used to estimate the cooling potential of thermal mass and night ventilation. APACHE simulation model used to confirm the estimates.	The bioclimatic analyses indicate that thermal mass and night ventilation should be sufficient to cover cooling demand in typical UK offices. This is confirmend by the simulaiton in most cases.
Blondeau et al. (1997)	Classroom	La Rochelle (FRA)	Measurements and simulations	An experimental field study and TRNSYS simulation carried out to assess the comfort advantages and cooling potential of night ventilation.	Night ventilation decreased indoor air temperatures by 2K. The simulations indicated that cooling energy reductions were 12 %, 25 %, and 54 % for set-points at 22°C, 24°C, and 26°C, respectively.
Bojic (2005)	Residential	Hot Humid (CHN)	Simulation	HTB" simulation model used to predict annual cooling demand for twelve alternative wall constructions.	The simulations indicate that if the walls' thermal capacity was reduced, it would lead to a 60 % increase of the cooling energy demand.
Braun (1990)	Office	not specified	Simulation	Investigation of building thermal mass and dynamic building control to reduce peak electricity demand and to offset peak cooling loads.	Cooling energy cost and peak electricity demand significantly reduced through optimal control of building thermal mass. Cost savings most significant in the presence of time-of-day rates.
Burch et al. (1984b)	Single zone test buildings	Moderate (MD, US)	Measurements and simulations	Six similar one-room buildings with equivalent U-value monitored. The effect of wall mass on the cooling energy requirements studied.	Heavy buildings observed to have significantly lower cooling energy use. Exposed mass facing the inside was most effective. Night ventilation and thermal mass reduced cooling energy use up to 36 %.
Givoni (1998)	not specified	Range of climates	Measurements and simulations	Test the effectiveness of thermal mass and night ventilation in lowering the indoor air temperature during daytime.	It was found that, for building with light construction, night ventilation had only a very small effect on reducing indoor maximum temperatures. However, it was very effective to lower indoor maximum temperatures for the building with high thermal mass (heavy construction). Also a simple predictive formula for indoor air temperature was developed and found to be applicable to a wider range of climatic conditions.

Design tools

A large number of the previous studies and computational methods on thermal mass were reviewed (Balaras, 1996). Sixteen different parameters were found for describing thermal mass effects (Givoni 1976, Ruud et al. 1990, Mathews et al., 1991). CIBSE Guide Volume A (1988) derived some factors for analyzing the transient behavior of a building structure. These factors, including the admittance, decrement factor and surface factor, are the functions of the thickness, thermal conductivity, density and specific heat capacity, as well as locations of the materials. However, the CIBSE method may not be used directly for thermal design.
Yam et al. (2003) studied the effect of internal thermal mass associating with the non-linear coupling between the natural ventilation and the indoor air temperature and also proposed a new concept of virtual sphere method for effective thermal mass design (Li and Yam, 2004). The idea is to lump up the mass elements into a virtual solid sphere with the radius determined from some significant dimensions of the mass (e.g. volume and surface area). Utilization of more complex tools (simulation codes) often requires a great amount of input information, but provide highly accurate results. Some of them are well-known software packages available on the market, for example ESP and TRNSYS.

Challenges and Opportunities

The technology of passive thermal mass is very well developed today. Some of the new design strategies were developed by combining passive and active techniques together, such as activation of the thermal mass or utilization of phase change materials in building constructions.

It was found that,

- The thermal mass of the building can have a positive effect on the indoor environment during the summer and winter period. In summer, heat is stored at daytime in the thermal mass, thus reducing the cooling load peaks. At nighttime, the night ventilation can help the heat release from the thermal mass. In winter, the stored heat is transferred back into the room during the late afternoon and late evening hours, reducing the heating demand.
- Thermal mass has also a positive effect on occupant's comfort through keeping the indoor air temperature within, in comparison to outdoor temperatures, relatively narrow range.
- When combined with passive cooling or heating techniques, the thermal mass elements have high energy conservation potential.

Barriers for further application were found to be based on the following:

- The effect of thermal mass is dependent on the climate context.
- The thermal properties of thermal mass elements and surrounding environment should be considered to exert its storage ability.
- For an effective thermal storage and release process, the surface heat transfer rate governing by the convective heat transfer coefficient and the surface area need to be sufficiently large. It is generally difficult to enhance the convective heat transfer rate significantly without using a mechanical fan. Thus, the surface area of the thermal mass is a crucial design parameter.

4 Thermo Active Building Systems (TABS)

Description of the concept - classification

Active building components are thermally heavy parts of the building construction (walls, ceilings, floors or in floors betweens storeys in multi-storey buildings), which are equipped with ducts for circulation of air or embedded pipes for circulation of water. Components with embedded pipes in floors in multi-storey buildings are mostly used today.

a) b) c)

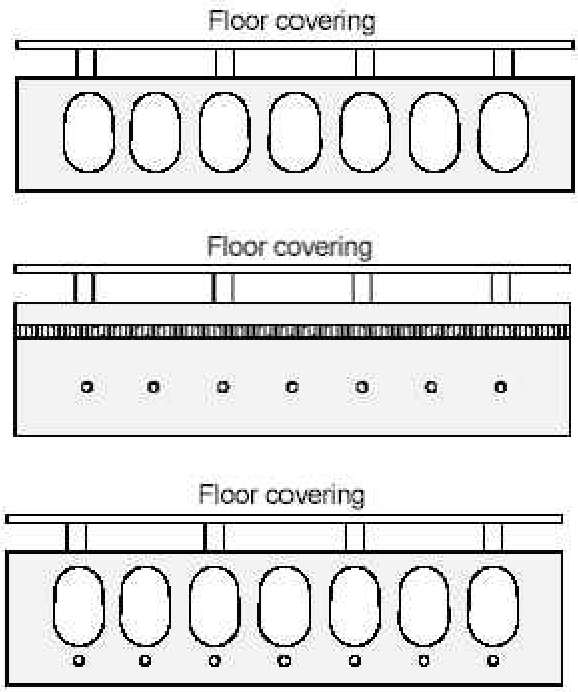


Figure 6.1: Basic types of currently used thermo active building components (Weitzmann 2002): a) hollow deck with cavities for air circulation; b) on-site constructed floor (with insulation); c) hollow deck with integrated pipes (hollow can be also filled up with polystyrene or other light materials)

Water based thermo active components are typically used in buildings in Central Europe (Figure 6.2). Pipes are commonly installed in the centre of concrete slab between the reinforcements. Usual diameter of the pipes varies between 17 and 20 mm. The distance between pipes is within the range 150 - 200 mm. Figure 6.2 shows cross-section of commercially available system.

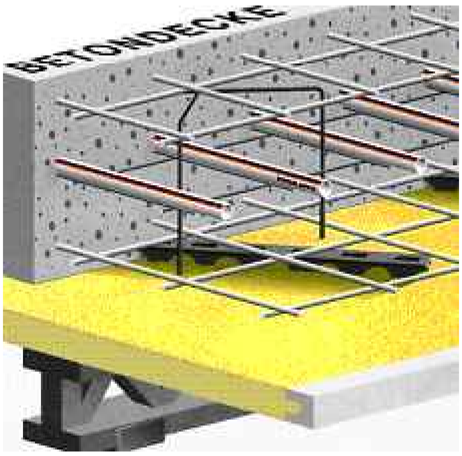


Figure 6.2: cross-section of the on-site constructed system (www.velta.de)

In some cases, also walls of the building are thermally activated (Figure 6.3). Component is particularly suitable for multi storey buildings and is commercially available.

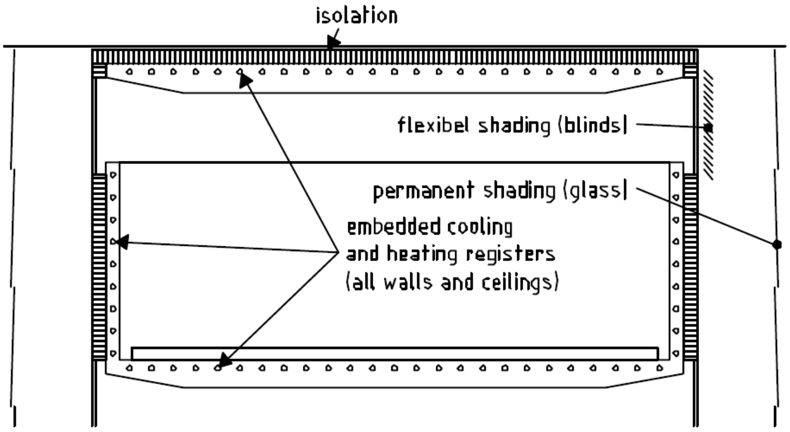


Figure 6.3: Cross section of the building with activated concrete slabs and walls (Annex44 2007)

Technologically, the design of thermo active components is based on the characteristics of other radiant systems: distance, diameter of pipes, thickness of the concrete layer, position of the pipes inside the concrete, supply water temperature and water mass flow rate. Besides the direct cooling and/or heating capacity, the TABS have also the thermal storage effect - the peak load during the day will be stored and removed by cooling during the night. Thermo active components have a large radiant part in the heat transfer between heated/cooled surface and room (Olesen 2000).

Influence of both convection and radiation can be expressed by means of combined heat transfer coefficient. The response time of the system is rather long due to its high thermal mass. Therefore, an individual room control is not reasonable, but a zone control (south – north) is often suitable solution. Small difference between heated/cooled surfaces (supply water) and the ambient temperature results in a significant degree of self-control effect, because a small change in this temperature difference will influence the heat transfer between the cooled/heated surface and the space significantly. In order to avoid condensation, the water temperature or the surface temperature and the absolute humidity should be controlled (surface temperature should be maintained above the dew-point of the ambient air for all operational conditions).

Examples of applications

The most of the component applications can be observed in moderate climatic zones. Installations in cold climatic zones are limited mainly by heating capacity of the system. Using the systems in hot and humid climate is limited by need to avoid condensation. Utilization of the thermally activated components effectively reduces the size of the ventilation system. It is not designed to extract cooling loads or heat the building but only supply fresh air for the occupants. This means that much lower air change rates can be used. If slightly cooled, supply air can also provide some additional cooling, when it is needed (during peak loads during extremely hot days, installation of the system in warmer climatic zones).

Name of building: The Centre for Sustainable Building (ZUB)
Type of building: Office
Location: Kassel, Germany
Owner: Zentrum für Umweltbewusstes Bauen e.V.,
Start of operation: Spring 2001
Architect: Arbeitsgemeinschaft Jourdan & Müller – PAS, Seddig Architekten
Engineering: Ingenieurbüro Prof. Hauser
Net conditioned area: 1347 m^2
Total energy use: 32 $kWh/m^2/yr$ (measured), 20% of standard

Figure 7: The Centre for Sustainable Building (ZUB) in Kassel, Germany (De Carli et al. 2003)

The office building belongs to the Centre of Sustainable Building (ZUB), University of Kassel, Germany. The building is an example of new low temperature heating/cooling systems implementation. The ZUB office building consists mainly of three different parts: one part for exhibitions and events, one part for offices and an experimental part for different kinds of research in innovative building technologies and building services concepts. The load bearing skeleton in reinforced concrete consists of round pillars with a distance of 5.40 m and flat concrete slabs for the floor/ceiling construction.

A water-based conditioning system with embedded pipes is used for heating and cooling of the offices. In the case of heating operation mode, the system works with water inlet temperatures controlled according to the outdoor temperatures (approx. 24°C). In case of cooling need, pipes embedded in the floor slab of the basement are used as a ground heat exchanger. Mechanical cooling is not required.

Reported performances- energy, cost, indoor environment (measurements, calculations)

In the study by Meierhans (1993), system with embedded pipes in the slab constructions of office buildings for heating and cooling was introduced. Results in the form of simulations (compare to the measurements) were presented for an office building in Horgen, Switzerland. The results indicated that the indoor temperature was kept at an acceptable range even during very hot outdoor conditions. Computer simulations of heating/cooling system with pipes embedded in the concrete slabs between the floors in a multi-storey building were conducted by Hauser et al. (2000). The simulated system supplied or removed the heat from the space by heated/cooled water flowing in the pipes. The results showed a significant improvement of thermal comfort by reducing the annual maximum operative temperature by 10 K (39°C - 29°C) compared to no cooling. Also in the dynamic simulation done by Olesen and Dossi (2004) the operative temperature was within the range 22–25°C during most of the working hours. The ranges of operative temperatures were sufficient to meet the requirements of the current standards.

Design tools

Commercially available building simulation programs can be used to determine behaviour of the system when installed in a particular building. Available capacity of the system, distributions of indoor temperatures and thermal comfort indices can be also evaluated. For the dynamic simulation of the entire system with embedded pipes acting together with the building construction, a validated model for a floor heating system and concrete core conditioning provided as a module of simulation program TRNSYS (TRNSYS-16 2004) can be used (Schmidt et al. 2000, Fort 1999). Also building simulation code IDA Indoor Climate and Energy 3.0, a whole-building simulator offers the opportunity to simulate TABS. Besides that, it allows simultaneous performance assessments of all building issues such as fabric and construction, glazing, HVAC systems, controls, indoor air quality, human thermal comfort and energy consumption. Performance of activated thermal mass system can be evaluated by the IDA module introduced by Hauser (2004).

Companies that dominate on the market handle the design of the activated thermal mass components with their own design (selection) software tools, which are intended only for internal use. Basically, two groups of calculating algorithms are used:

- Steady-state calculations (based on the standard EN 1264 for floor heating/cooling, CEN TC228)
- Dynamic calculations (FEM, FDM)

Barriers and opportunities

Opportunities of using TABS are given as follows:

- Due to the utilization of the thermal mass, cooling and heating loads can be reduced and shifted to off-peak hours.
- The temperature of the cooling/heating water can be close to desired room temperature. This means high potential for using renewable energy sources (heat pumps, ground heat exchangers etc.), which can operate with high efficiency.
- The cooling system does not have to be designed to cover the maximum heat load. This leads to reduction of the refrigeration equipment or even to its omission.
- Peak loads from the daytime can be removed during the nighttime when the prices of electricity are lower. This leads to lower operation costs.
- Night-time ventilation can be used to cover or reduce cooling loads.
- As the ventilation systems only have to be sized for the ventilation rate needed for acceptable indoor air quality, ducts can be much smaller and a suspended ceiling is not needed.
- The avoidance of suspended ceilings has the big advantage of reducing the total building height, resulting in significant savings on construction costs and materials used.
- Using surface heating/cooling creates safe and comfortable indoor environment (more space in the rooms, no danger of burns).

Barriers, however, were found to in the following context:

- The effect of passive utilization of the thermal mass is dependent on the climate context.
- The thermal properties of the passively used thermal mass elements and surrounding environment should be considered to exert its storage ability. The surface area of the element needs to be sufficiently large to ensure sufficient heat transfer rate.
- TABS are suitable for buildings with low heat/cooling loads (40 – 50 W/m^2). High thermal insulation of the building envelope and proper solar shading is necessary.
- There should be the balance between heating losses and cooling loads, so that the system can work optimally (the same heat exchange surface is used for both cooling and heating).
- Without the suspended ceiling, the acoustical requirements must be solved in other ways.

- Buildings with thermo active components cannot be expected to keep a fixed temperature. Further research is needed to evaluate occupant responses to the temperature drifts and the influence of these drifts on the performance of office work.
- Individual control of the indoor thermal parameters is possible only when the TABS are used in combination with additional air-conditioning/heating system.
- High standard of building construction management is needed.
- Optimization of the system, based on the experience, measurements and simulations, is needed in the beginning of operation.

Limitations

- Heating/cooling capacity of the system is approximately 40 – 50 W/m^2. In buildings with higher need additional systems are needed.
- Individual control is not possible. Building can be divided into zones.
- Non-steady indoor environment – operative temperature drifts can be expected.
- Suspended ceilings should not be used; acoustic problems and lightning installations need careful design.
- During the heating period, there is the risk of cold downdraft at windows, which may be solved by the design of windows with glazing U-factors less than 1.2 W/(m^2 K), or with an additional heating in the perimeter area.
- Regards the cooling period, the control of humidity may limit the cooling capacity of the radiant system.

5 Ground Coupled Systems

Description of the concept - classification

An Earth-to-Air Heat Exchanger (ETAHE) ventilates air to the indoor environment through one or several horizontally buried ducts. In this way, the ground's large thermal capacity and relatively stable temperatures are used to preheat or pre-cool the air, resulting in energy savings for the building.

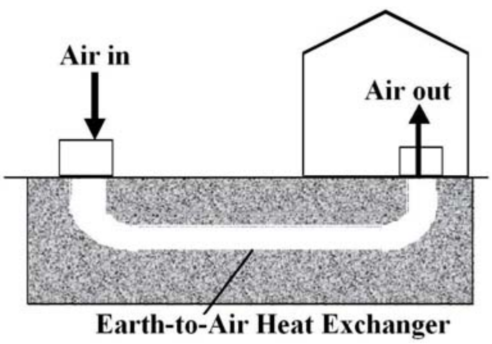


Figure 8: Building with an Earth-to-Air Heat Exchanger (Annex44 2007)

The ETAHE technology has been applied in different types of buildings. Various names have been used, such as Earth Cooling Tube, Ground Coupled Air System, Cool-Tube in-Earth Heat Exchanger, Earth Air Tunnel, Earth Contact Cooling Tube, Earth Tube Heat Exchanger, Buried Pipe Cooling System, Underground Solar Airheater, Earth Air-Pipes System, Air-Soil Heat Exchanger, Embedded Duct, Earth Channel, Hypocaust, and Earth-to-Air Heat Exchanger. The name Earth-to-Air Heat Exchanger is adopted here because it is relatively common and it represents the principle of the technology without limiting its physical configurations.

Most existing ETAHE systems are installed in mechanically ventilated buildings, in which electrical fans provide the airflow driving forces. Recently, to reduce the airflow resistance in an ETAHE as well as the related fan energy consumption, some hybrid ventilated buildings have adopted very large cross-sectional ducts. The integration of ETAHE and hybrid ventilation is regarded as a new approach to improving building energy efficiency.

The earth is a steady and practically infinite heat source, sink, and storage medium due to the high thermal inertia of soil. As far as soil temperatures are concerned, an ETAHE should be installed as deep as possible since the temperature fluctuations are dampened deeper in the ground. However, the excavation cost for laying an ETAHE very deep may not be economical. When outdoor air is drawn into an ETAHE duct, the temperature difference between the air and the duct causes convective heat transfer, which changes the duct temperatures. The resultant temperature gradients from the duct surface to its surrounding soil will further cause new temperature distributions in the soil. Moisture diffusion takes place as a simultaneous process, which affects the heat transfer to some extent. The temperature change of air from the inlet to outlet represents a sensible heat variation. When the duct material is moisture-permeable or the duct surface temperature reaches the dew point temperature, latent heat changes may take place through condensation, evaporation, or moisture infiltration. In most systems, a certain mount of energy has to be spent to circulate the air. To enhance the heat convection one may think of having longer pipes, enlarging their surface area and roughness, or creating turbulence etc. However, these also result in more energy cost for circulating the air. In addition, the dissipation of fan's energy may release heat to the circulating air.

Examples of applications

This project describes the new built office building of the Nord-Trøndelag College (HiNT) in Levanger, located 80 km north of Trondheim, Norway. The building was ready for occupation in August 2002. It has a common wing with meeting rooms and educational areas. Two other wings are office areas.

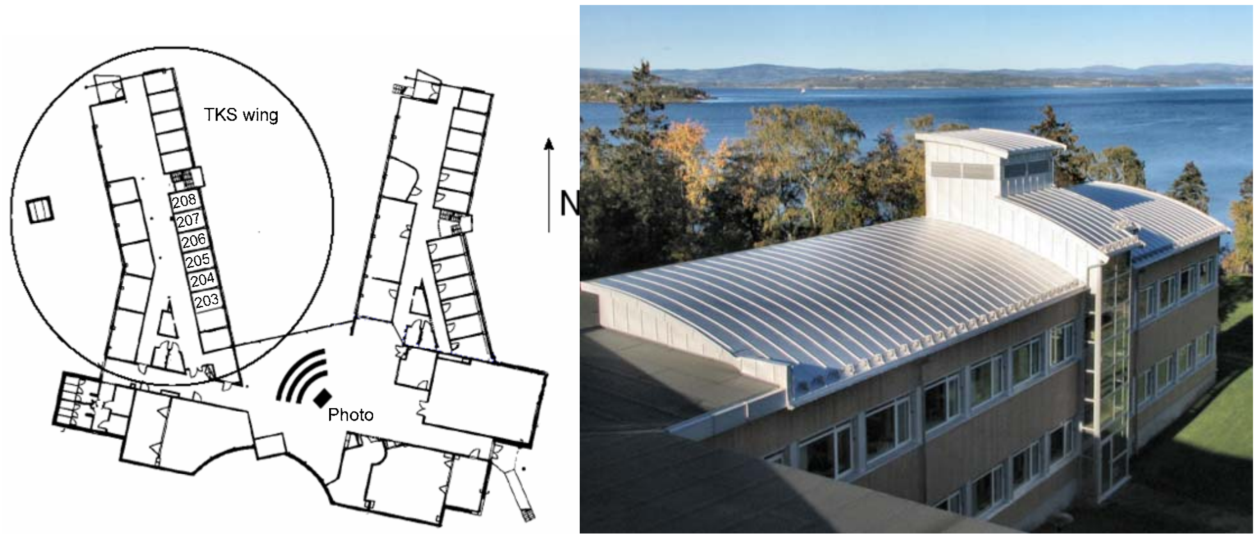


Figure 9: One wing of the HiNT building

The building has two storeys, no basement, but instead a culvert for supply of ventilation is embedded in the ground along the central axis of the wing. The HiNT-wing has a net area of 478 m^2, of which 269.5 m^2 are used as office cells. Each cell is about 9 m^2. The gross area of the wing is 835 m^2, of which 112 m^2 is used for culvert, air intake tower and exhaust tower (Mathisen et al. 2005).

The energy concept of this building explores the following features:

- Hybrid ventilation
- Earth coupling (for pre-heating and –cooling air)
- Passive cooling by exposing concrete ceiling for night-time ventilation and improved thermal comfort
- External shading with control

The hybrid ventilation system is of so called culvert type. In principle it is constructed as shown in Fig 10. The ducts from the culvert to the rooms are buried in the ground beneath the floor. At the façade the ducts turn 90° upwards. The ducts end in damper placed inside the supply air terminal devices which are placed at the floor beneath the windows. Air to the first floor is supplied through enclosed ducts at the inside of the façade.
In this project the potential energy savings and thermal comfort benefits of exposing the concrete ceiling to the indoor air in place of the original lowered false ceiling is explored.

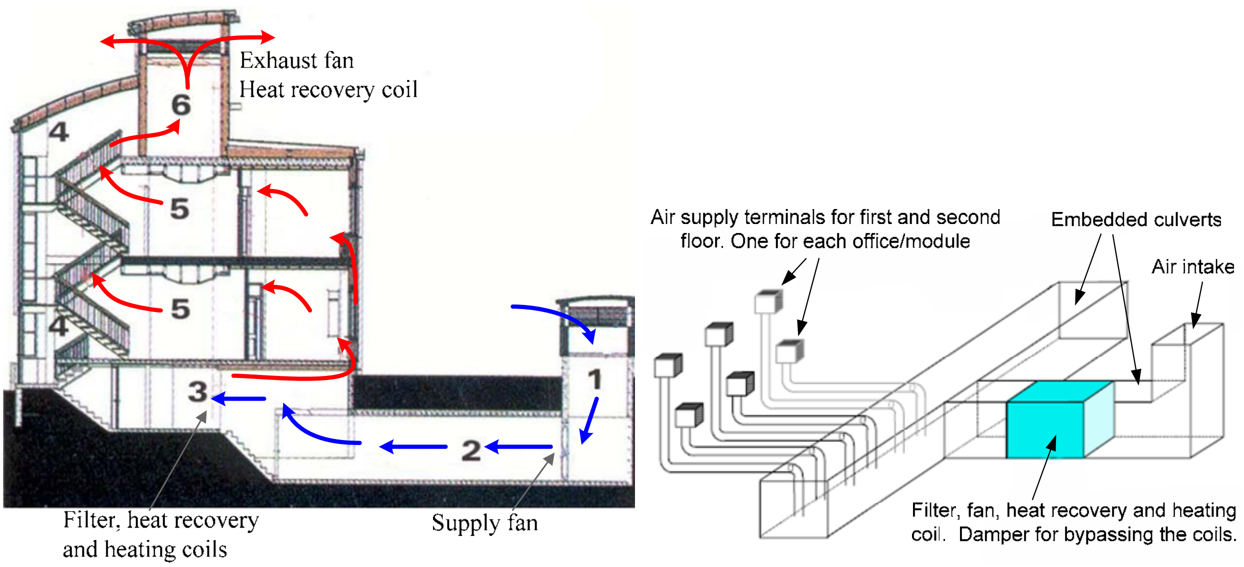


Figure 10: Ventilation system

From the offices the air flows through grilles places close to the ceiling and into the corridor. Exhaust of air takes place through corridors and stairways up to the tower on the roof. The exhaust air tower contains a heat recovery coil and a fan. Radiators are placed beneath each window. None of the offices have mechanical cooling.

Reported performances- energy, cost, indoor environment (measurements, calculations)

Mathiesen et al (2004) monitored the energy use for heating, ventilation and electric equipment in a building with hybrid ventilation and displacement air supply by adjusting control parameters. The building has a culvert embedded in the ground and under the building, and displacement ventilation in the office rooms. A simulation model was set-up in ESP-r and calibrated. The results show that it is possible to save up to 25 % of the total energy use without compromising thermal comfort. Several other ETAHE systems have been monitored and reported for various purposes, such as evaluation, simulation validation, optimal control determination, and commissioning. Some detailed reports are available in Hollmuller (2002), Kumar et al. (2003a), Pfafferott (2003), Wachenfeldt (2003), Burton (2004), and Ghosal et al. (2004).

Design tools

Santamouris and Asimakopoulos (1996) presented a calculation chart, which can predict an outlet air temperature given ETAHE's length, diameter, depth, air velocity and inlet air temperature. The method is based on simplified statistical analysis and regression techniques so its accuracy and features are limited.

WKM (available at http://www.igjzh.com/huber/wkm/wkm.htm) is a computer program developed to size ETAHEs.

The Division of Building Physics and Solar Energy, University of Siegen, Germany, developed commercial software, GAEA (Graphische Auslegung von Erdwärme Austauschern) for design of ETAHE (Benkert et al. 1997, Benkert and Heidt 1998, Benkert 2000). This software is based on calculations of heat exchange among the soil, the buried pipes and the air in the system. The variations of soil temperature, airflow rate, and ambient air temperature are taken into account. An optimization routine presents a choice of possible layout variations and their assessment concerning heat gains and economics. A validation study of GAEA was published by Heidt and Benkert (2000).
Under the framework of the IEA-ECBCS Annex 28, early design guidance for different weather conditions and locations was developed by Zimmermann and Remund (2001) with a few design charts and tables. In an EU project, a design tool was developed under the guidance of AEE Gleisdorf and Fraunhofer ISE by 15 engineering companies (Reise 2001).

De Paepe and Janssens (2003) developed a one-dimensional analytical method, which can be used to analyze the influence of the design parameters of an ETAHE on its thermo-hydraulic performance. A relationship between a specific pressure drop and the thermal effectiveness was derived. This was used to formulate a design method which can be used to determine ETAHE's characteristic dimensions. The desired design is defined as a system with optimal thermal effectiveness as well as an acceptable pressure loss. The choice of the characteristic dimensions thus becomes independent of the soil and climatological conditions. This method is claimed to allow designers to choose a proper configuration for an ETAHE with an optimal performance.
TRNSYS (Klein et al. 2004) is a transient system simulation program with a modular structure that can be designed to solve complex energy system problems by breaking the problem down into a series of smaller components. Hollmuller and Lachal (1998) developed an ETAHE model compatible with the TRNSYS environment. Energy and mass balance within underground ducts account for sensible as well as latent heat exchanges between air and ducts, frictional losses, diffusion into surrounding soil, as well as water infiltration and flow along the ducts. Local heating from integrated fan motor can be taken into account at the duct inlet or outlet. Direction of airflow can be controlled (stratification in case of heat storage) and flexible geometry allows for non-homogenous soils and diverse border conditions.

Barriers and opportunities

ETAHE technology has been used in many buildings with good success. It has been proven applicable for wide range of climates and various types of buildings, such as livestock houses, greenhouses, residential and commercial buildings. For buildings with moderate cooling load, properly sized ETAHE systems may become alternatives to many mechanical heating and cooling systems. Buildings with the following favourable factors may become the potential users of ETAHEs:

- moderate cooling loads
- low ground temperature
- large daily outdoor air temperature swings
- relatively low requirements for indoor environment
- displacement ventilation system

Hybrid ventilation has very good potential for future building applications. When an ETAHE needs to be integrated into a hybrid ventilated building, the pressure loss through the duct is a critical issue. Large cross-sectional area ducts are favourable for the integration.

Although many simulation studies have been done in this area and many applications have achieved successful performances, there are still some issues that need to be studied in the future, such as

- the complex airflow and heat transfer in large cross-sectional ETAHE ducts
- the optimization of system design and control strategy
- the balance between heating and cooling (diurnal and seasonal)
- long-term monitoring for soil temperature development to access if the capacity of the system is sustainable
- interrelated constraints between minimizing initial investment, enhancing heat transfer, and reducing operation cost
- integrated system design under the whole building concept (taking into account the interaction between ETAHE and building energy system) to achieve system optimization
- development of design tools
- cost estimation

6 Phase Change Material (PCM) Systems

Description of the concept - classification

The use of PCM (Phase Change Materials) in the construction field is aimed at being a solution for monitoring of thermal fluxes and exploitation of solar energy by using its enormous capacity for accumulating latent heat around temperatures close to its melting point. In fact, by exploiting their latent heat of fusion, and to a lower extent, their specific heat, these materials act as heat accumulators by absorbing and discharging heat while keeping their temperature unaltered and thus avoiding the overheating of the elements they are contained in.

Latent thermal-storage media products are able to absorb large quantities of thermal energy without rising their own temperature within a limited temperature range around their melting point (i.e. at the phase change from a solid to a liquid state or vice versa). In building construction, this property can be exploited as means of heating or cooling without the use of additional energy. Within the relevant temperature range, the thermal storage capacity is much greater than that of heavy, solid building materials like concrete or brickwork. For that reason, latent thermal-storage media are commonly used in lightweight forms of construction.

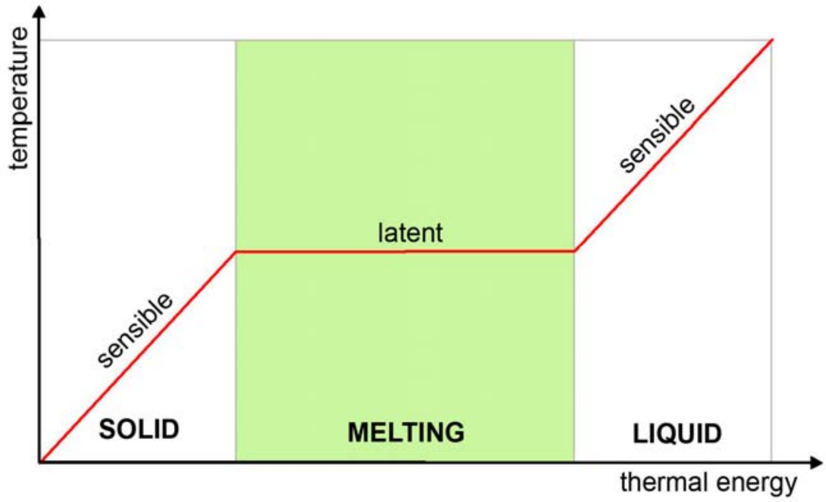


Figure 11: Temperature-energy diagram of one typical PCM material.

There are many kinds of different applications, within the construction field, where it is possible to use the heat storage capacity of PCM. The whole applications use the PCM materials for increasing the thermal inertia or the thermal storage capacity of the components, for improving the use of solar and natural energy, increasing the internal comfort of the building, for reducing the use of heating and cooling system that do not utilize renewable energies.
A large number of organic and inorganic substances are known to melt with a high latent heat of fusion in any required temperature range. Each kind of different phase change material has different thermodynamic, kinetic, chemical proprieties, and the choice of the suitable PCM is made considering these proprieties, together with economical considerations.

PCM are ‘‘latent’’ heat storage materials. They use chemical bonds to store and release heat. The thermal energy absorption and release occur when a material changes from solid to liquid, or liquid to solid. This is called a change in state or phase. PCM, having melting temperature between 20 and 36°C, were used/recommended for thermal storage in conjunction with both passive storage and active solar storage for heating and cooling in buildings.
When a solid PCM is heated up and reaches its melting point, it goes through a phase change, from solid to liquid. During this process the material absorbs a certain amount of heat, known as melting enthalpy. Despite the heat input, the temperature of the material holds at a relatively constant temperature, even though phase change is taking place. Thus we speak of latent (concealed) heat having been taken up by the material. Equally, when the phase change process is reversed, that is from liquid to solid, the stored latent heat is released, again at a nearly constant temperature. Unlike sensible storage materials, such as water, masonry or rocks, PCM stores much more heat per unit volume and another key advantage with the use of a PCM is that heat storage and its recovery occurs isothermally, which makes them ideal for space heating/cooling applications. The advantage of a PCM is the use of the latent heat which is available during the phase change process. A smaller amount of the heat storage capacity (depending on the temperature difference) consists of sensible heat. For example the specific heat capacity of latent heat paraffins is about 2.1 kJ/(kg·K). Their melt enthalpy lies between 120 and 160 kJ/kg, which is very high for organic materials. The combination of these two values results in an excellent energy storage density. Consequently, latent heat paraffins/waxes offer four to five times higher heat capacity by volume or mass, than water at low operating temperature differences.

A large number of PCMs are known to melt with a heat of fusion in the required range. PCMs are categorized as Organic, Inorganic and Eutectic materials.

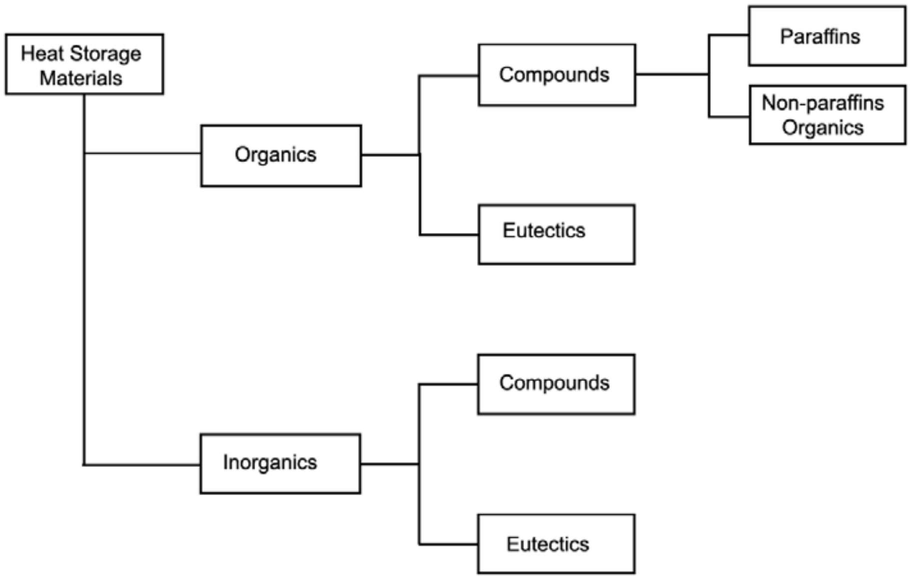


Figure 12: Typologies of phase change heat storage materials.

Organic materials are further described as paraffin and non-paraffin. Organic materials include congruent melting, self-nucleation and usually non-corrosiveness to the container material. Commonly used organic PCMs for heating and cooling in buildings should be with their melting point and latent heat of fusion in the range of 20–32°C.
Inorganic materials are further classified as salt hydrate and metallics. Inorganic compounds have a high latent heat per unit mass and volumes have low cost if compared to organic compounds and are fireproof. However they suffer from decomposition and supercooling which further can affect their phase change properties. An eutectic is a minimum-melting composition of two or more components, each of which melts and freeze congruently forming a mixture of the component crystals during crystallization.

Particularly in warm climates, houses are frequently built using lightweight construction materials, which do not provide sufficient thermal mass for storage of heat. These houses are therefore overheated during daytime, but rapidly cool down at night. In order to compensate these fluctuations in temperature, the air conditioning is used during the day and a heating system in the evening.
A PCM layer can be placed in buildings to increase their thermal mass. This will ensure that the thermal energy created by solar radiation is stored in the walls during daytime and then released to the room, when the ambient temperature has dropped or released outside the building. As a result, the room temperature will, in general, be more comfortable and less switched, and energy consumption for both air conditioning and heating will decrease. Possible building elements for integration are

- within wall constructions
- in floor stratifications or in underfloor heating and cooling systems
- in the ceiling
- in a electric floor-heating system.

Examples of applications

There are some studies that have examined the shifting of heating and cooling loads to off peak times of the electrical utility but did not reach general conclusions regarding optimal PCM properties. Their analysis looked at potential applications of PCM wallboard as a load management device for passive solar applications and found out that it saved energy with reasonable pay back time periods.

Reported performances- energy, cost, indoor environment (measurements, calculations)
Peippo et al. (1991) have shown that a 120 m^2 house in Madison, Wisconsin (43_N), could save up to 4 GJ a year (or 15% of the annual energy cost). Also, they have concluded that the optimal diurnal heat storage occurs with a melt temperature 1–3°C above average room temperature. Claims are made that PCM wallboards could save up to 20% of residential house space conditioning cost.

Design tools

While analytical models of several PCM building elements are available, very few authors have worked on the simulation of the effect of PCM in buildings using whole thermal building simulation programs (Peippo et al. 1991, Feustel and Stetiu, Jokisalo et al, Schossig et al). Peippo et al. were one of the first to discuss the use of PCMs walls for short-term heat storage in a building simulation environment. In their proposal all surfaces of the south-facing direct-gain room excluding the floor were covered by PCM panels. The PCM considered was fatty acid impregnated into conventional 13 mm-thick plasterboard. The energy simulation balances were analysed by the code FHOUSE (Aro-Heinil and Sunanen). Owing to computational limitations, the effect of latent heat of the PCM was accounted for by defining an effective specific heat capacity. The project from Feustel and Stetiu studied the use of PCM imbedded in gypsum wallboards. A functional description of the specific heat was implemented into some of the wall modules available for the program RADCOOL.
The paper by Jokisalo et al. include the model of a concrete wall that contains macroencapsulated PCM, that is, tubes filled with a hydrated salt. The mathematical model of this wall is included to the component of TRNSYS14.2 (Beckman et al.) that simulates the behaviour of a single room. These algorithms cannot be easily included in simulations of more complex buildings with different zones. The project from Schossig et al. is about microencapsulated PCM mixed with gypsum for interior wall application. The authors implemented the possibility to calculate non linear thermal properties of construction materials in the simulation environment ESP-r (Clarke).

Barriers and opportunities

Energy storage in the walls, ceiling and floor of buildings may be enhanced by utilising Phase Change Materials.

- Phase change materials can provide large latent heat storage over the narrow range of temperature typically encountered in buildings, thus they can improve the thermal comfort degree.
- Utilization of the latent heat is one of the most efficient means of heating due to a high capacity of heat storage at a constant temperature of the storage medium.
- The use of PCM (Phase Change Materials) in the construction field aims to be a solution for the control of thermal flows and the exploiting solar energy by using its enormous capacity for accumulating heat around temperatures close to its melting point.
- In effect, by exploiting their latent fusion heat, and in smaller part, their specific heat, these materials act as heat accumulators; absorbing and discharging heat keeping their temperature unaltered and thus avoiding the overheating of the elements they are contained in.

The main problems encountered are listed below:

- Determination of the characteristics of the PCM layer (thickness and melting point) and the evaluation of the external layer's (that absorbs solar radiation) important characteristics, trying to eliminate the effect of daily solar radiation by using the PCM layer.
- The choice of the stratification and functional model, considering the climate contest, type of building and the orientation of the wall surface is very important for having a desiderated performance of the PCM.
- Furthermore the application of the phase change materials is subject to two fundamental restrictions: firstly, the heat transfer between the air and the wall limits the maximum storage power within a day/night cycle; secondly, the application is fully dependent on the outdoor temperature of the night air as a heat sink. In some building types or under certain climatic conditions, these restrictions appreciably limit the applicability of such materials.
- An important limitation of the use of some kind of PCM, for example the inorganic hydrates salt is the durability of these substances.
- The principle problem attributed to these salts, but on the other hand to hydrate salts as well, lies in performance loss with repeated thermal cycles, which entails a substantial lowering of their storage and discharge capacity during phase change. This phenomenon cannot be ignored as already after 20 – 40 cycles' latent heat passes from 238 kJ/kg to 63 kJ/kg diminishing over 70%.
- The possibility to use PCM in the building industry can be realistic if its performance in time can be stabilized in order to control them and keep them unchanged. In order to do so first and foremost all the phenomena which determine their loss of storage capacity and deterioration in time have to be observed and evaluated.

7 Dynamic insulating walls (DIW)

Description of the concept - classification

Primarily, the function of insulation is to keep the heat contained in the building in the winter season, and to keep the heat out of the building in the summer. Building insulation slows the heat flow by conduction, radiation and convection. In conventional building envelope design, convection occurs as air circulates through the insulation material, and is usually a minor component. However, in dynamic insulation, where air is intensively drawn through the building envelope to reduce the conduction heat loss, the influence of convection has a significant effect on the overall thermal performance of the building envelope. Therefore, both conduction and convection needs to be included in the thermal analysis of dynamic insulation.

It has to be underlined that DIW is still a relatively new technology and that the research has still to be further developed. Results and approaches so far proposed by different research groups, in fact, do not show a complete agreement on and are not generally shared.

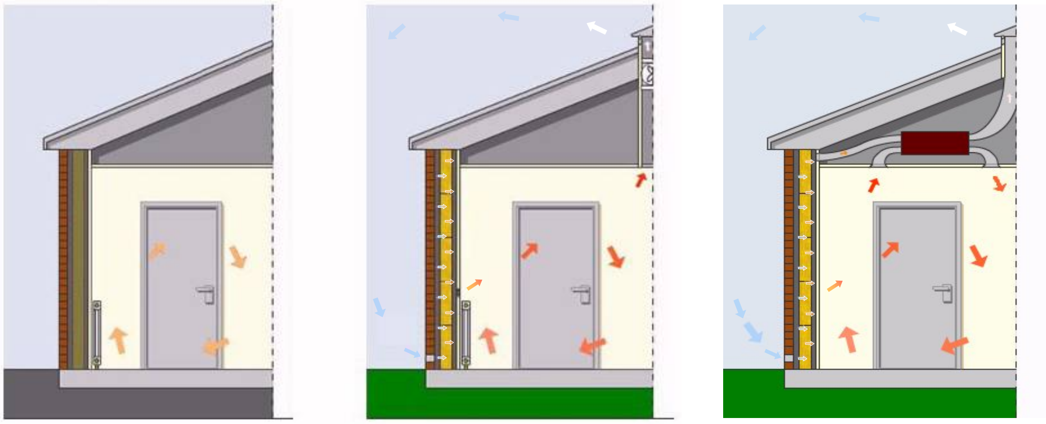
The concept of dynamic insulation (DI) is to effectively use the combination of conventional insulation and heat exchange characteristics of a wall to pre-heat fresh air for ventilation. It is regarded as one possible method for reducing building envelope heat losses while achieving better indoor air quality. The existing technology of dynamic insulation can be divided into two catalogues:

- The design using cavities to circulate the fluid (mostly air) in the wall. The air flow direction in the cavities is generally parallel to the wall – wall acting as a heat exchanger.

- Breathing wall design which let the gas (mostly air) transfer through the permeable insulation. The interaction of gas phase and solid phase can also act as a contra-flux mode heat exchanger (Baker, 2003).

Though ventilated walls which use a combination of air cavities have been presented, such as Baily (1987) and Chebil (2003), currently the research and application of dynamic insulation system focus on the latter, which is also called a breathing wall.

This *Dynamic Insulation (Breathing) Wall* (DIW) concept is illustrated in Figure 13. The dynamically insulated walls and roof function as ventilation source, heat exchanger and filter of airborne pollution, specifically *Particulate Matter* (PM). Ventilation air enters the building pre-heated in winter and pre-cooled in summer, using the heating and cooling energy that would otherwise be lost through conduction and convection to atmosphere. At all times, air comes in filtered. DIW thus address the generic, headline requirement of all buildings and building types for efficient heating, cooling, ventilation and good *Indoor Air Quality* (IAQ).



(Conventional) (DBB Option 1) (DBB Option {n})

Figure 13: DBB concept and implementation using in-wall DI

DIWs potentially use less energy *and at the same time* provide high ventilation rates compared to modern, hermetically sealed buildings that seek isolate the building from its environment. DIW offers high performance thermal insulating properties using thin-wall construction.

A laboratory test of measuring the thermal performance of a porous brick material has been conducted and reported by SINTEF Building Research (Aurlien 1997). Heated air was drawn through the test wall. The results indicated that the cooling effects of a porous brick material could be used to change climatic conditions in a building. Controlling these effects is still not solved and needs further research.

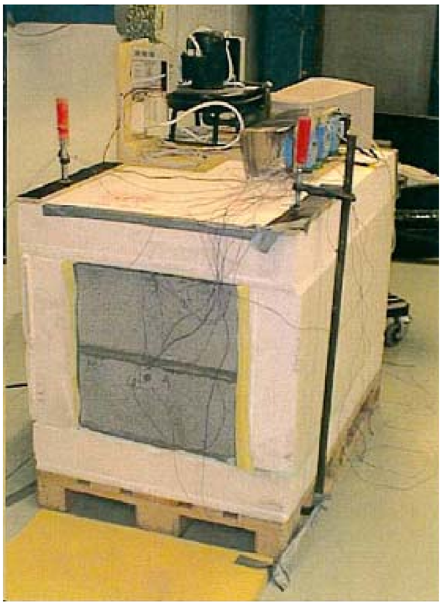


Figure 14: Laboratory test of a cooling wall (Aurlien 1997).

Examples of applications

The market already offers high performance modular dynamic insulation products, such for example the Energy*flo*™ cell (Figure 15). This technology has been developed by The Environmental Building Partnership Limited, UK. Available in thickness of 90mm, 135mm, 170mm, the product can be used in most building types to reduce energy demand for heating and cooling, and to improve indoor air quality through increased fresh air ventilation. Similar to the dynamic insulated wall presented by Baker (2003) and Dimoudi et al (2004), Energy*flo*™ cell also comprises two components: fiber-base filtration media and a rigid encasement package.

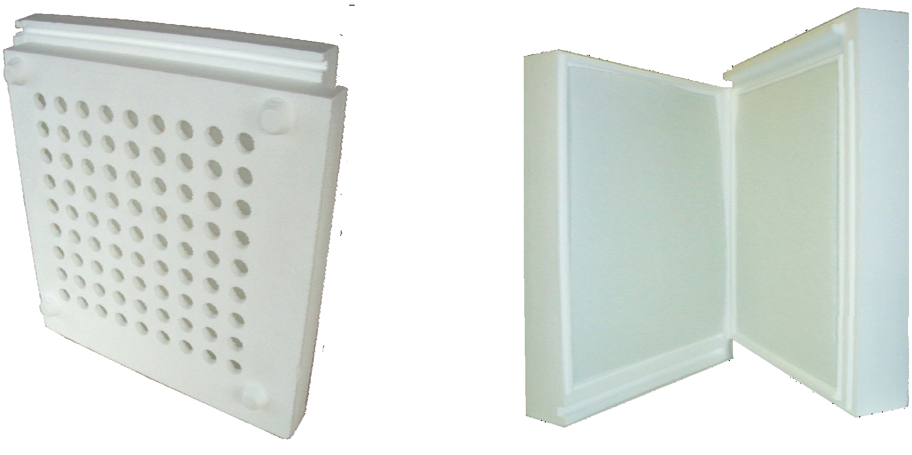


Figure 15: Example of Energyflo™ cells (Courtesy of EBP)

Reported performances- energy, cost, indoor environment (measurements, calculations)

Baker (2003) carried out an extensive experimental work to study the impact of ventilation rate and solar radiation; etc on the performance of a dynamic wall. As part of a wider study of dynamic insulation, an outdoor PASSYS test cell was used to determine the thermal performance of a prototype dynamically insulated wall for a range of air velocities. The thermal transmission losses, solar gains and ventilation heat recovery have been determined over a range of ventilation rates through the wall. The influence of the airflow rate on the air supply and internal wall surface temperatures was also investigated.

Dimoudi et al (2004) reported the hourly variation of internal-external surface temperature difference and conductive heat flux at the internal surface, under real outdoor conditions during a one day period. The results show that depending on the ambient conditions during the day, the operation of the dynamic insulation may change from contra-flux mode to pro-flux mode.

The experimental work of Crowther (1995) focused on the influence of the inner and outer air film on the thermal performance of the dynamic insulation. The results show that heat resistance of the inner surface is determined by natural convection and radiation, while the heat resistance of the outer surface is determined primarily by radiation.

The Environmental Building Partnership Ltd (EBP) has taken the important step of developing a prototype modular DI product, the Energyflo™ cell (EBP, 2005), for mainstream building construction. The product is a versatile replacement for conventional thermal insulation in buildings, and can be used in virtually any type, shape, form, size or age of building. It is currently being trialed in a new residential housing development by CALA Homes (East) Ltd in the City of Edinburgh, Scotland.

Design tools

Though the concept of dynamic insulation was developed decades ago, the implementation of this technology is still in the early stage. Until now, no special design tools for the design of dynamic insulated wall have been reported. However, concerning the thermal performance, some commonly used building energy analysis tools, such as TRNSYS, can be modified to incorporate dynamic insulation elements.

Barriers and opportunities

Concerning energy consumption, the following benefits are claimed for the application of dynamic insulation:

- Less energy is required to maintain an indoor air temperature, thus the operating costs for space heating and cooling are reduced.
    - Simulation (Krarti, 1994) of a room with a dynamic insulated wall showed that the overall energy saving may reach 20%, while the simulation results by Baily (1987) point out the energy saving during a heating period vary from 7% to 14%, without any additional equipment such as a heat pump.
    - The product Energy*flo*™ cell is also claimed to reduce the required heating and cooling load by 10%, compared to the Scotland building regulation standard.
- As low heat loss can be achieved by using a thin dynamic insulated wall, it is possible to avoid the need to use thick wall construction to meet the building regulations to reduce construction cost.
- By using dynamic insulation, the wall becomes the ventilation source, thus saving the cost of supplying and installing ventilation ducts.
- As dynamic insulation is generally working in contra-flux mode, it will also prevent the water vapor getting into the wall from the interior, therefore reducing the risk of condensation in the wall.

Meanwhile, working as an air filter, dynamic insulation can remove airborne particulate pollution from the ventilation air. Therefore better indoor air quality could be provided for the building occupant. Maintenance of such a filter system is still an issue and current research has not yet addressed the problem of filter cleaning.

Though theoretical analysis and experimental tests have been conducted to evaluate the performance of dynamic insulation, and the possibility of its implementation has been discussed, there are still problems in the application of dynamic insulation. Specific barriers are as follows:

- Technical problems exist concerning moisture transport in the insulation. Therefore it lacks the effective way to avoid possible condensation in the insulation under certain conditions.
- The guideline for dynamic insulated wall design is not well developed. Suggestions should be made concerning the aspects such as: what is the suitable thickness for each sub-layer, what kind of material is more appropriate, and how to determine the dimension of an inlet crack.
- There is a conflict between the minimization of heat loss by reducing air flow rate, and the removal of water vapor and other indoor pollutants by increasing air flow rate. Thus the air flow rate should be optimized.
- The dynamic insulation has not been integrated in the commonly used building design tools such as DOE2, EnergyPlus, Esp-r, and TRNSYS.
- The impacts of dynamic insulation on the requirements of building regulations and standards have not been investigated.
- For the application of dynamic insulation, other parts of the building need to be well insulated, this may bring difficulties in construction process and increase the construction cost.
- The property of materials concerning the air permeability and water vapor permeability is not accessible to some designers.
- Building designers are still unfamiliar with the concept of dynamic insulation. It may take a long time for them to recognize the advantage of this technique and implementing it in their designs.

8 Conclusions and recommendations

A brief overview of concepts for activation of thermal mass for enhancing the energy efficiency of buildings was given. The review included a brief description of the concepts, their reported energy performance, and cost data where available. The need for research in order to further develop the concepts is discussed in the following.

Passive thermal mass

The technology of passive thermal mass is very well developed today. Some of the new design strategies were developed by combining passive and active techniques together, such as activation of the thermal mass or utilization of phase change materials in building constructions.

The heat transfer between the room air and the thermal mass is crucial for an effective storage process. Depending on air flow patterns the convective heat transfer can vary significantly, especially in buildings using natural ventilation for night-time cooling. However, commercial building energy simulation codes normally use one homogenous air temperature for each zone and simplified models for the convective heat transfer coefficient. Therefore improved modelling algorithms in building energy simulation codes are required in the field of air exchange and heat transfer to assure a reliable prediction of the heat storage in thermal mass and the performance of passive cooling by night-time ventilation.

- Improved control strategies (development and testing)
- Fundamental research on the relationship between drifting operative temperature and human thermal sensation, prevalence of Sick Building Syndrome (SBS) symptoms and performance (definition of new performance criteria)
- Further studies of optimization algorithms based on measurements and simulations.
- Comparison of different system combinations should not focus only on energy issues. The construction and running costs of building and system, comfort and productivity of the occupants and the environmental impact must also be considered. Also first costs (including installation) and running costs (including maintenance) during the lifetime of the building should be included in any economic considerations.
- In particular the trade-offs with acoustic requirements need further studies

Active thermal mass

The technology of thermal mass utilization, both passive and active is very well developed today. Systems are commercially available. Future development will focus on simplification of the system on-site construction. This requires higher level of prefabrication. There are several studies showing the use of TABS together with Phase Change Materials (PCM) integrated in building constructions (walls). This approach can be mainly applied for lightweight structure buildings and retrofits.

Future research should focus on:

- Improving modelling algorithms in building energy simulation codes to be able to sufficiently predict convective heat transfer between passive thermal mass components and room air
- Study of the combination of the TABS with other responsible building elements (e.g. PCM, double-skin facades)
- Fundamental research on the relationship between drifting operative temperature and human thermal sensation, prevalence of SBS symptoms and performance (definition of new performance criteria)
- Further studies of optimization algorithms based on measurements and simulations.
- Testing TABS using different renewable energy sources (solar and geothermal energy, waste heat from industrial processes etc.)
- Comparison of different system combinations should not focus only on energy issues. The construction and running costs of building and system, comfort and productivity of the occupants and the environmental impact must also be considered. Also first costs (including installation) and running costs (including maintenance) during the lifetime of the building should be included in any economic considerations.

Ground coupled systems (ETAHE)

Although many simulation studies have been done in this area and many applications have achieved successful performances, there are still some issues that need to be studied in the future, such as

- the complex airflow and heat transfer in large cross-sectional ETAHE ducts
- the optimization of system design and control strategy
- the balance between heating and cooling (diurnal and seasonal)
- long-term monitoring for soil temperature development to access if the capacity of the system is sustainable

- interrelated constraints between minimizing initial investment, enhancing heat transfer, and reducing operation cost
- integrated system design under the whole building concept (taking into account the interaction between ETAHE and building energy system) to achieve system optimization
- development of design tools
- cost estimation

Phase Change Materials (PCM)

Future research should focus on the following:

- Determination of the characteristics of the PCM layer (thickness and melting point) and the evaluation of the external layer's (that absorbs solar radiation) important characteristics.
- Choice of stratification and functional model, considering the climate contest, type of building and the orientation of the wall surface is very important for having a desiderated performance of the PCM.
- Identify limits of applicability of such materials in different climatic contexts.
- Durability tests of these substances in different time ranges (after 20 – 40 cycles' latent heat passes from 238 kJ/kg to 63 kJ/kg diminishing over 70%).
- Stabilize performance of PCM in the building industry. More observation and evaluation of the phenomena which determine their loss of storage capacity and deterioration in time is essential.

Dynamic Insulating Walls (DIW)

Research on dynamic insulation until now focuses on heat transfer process and focus has been on its ability to reduce energy consumption. For the purpose of having this technique implemented in real buildings, future work needs to be performed at least on the following aspects:

- Moisture exists in the real environment and will affect the performance of dynamic insulated walls. Taking advantage of appropriate air flowing through the wall, dynamic insulation will have better performance in reducing the risk of condensation, compared with the conventional wall. However, under some conditions, such as the sun shining on wet timber cladding, condensation may occur in the dynamic insulated wall (Taylor and Imbabi, 1998). Therefore, research is needed to evaluate the thermal performance of the dynamic insulation by using a couple heat and moisture transfer model, and to find out the appropriate method to avoid the occurrence of condensation.
- So far, the influence of long wave radiation has not been considered in the simulation. Therefore a comprehensive heat transfer analysis combining conduction, convection, as well as radiation is needed, especially considering the radiation between different layers.
- To assure that the dynamic insulation operating in contra-flux mode, de-pressurization of the building is needed. The pressure drop must be no greater than 5-10Pa, otherwise the occupants will find it difficult to open doors and windows. Therefore the control strategy for air supply needs to be studied and optimized to minimize the electricity consumption. Dimoudi et al (2004) concluded that to keep the indoor environment under adequate de-pressurization, the fan should be operated with variable speed. Thus a control strategy is needed for the application of dynamic insulation in real environmental situations.

Overall recommendations

The different concepts regarding activating thermal mass for enhancing the energy efficiency of buildings have different levels of development. While passive thermal mass is very well developed today some of the new design strategies were developed by combining passive and active techniques together, such as activation of the thermal mass or utilization of phase change materials in building constructions. Further research should focus on optimizing costs, construction time and buildability. Also, improved control strategies should be developed and tested. Design guidelines could be developed focusing on practical applications of integrated thermal mass systems in buildings.

When looking at the activation of thermal mass it became obvious that systems are commercially available today. Future development should focus on simplification of the system for on-site construction. This requires higher level of prefabrication. Further application studies could help to identify the potential for local and international market opportunities. The development of design guidelines can help to enhance the applicability of such systems.

ETAHE simulation studies have been done and many applications have achieved successful performances. Achieving system optimization implies an integrated system design under the whole building concept (taking into account the interaction between ETAHE and building energy system). The control strategy plays an important role as well as an integrated design approach in order to ensure minimal initial investment, enhancedperformance, and reduced overall operation cost. Passive energy design guidelines can help to promote this technology.

There are several studies showing the use of TABS together with Phase Change Materials (PCM) integrated in building constructions (walls). This approach can be mainly applied for lightweight structure buildings and retrofits. Here, further studies could be useful to identify the role of concrete in future construction developments. The variety of PCM makes further studies necessary to design these new materials for local products. Especially the interactivity of material science with energy performance optimization makes this a rather challenging task. This should also be seen in context of sustainable material selection and the applicability of these new materials to integrate into the construction recycling process.

DIW systems are just emerging technology. Further development is needed to identify the most promising building type, to develop performance prediction procedures and simulation tools in order to reduce risk when applying this concept. There is also a need to test the applicability of these concepts in harsh heating dominated climates.

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