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Application of PCM thermal energy storage system to reduce building energy consumption

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Abstract The building sector is known to make a large contribution to total energy consumption and CO_2 emissions. Phase change materials (PCMs) have been considered for thermal energy storage (TES) in buildings. They can balance out the discrepancies between energy demand and energy supply, which are temporally out of phase. However, traditional PCMs need special latent storage devices or containers to encapsulate the PCM, in order to store and release the latent heat of the PCM. The proper design of TES systems using a PCM requires quantitative information and knowledge about the heat transfer and phase change processes in the PCM. In Korea, radiant floor heating systems, which have traditionally been used in residential buildings, consume approximately 55% of the total residential building energy consumption in heating. This article reviews the development of available latent heat thermal energy storage technologies and discusses PCM application methods for residential building using radiant floor heating systems with the goal of reducing energy consumption.

Keywords Thermal energy storage · Phase change materials (PCM) · Radiant floor heating system · Building energy consumption

Introduction

The rapid growth in world energy use has already raised concerns over supply difficulties, exhaustion of energy resources and heavy environmental impacts such as ozone layer depletion, global warming, and climate change. The International Energy Agency has gathered frightening data on energy consumption trends. During the two decades of 1984–2004, primary energy grew by 49% and CO_2 emissions by 43%, with an average annual increase of 2 and 1.8%, respectively. Current predictions show that this growing trend will continue. Energy use by nations with emerging economies (Southeast Asia, Middle East, South America and Africa) will grow at an average annual growth rate of 3.2% and by 2020 will exceed that for the developed countries (North America, Western Europe, Japan, Australia and New Zealand) at an average growth rate of 1.1%. The case of China is striking, taking only 20 years to double its energy consumption at an average growth rate of 3.7% [1].

The building sector is known to contribute largely in total energy consumption and CO_2 [2, 3]. Recent reports by the Intergovernmental Panel on Climate Change (IPCC) have raised public awareness of energy use and the environmental implications, and generated a lot of interest in gaining a better understanding of the energy use characteristics in buildings, especially their correlations with the prevailing weather conditions. In 2002, buildings worldwide were estimated to account for about 33% of the global greenhouse gas emissions [4]. In their study on climate change and comfort standards, Kwok and Rajkovich [5] reported that the building sector accounted for 38.9% of the total primary energy requirements in the United States, of which 34.8% was used for heating, ventilation and air-conditioning.

Thermal energy storage (TES) is an useful tool for improving energy efficiency and increasing energy savings. There are three ways to store thermal energy: chemical energy (reversible reactions), sensible heat, and latent heat

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(LH) [6]. Among them, LH storage is the most attractive one due to its high storage density and small temperature variation from storage to retrieval [7]. In latent heat TES (LHTES) systems, energy is stored during melting and recovered during freezing of a phase change material (PCM). A great variety of inorganic and organic PCMs (salt hydrates, metals and alloys, fatty acids/esters, paraffins, etc.) and their mixtures have been investigated as LH storage materials [8, 9]. Among the investigated PCMs, paraffins have been widely used for LHTES applications due to their large LH and proper thermal characteristics such as little or no supercooling, low vapor pressure, good thermal and chemical stability, and self-nucleating behavior [10].

Korea belongs to the second group of nations requiring mandatory reduction of greenhouse gas emissions starting in 2013, for all industries, but especially for building production activities, which, due to their consumption of a great deal of energy and production of an inordinate amount of waste, have become a major focus for greenhouse gas reduction efforts [11]. In Korea, radiant floor heating (ONDOL) systems have traditionally been used in residential buildings. This type of residential building consumes approximately 55% of the total residential building energy consumption in heating. Therefore, decrease in heating energy consumption will significantly reduced total residential building energy consumption.

This article reviews the development of available LHTES technologies and discusses PCM application methods for residential building using radiant floor heating systems in order to reduce building energy consumption.

PCMs

Definition

PCMs are energy storage materials that have considerably higher TES densities than sensible heat storage materials and are able to absorb or release large quantities of energy at a constant temperature by undergoing a phase change [12]. As noted above, among the three ways to store energy, LH storage is the most attractive because it can store and release very large quantities of energy per unit weight of a PCM at a nearly constant temperature [13]. The thermal energy transfer occurs when a material changes from solid to liquid, or liquid to solid. Initially, these solid–liquid PCMs perform like conventional storage materials: their temperature rises as they absorb heat. Unlike conventional (sensible) storage materials, PCMs absorb and release heat at a nearly constant temperature. They store 5–14 times more heat per unit volume than sensible storage materials such as water, masonry, or rock. Many PCMs are known to melt with a heat of fusion in any required range. However, to be used as LH storage materials, these materials must exhibit certain desirable thermodynamic, kinetic and chemical properties. Moreover, economic considerations and material availability must be considered [11].

Classification

The numerous PCMs are categorized as organic, inorganic and eutectic materials, which can be identified as PCM from the point of view of melting temperature and LH of fusion. Of these, PCMs with a melting point between 20–60 °C are applicable to residential building using radiant floor heating systems.

Organic PCMs

Organic materials are further described as paraffins and non-paraffins. Organic materials offer congruent melting, self-nucleation and usually non-corrosiveness to the container material. Organic PCMs have desirable cohesion, chemical stability, non-reactivity and recyclability as their advantages. However, they have comparatively low heat conductivity in the solid state and low LH capacity. The melting point and LH of fusion of the organic PCMs commonly used for residential building using radiant floor heating systems are listed in Table 1.

Inorganic PCMs

Inorganic compounds have a high LH per unit mass, a low volume cost compared to organic compounds, and are nonflammable. However, they suffer from decomposition and supercooling which can further affect their phase change properties. Inorganic PCMs have high LH and high heat conductivity and are cheaper than organic PCMs and eutectic PCMs. Furthermore, they are fire-resistant due to

Table 1 Organic PCMs for residential building using radiant floor heating systems

Compound	Melting point/°C	Heat of fusion/kJ kg^{-1}
Paraffin C_{16}–C_{18}	20–22	152
Polyglycol E600	22	127.2
Paraffin C_{13}–C_{24}	22–24	189
1-Dodecanol	26	200
Paraffin C_{18}	27.5	243.5
Vinyl stearate	27–29	122
1-Tetradecanol	38	205
Paraffin C_{16}–C_{28}	42–44	189
Paraffin C_{20}–C_{33}	48–50	189
Paraffin wax	64	173.6

their nonflammable property. However, they need coagulants due to their large volume change when organic PCMs are changing to the opposite state. The melting point and LH of fusion of the inorganic PCMs commonly used for residential building using radiant floor heating systems are listed in Table 2.

Eutectics

A eutectic is a minimum-melting composition of two or more components, each of which melts and freezes congruently forming a mixture of the component crystals during crystallization [14]. Eutectic PCMs have a sharply formed melting point in phase changing and a measurement density that is similar to that of the organic substances. However, little research has been conducted on their properties. The melting point and LH of fusion of the eutectics commonly used for residential building using radiant floor heating systems are listed in Table 3.

Table 2 Inorganic PCMs for residential building using radiant floor heating systems

Compound	Melting point/°C	Heat of fusion/kJ kg^{-1}
$KF{\cdot}4H_2O$	18.5	231
$Mn(NO_3)_2\ {\cdot}H_2O$	25.8	125.9
$CaCl_2{\cdot}6H_2O$	29	190.8
$LiNO_3{\cdot}3H_2O$	30	296
$Na_2SO_4{\cdot}10H_2O$	32.4	254
$Zn(NO_3)_2{\cdot}6H_2O$	36	146.9
$Na_2S_2O_3{\cdot}5H_2O$	48	201
$Na(CH_3COO){\cdot}3H_2O$	58	226

Table 3 Eutectics for residential building using radiant floor heating systems

Compound	Melting point/°C	Heat of fusion/kJ kg^{-1}
66.6% $CaCl_2{\cdot}6H_2O$ + 33.3% $MgCl_2\ {\cdot}6H_2O$	25	127
48% $CaCl_2$ + 4.3% NaCl +0.4% KCl + 47.3% H_2O	26.8	188.0
47% $Ca(NO_3)_2{\cdot}4H_2O$ + 33% $Mg(NO_3)_2{\cdot}6H_2O$	30	136
60% $Na(CH_3COO){\cdot}3H_2O$ + 40% $CO(NH_2)_2$	31.5	226
61.5% $Mg(NO_3)_2{\cdot}6H_2O$ + 38.5% NH_4NO_3	52	125.5
37.5% Urea + 63.5% acetamide	53	n.a.
58.7% $Mg(NO_3){\cdot}6H_2O$ + 41.3% $MgCl_2{\cdot}6H_2O$	59	132.2
67.1% Naphthalene + 32.9% benzoic acid	67	123.4

Transition of PCMs for building materials

Traditional PCM

PCMs have been developed for various applications due to their different phase change intervals: materials that melt below 15 °C are used to maintain a cool temperature in air-conditioning applications, while materials that melt above 90 °C are used to reduce the temperature if there is a sudden increase in heat to avoid ignition. The materials with intermediate melting points can be applied in solar heating and for heat load leveling applications [15]. Materials studied over the last 40 years include hydrated salts, paraffin waxes, fatty acids and eutectics of organic and inorganic compounds. However, PCMs cannot easily be used directly in practical applications because of their weak thermal stability, high supercooling effect and low thermal conductivity. Therefore, enhanced PCMs have been developed to overcome these difficulties. In one instance, Kim et al. [9] studied the effect of exfoliated graphite nanoplatelets (xGnP) addition on the thermal properties of the paraffin wax/xGnP composite prepared as form-stable PCM, and reported that the thermal conductivity of PCM increased with increasing graphite mass fraction.

Encapsulated PCM

For application to building materials, PCMs require special LHTES devices in different shapes or elements such as shell and tube PCM heat exchangers or many cans to encapsulate them since they change from solid to liquid during the energy storage period. Although the use of such materials solves the problem of PCM leakage during solid–liquid phase change, it increases not only the heat resistance but also the cost of the LHTES system. However, these problems can be overcome using micro/nano PCM capsules that can be prepared by encapsulation of PCM into a polymeric structure. Microcapsules are defined according to their parameters such as particle diameter, shell thickness, thermal capacity, conductivity, and durability. The thickness of the particle walls may be less than 1 μm, and particle diameters vary within the range of less than 1 μm to more than 300 μm, depending on the method of encapsulation, but are typically 20–40 μm. The PCM content of a capsule may be up to 80–85% [16–18].

Microencapsulation is an important technique in the industrial, agricultural, and medical fields by which a core material can be protected by a shell. Many substances have been encapsulated such as paints, liquid inks, toner, perfumes, pesticides, drugs, and PCMs. Recently, this technique has been used to expand the potential application fields of PCMs. Microencapsulated PCM (MPCM) is a form of PCM encapsulated in natural and synthetic polymeric capsules [19, 20].

MPCMs have been manufactured in various ways. Wang et al. [21] made an original MPCM slurry which was prepared via a micro-encapsulation process and consisted of microencapsulated hexadecane ($C_{16}H_{34}$) particles and the pure water. Diaconu [22] introduced microencapsulated paraffin as the most frequently used PCM with melamin–formaldehyde resinous shell. Alkan et al. [23] developed MPCM, consisting of docosane with poly(methyl methacrylate) (PMMA), by focusing on the preparation, characterization, and determination of thermal properties. Lai et al. [24] made PCM gypsum board, which consisted of paraffin as a core material and polymer as shell. Veerappan et al. [25] investigated the phase change behavior of 65 mol% capric acid and 35 mol% lauric acid, calcium chloride hexahydrate, n-octadecane, n-hexadecane, and n-eicosane inside spherical enclosures to identify a suitable heat storage material. Bayés-Garcıa et al. developed PCMs microcapsules by two different methods. The main difference between these methods is the shell composition, as they are composed of different coacervates (Sterilized Gelatine/Arabic Gum for the SG/AG method and Agar–Agar/Arabic Gum for the AA/AG method) [26].

Microcapsules offer the following advantages: (1) protecting the PCM against the influences of the outside environment, (2) increasing the heat-transfer area, (3) permitting the core material, due to coating, to withstand changes in PCM volume, as the phase change occurs, and (4) allowing small and portable TES systems [27, 28]. Many methods have been developed for the microencapsulation of paraffins, such as interfacial polymerization, in situ polymerization, and sol–gel [29]. Melamine–formaldehyde, urea–formaldehyde and polyurethane are usually selected as microcapsule shell materials for the PCMs encapsulation [30–33].

Shape-stabilized PCM

In recent years, a new type PCM called shape-stabilized PCM (SSPCM), composed of PCM and supporting materials has been developed. Different PCMs should have congruent supporting materials. If the PCM is based on paraffin, the supporting material should have a similar skeleton, such as high-density polyethylene (HDPE), polypropylene (PP), and styrene–butadiene–styrene (SBS). Paraffin can be easily dispersed into the network formed by the supporting material. As long as the operating temperature is below the melting point of the supporting material, the SSPCM can maintain its shape even when the paraffin changes from solid to liquid [34].

Many studies on SSPCMs had been carried out. Xu et al. developed a new kind of SSPCM plate, which consists of 70 wt% paraffin as the dispersed PCM and 15 wt% polyethylene and 15 wt% SBS block copolymer as the supporting materials. The thermal and physical properties of the developed SSPCM were evaluated for application as a walling product [35]. Lin et al. developed SSPCM plates, which consist of 75 wt% paraffin as a dispersed PCMs and 25 wt% polyethylene as a supporting material. This SSPCM system can be used for heat storage by using cheap nighttime electricity and discharging the heat stored at daytime [36]. Zhang et al. developed SSPCM consisting of paraffin with a melting point of 20 or 60 °C chosen as PCM and HDPE or a composite as supporting material [37]. Cheng et al. reported that the thermal conductivity of shape-stabilized paraffin/HDPE composite PCM was improved by the addition of graphite powder and expanded graphite [38]. Alkan et al. [39] described the preparation of MPCMs by coating n-eicosane with PMMA shell to improve the thermal properties and thermal reliability.

Building applications of PCMs

Review of PCM applications

PCMs have been considered for TES in buildings since 1980. By implementing PCMs in gypsum boards, plaster, sandwich panel, concrete or other wall covering materials, TES becomes a part of the building structure, and is useful even for light-weight buildings. An important disadvantage of light weight building is their low thermal mass. They tend to have high temperature fluctuation, which result in a high heating and cooling demand. The application of PCM in such building is very promising, because of their capability to smooth temperature variations.

PCM applications to wall

Ahmad et al. describe the manufacture of wallboards from commercial panels in order to lower the investment costs, after gypsum walls were used in a first attempt. The prerequisite specifications were to obtain a wallboard thickness of less than 5 cm and to choose commercial light panels to minimize the investment. To exploit their high heat storage capacity, these panels were filled with PCM, first with paraffin granulates, and then with PEG 600 [40].

Shilei et al. describe the formation of compound phase change wallboards by combining gypsum boards with PCM. By contrasting the impact on indoor thermal environment between the phase change wall room and ordinary wall room in a wintertime experiment, phase change wallboards have been shown to weaken indoor air fluctuation, reduce the heat transfer to outdoor air and improve indoor thermal comfortableness by maintaining the warmth [41].

De Grassi et al. describe that adequate estimation of the energetic improvements that are achieved via the insertion of PCM inside light dry assembled walls is an important step in order to quantify the comfort advantages that can be derived from the use of such materials. The results obtained therefore provide additional information support when we try to interpret the time dynamics due to heat exchange. From the empirical point of view, the use of a model represents a valid instrument to verify if the presence of PCM inside walls contributes to improving the comfort condition of buildings [42].

Carbonari et al. describe that a finite element numerical algorithm for the simulation of two-dimensional problems of heat transfer with phase change is validated, by comparing the numerical results with the experimental ones deriving from tests carried out on two different kinds of PCM-containing sandwich panels. The very good approximation affecting the numerical results, as compared with the experimental ones, suggests that it can be a powerful design tool for every kind of PCM-containing building element [43].

Darkwa et al. describe the effectiveness of integrating PCMs into building fabrics in order to minimize energy consumption and CO_2 emissions in the building sector. In order to assess the thermal effectiveness of this concept, composite PCM drywall samples have been evaluated in a model passive solar building. They conclude that the laminated wallboard with a narrow phase change zone would be more effective in moderating nighttime temperature in a passively designed room [44].

Huang et al. summarize the results of a detailed theoretical investigation and analysis of TES and temperature control achieved using passive building construction elements incorporating PCMs. The predictions detail the effects of using various quantities of different PCM materials with phase change temperatures of 28 and 43 °C incorporated into a selection of wall constructions for selected ambient conditions of temperature and insolation. As a result, comparative analyses of cavity wall systems show the advantages of using LH, low temperature, storage systems, for passive solar energy and building design [45].

Zhou et al. describe the application of PCM-gypsum composite and SSPCM plates in a building for passive solar heating. The results show that PCM composites with a narrow phase transition zone provide better thermal performance, both mixed type PCM-gypsum and SSPCM plates effectively shave the indoor temperature swing by 46 and 56%, respectively and the SSPCM plates respond more rapidly than the mixed type PCM-gypsum and prove to be thermally more effective in terms of utilizing the LH [46].

Castellón et al. [47] demonstrate the feasibility of using an MPCM in sandwich panels to increase its thermal inertia, and to reduce the final energy demand of the buildings.

Also, other researchers reported that the application of PCMs showed a good enhancement of economize building energy [48–50].

PCM applications to floor

Xu et al. describe that SSPCM has the following salient features: large apparent specific heat for phase change temperature region, suitable thermal conductivity, and absence of any container. A model of analyzing the thermal performance of this SSPCM floor is developed in order to examine the influence of various factors on the room thermal performance. The analysis results are as follows: (a) for the purpose of narrowing indoor air temperature swing, the suitable melting temperature of PCM is roughly equal to the average indoor air temperature of sunny winter days; (b) the heat of fusion and the thermal conductivity of PCM should be larger than 120 kJ/kg and 0.5 W/(m K), respectively; (c) the thickness of the SSPCM plate used under the floor should not be larger than 20 mm; (d) tile or metal is better than wood as covering material; and (e) the air-gap between the PCM plates and the floor should be as small as possible [35].

Zhang et al. studied the application of SSPCM in energy efficient buildings and present the following conclusions: (a) by using different paraffin, the melting temperature of SSPCM can be adjusted; (b) for PCM floor or wallboard to absorb solar energy to narrow the temperature swing in a day in winter, the suitable melting temperature of the PCM should be a little higher than the average indoor air temperature of the room without PCM for the period of sunshine; and (c) the PCM layer used in the aforementioned application should not be thicker than 2 cm [37].

Halawa et al. describe the numerical analysis of the melting and freezing of a PCM thermal storage unit with varying wall temperature. The thermal storage unit under analysis consists of several layers of thin slabs of a PCM subjected to convective boundary conditions where air flows between the slabs. Freezing or melting of PCM can be divided into three stages: (a) predominantly sensible heat exchange where the greatest heat transfer takes place, (b) predominantly LH exchange with nearly constant heat transfer rate and (c) predominantly sensible heat exchange with very low heat transfer rate [51].

Other applications

Weinlader et al. describe that double glazings combined with PCMs result in daylighting elements with promising properties. Light transmittances in the range of 0.4 can be achieved with such facade panels. Compared to a double glazing without PCM, a facade panel with PCM shows about 30% less heat losses in south-oriented facades. In addition, solar heat gains are reduced by about 50%. As a result, facade panels with PCM are a good supplement to conventional windows. Best installed in places where no visual contact to the environment is needed, they provide homogeneous illumination and thermal performance with very low heat losses [52].

Koschenz et al. describe the development of a thermally activated ceiling panel for incorporation in lightweight and retrofitted buildings. The design for the new ceiling panel exploits the properties of the PCM paraffin. Simulation calculations and laboratory tests were used to demonstrate that a 5 cm layer of MPCM (25% by weight) and gypsum suffices to maintain a comfortable room temperature in standard office buildings [40].

Cabeza et al. study the thermal aspects of a new innovative concrete with PCMs. In the construction and experimental installation of two full size concrete cubicles. The study results show the energy storage in the walls by encapsulating PCMs and the comparison with conventional concrete without PCMs leading to an improved thermal inertia as well as lower inner temperature [53].

Xiao et al. describe the establishment of a simplified theoretical model in order to optimize an interior PCM for energy storage in a lightweight passive solar room. The analytical results show that the interior PCM has little effect on average indoor air temperature and the amplitude of the indoor air temperature fluctuation depends on the product of surface heat transfer coefficient hin and area A of the PCM panels in a lightweight passive solar room [54].

Zhou et al. investigate the effect of SSPCM plates combined with night ventilation in summer. Their results show that the SSPCM plates could decrease the daily maximum temperature by up to 2 °C due to the cool storage at night [55].

PCM application method for radiant floor heating system

Radiant floor heating (ONDOL) systems

Radiant floor heating systems have been used conventionally in Korea since 400 B.C [56]. As seen in Fig. 1, before the 1950s, firewood was used as fuel, and the opening for the fuel input was a gate where forest fuel passed. The heat generated by burning firewood in the fire pocket was simultaneously used for cooking and heating. The fire hill was designed to protect against adverse strong winds from the chimney, and the flue was a flame pathway. The stone slab was a thermal storage mass, which kept the floor surface warm, and eventually, the human body. This system ran twice a day in the early morning while preparing breakfast, and in the evening in time for dinner [57].

After the 1950s, the ONDOL system has been modified many times for various reasons, such as to protect the forest resources and to prevent death from CO gas poisoning from anthracite [58]. For a short while, briquettes were used, but with Korea's rapidly increasing economic power since the 1970s, residential building has become dominated by the development of high-rise apartments featuring a modernized ONDOL system using a gas boiler instead of wood or briquettes. Hot water from a boiler is piped to the floor coil, which is an X-L pipe underneath the floor surface. The thermal storage mass consists of the cement mortar in place of the stone slab. Nevertheless, the principle of the ONDOL floor heating system has remained essentially the same, even as its form has changed. The finishing materials of the flooring material should therefore be thermo-physiologically comfortable. Various researchers have endeavored to study the physiological response of the human body to the surface of various flooring finishing materials. The recommended floor surface temperature is in the range of 19–26 °C. Nonetheless, to sufficiently heat the entire room volume, floor-heating systems can be set with a floor surface temperature as high as 29 °C. Although such previous research yielded significant benefits, it suffered from the limitation of not considering the Korean peoples' habit of sitting on the floor. Consequently, a number of Korean researchers explored various flooring finishing materials and determined the ideal floor surface temperature for a person in a sitting position to be 22.0–38.8 °C [59].

Koreans enjoy using this ONDOL floor heating system. Recently, the radiant floor heating system has become widely used in the world due to its energy savings and health benefits. Like other countries, the energy

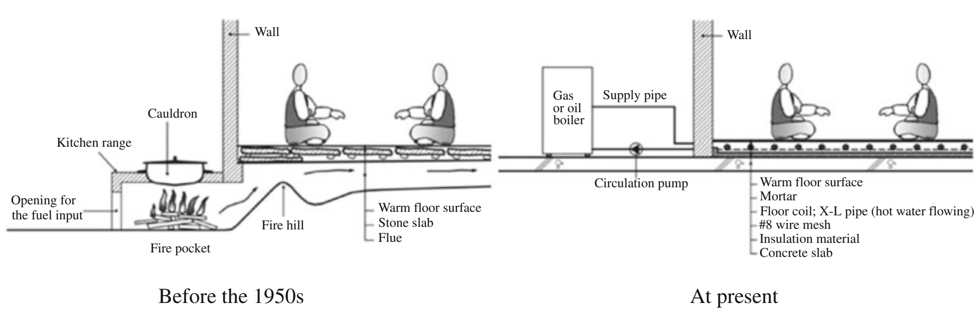

Fig. 1 The radiant floor heating system [57]

consumption for buildings is a large proportion of the total energy consumption in Korea. Especially, Korean residential buildings that use radiant floor heating systems consume more than half of building energy in heating. Therefore, efforts have been made to reduce heating energy in many ways, including the use of vacuum insulation panels, high performance window systems, and high performance ventilation systems. However, in the absence of much research on the application of PCM as a building material, further study is required on the application of PCMs in proper heating systems.

PCM application methods for radiant floor heating systems

As aforementioned, PCM as a building material has been applied in numerous studies but insufficient study has been conducted in residential building using ONDOL (radiant floor heating) systems. The most important characteristic to consider is the heat capacity and melting point of the PCM in its application to building materials. However, the residential building using radiant floor heating systems presents a different thermal distribution compared with that using convection heating systems. Therefore, to apply the PCM in residential building using radiant floor heating systems, the interaction between the heat in the room temperature and the building material must be known. Figure 2 shows the indoor air temperature distribution in the heating system. The indoor air temperature deviation from the flooring finishing materials to the ceiling is larger for radiant floor heating systems than for other heating systems shown in the graph.

Therefore, the PCM having appropriate melting point temperature should be considered because of the thermal difference between the inside and outside of the building.

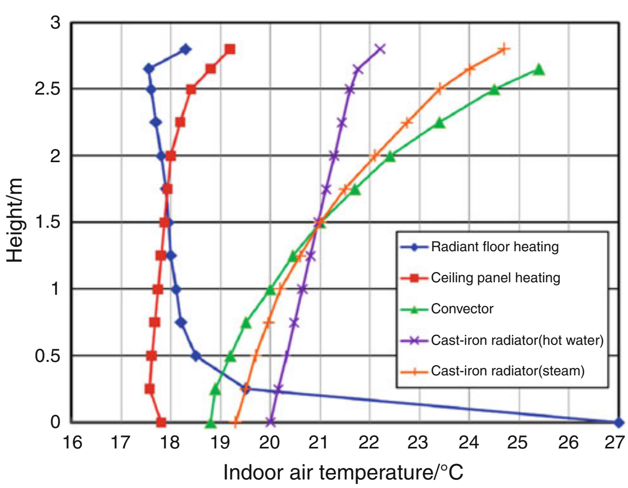

Fig. 2 Comparison of indoor temperature distribution on heating systems

For example, the PCM duct required to apply convection heating to the building can't achieve a high performance in the case of the building using radiant floor heating systems because the temperature of the ceiling is lower than that of the ceiling in a building using convection heating systems. Therefore, PCM can't change the phase because the temperature doesn't reach the PCM's melting point. On the other hand, the flooring finishing materials present a higher temperature than that of other heating systems: the floor temperature of 27 to 36 °C is higher than the 15 °C that is typical in other heating systems. Figure 3 shows that the Ministry of Land has specified the standard floor formation. It reveals that hot water pipes are built in the floor as the heating medium of radiant floor heating systems. In addition, the temperature of hot water in the pipe can rise as high as 80 °C. Therefore, the flooring materials that are applied when radiant floor heating systems are used need to have a much higher melting point than in other building heating systems.

Lin et al. [36] studied electric radiant floor heating systems in buildings by using SSPCM plate. Their study presents that 75 wt% paraffin is used as the PCM and 25 wt% polyethylene as the assistant material. The temperature of the phase change and the melting point of paraffin are both 52 °C, indicating that the PCM with a sufficiently high melting point is applied as an example, unlike the PCM having a melting point between 20–30 °C in typical buildings. The following conclusions can be made based on the study results: (a) The room temperature of the system rises without increasing the thermal difference. (b) The temperature of the PCM plate is preserved for a long time after the heating is stopped. This offers the effective economic profit based on the difference of electricity charges because more than half of the entire electric thermal energy is moved from the peak load to the non-peak load. (c) The difference of the indoor temperature according to the vertical direction is small because the

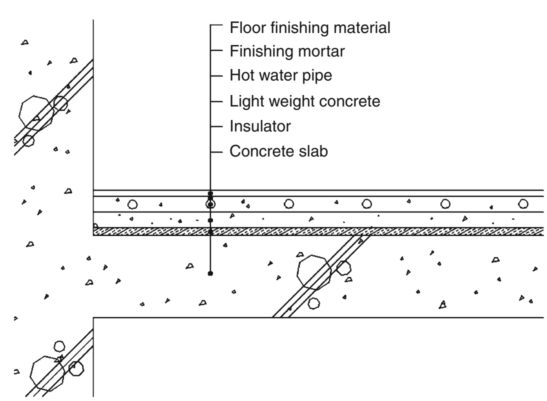

Fig. 3 Standard floor formation for the Korean Ministry of Land

radiant floor heating system heats the indoor air comfortably and efficiently.

Summary

The need for energy conservation has become critical due to global warming. To solve this problem, resident buildings must be designed to reduce energy consumption and control indoor temperature automatically. The application of PCM as a building material will contribute to solving this problem. PCMs can be used to improve the thermal performances of building fabrics and help moderate the indoor temperature variations.

Many PCMs have been developed for various applications due to their different phase change intervals. The materials with intermediate melting points can be applied in solar heating and for heat load leveling applications.

However, PCMs cannot easily be used directly in practical applications because of their weak thermal stability, high supercooling effect and low thermal conductivity. In addition, for application to building materials, PCMs require special LHTES devices in different shapes or elements such as shell and tube PCM heat exchangers or many cans to encapsulate them since they change from solid to liquid during the energy storage period. However, these problems can be overcome using micro PCM capsules that can be prepared by encapsulation of PCM into a polymeric structure. In recent years, SSPCM, a novel compound PCM consisting of paraffin as the dispersed PCM with HDPE or other materials as the supporting material, has attracted research attention.

PCMs have been considered for thermal energy storage in buildings. By implementing PCMs in gypsum boards, plaster, sandwich panel, concrete or other wall covering materials, TES becomes a part of the building structure, and is useful even for light-weight buildings.

In Korea, radiant floor heating systems, which have traditionally been used in residential buildings, consume approximately 55% of the total residential building energy consumption in heating. Therefore, PCMs need to be applied to reduce the heating load. However, residential buildings using radiant floor heating systems have a substantially different temperature distribution from buildings using other heating systems because the hot water pipe heating medium is installed under the finishing materials, leading to a significant difference of vertical indoor air temperature. Therefore, the melting point of PCMs suitable for temperature distribution of residential building using radiant floor heating systems should be considered to optimize the PCM performance. Such application will decrease the building heating and cooling load, thus reducing the building energy consumption and ensuring a comfortable indoor environment.

To achieve these goals, the choice of PCMs suitable for each material and construction part is influenced by the larger indoor air temperature deviation from the flooring finishing materials to the ceiling compared to that in other heating systems. Therefore, studies on the application method of building materials using technologies of encapsulated PCM and SSPCM are needed. Furthermore, the energy efficiency of radiant floor heating systems needs to be experimentally investigated after the actual application of building materials using PCMs to residential building, for scale model and simulation analysis.

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