

Integrated Design and Development of Energy-Efficient Buildings

J. T. Kim¹, H. J. Han², and K. Chen³

¹Department of Architectural Engineering, Kyung Hee University, Yongin-si, Korea, jtkim@khu.ac.kr

²Graduate School, Department of Architectural Engineering, Kyung Hee University, Yongin-si, Korea, hjhan@khu.ac.kr

³Department of Mechanical Engineering, University of Utah, Salt Lake City, Utah, U.S.A., chen@me.utah.edu

ABSTRACT: This paper gives a concise review of recent design and development of energy-efficient buildings and sustainable architecture. The most important breakthrough in these areas was probably the high-efficiency solar cell that has achieved a conversion efficiency higher than 40 %. To take advantage of the high conversion efficiency, hybrid or cascade solar systems composed of different types of energy systems have been proposed and/or investigated. A survey of green and innovative building envelope and illumination designs such as bi-directional thermodiodes for both winter heating and summer cooling applications, soap bubble-filled greenhouse envelopes, fiber-optic solar lighting systems, and high-power LED lamps was also included in the review. These technologies can be easily integrated for improved energy efficiencies in different categories. In addition, new designs and ideas that can be implemented to improve the energy efficiency and/or reduce greenhouse gas emissions and environment impacts of new or existing buildings are proposed and discussed.

Keywords: integrated design, energy efficient building, daylighting, sustainability

1. INTRODUCTION

Owing to the energy crisis and urgency of global warming and other environmental concerns, green/sustainable building – the synonym of today's high-performance building [1, 2] – has become a fast-moving movement across most of the world in recent years. (Strictly speaking, the word “green” does not include the full meaning of sustainability as was pointed out in [3]. Sustainability is maintaining ecological balance. On the other hand, some characteristics of green design such as

indoor environmental quality have no impact on maintaining ecological balance.) The LEED (Leadership in Energy and Environmental Design) rating systems and design guides for green buildings developed by the U.S. Green Building Council (USGBC) were cited and discussed in most new architecture or green building books (e.g., [4]). For a building to be rated or certified as green or high-performance, it must score higher than standard (or code) buildings in several categories such as water and energy efficiencies, indoor environmental quality, and conservation of

materials and resources [1]. Of the many different categories of concern, energy efficiency is one of the most significant indicators when evaluating the sustainability performance of an architectural design. In Lerum's book [2] the performance of a building was defined mainly as its annual specific energy use. The theme of this paper is building energy efficiency.

Large and ever-increasing numbers of books, reports, and papers on energy efficient buildings have been published by EEBA (Energy Efficient Building Association), USGBC, US DOE, and ASHRAE in the United States and their equivalent institutes or counterpart organizations in other countries. Some educational institutes also published their faculty's notes and work for students interested in improving building energy efficiency (e.g., [5]).

2. BUILDING ENERGY USE AND EFFICIENCY

Although annual specific energy use (annual energy use per unit floor area) is commonly used to measure the performance of an energy-efficient building, it often includes only the energy consumed for the maintenance and operation of a building. The calculation and analysis of building energy efficiency and usage are incomplete without taking into account the energy embodied in building materials and products. This embodied energy encompasses the energy consumed in the manufacturing, transportation, and installation processes of converting raw materials to final products [3]. Many tools, databases, and standards are available in references such as [3] for the calculation of embodied energy of common building materials and products. Life cycle analyses and estimations of energy consumption and recovery from disposing and recycling building materials and products should also be carried out for a more accurate assessment of building energy efficiency.

In the United States, Energy Star (a US government-backed program to identify and promote energy-efficient products [4])-qualified homes must be at least 15% more energy efficient than homes built to the 2004 International Residential Code. Each Energy Star rated residential house is estimated to save about 2000 kWh (kilowatt-hours) of electricity annually [6]. As of the year 2007, there were no international standards established for building energy performance [2]. At present, building annual energy consumptions still vary significantly among developed countries. For instance, the annual specific energy use of educational buildings in the United States was about 250 kWh/m² in 1999. In comparison, school buildings in Norway were required to meet a predicted annual specific energy use of about 110 kWh/m² by the year of 2009 [2, 7].

The units used in the calculation of building energy use imply that electricity is the primary energy form consumed by buildings. The prices of different energy forms and their impacts on the environment are quite different. As a result the authors feel that it is necessary to distinguish the consumptions of high- (e.g., electricity and mechanical energy) and low- (e.g., heat and chemical energy) grade energy forms if more accurate and fairer energy-efficiency standards and rating systems are to be established for buildings and houses.

Most utility companies charged natural gas and heating oil (both are low-grade energy) at about 1/3 of the rate of electricity. Considering that the coefficients of performance of most heat pumps are in the neighborhood of 3, one unit of electricity consumed by a heat pump therefore can transfer about 3 units of heat from a low-temperature region to a high-temperature region. For this reason the costs of chemical or electrical energy used for space or water heating are about the same, but the amounts of energy consumed differ considerably. The buildings that employ heat pumps for

space heating can provide approximately 2 times more heat than the buildings using natural gas or heating oil as the heat source if both must not exceed the same quota of annual energy use. In addition, converting electricity to other energy forms has little impact on the environment in comparison with the combustion of natural gas or heating oil. Furthermore, fossil fuel-burning power plants in some areas have already paid fines and extra taxes for air pollution, and the end users should not be penalized twice for the environment impact of burning fossil fuels. It is therefore suggested that specific exergy or availability [8] – a measure of the content of high-grade energy of an energy source – instead of internal energy should be used in the calculation of building energy use.

The features that contribute to improved building energy efficiency were listed in many books, magazines, and journals on architecture design and energy-efficient building. These features include higher level of insulation, high-performance windows, tighter exterior construction, ducts that don't leak, more efficient heating and cooling equipment and lighting and appliances [6], use of sustainable energy, and energy-efficient architectural designs. Recent developments and research results of these features are reviewed in the next section. Attention in the review is focused primarily on the technologies that can be easily integrated for improved energy efficiencies in different categories (e.g., heating and illumination), or multifunction-capable designs such as the micro-CHP that produces both heat and electricity, or the smart wall that can be used for both winter heating and summer cooling.

The review is by no means complete, and the authors' knowledge and research interests limit this concise review to the areas they are more familiar with. Also presented in Section 3 are some of the authors' recent research results and ideas about energy – efficient buildings.

3. DEVELOPMENTS IN AND RESEARCHES ON ENERGY-EFFICIENT BUILDINGS

3.1 Energy-efficient architectural designs

A detailed site analysis is essential to the design and estimation of annual energy use of a building. South-facing windows are favorable in the northern region of the north hemisphere, as this design can harness more solar energy in the winter. Concrete floors, Trombe (using masonry) or water (using water) walls, roof ponds [9], and other designs of thermal energy storage are often used in conjunction with south-facing windows to store solar energy during the daytime. Shading devices must be used to control unwanted sunrays in the summer. The outlets of a stack ventilation system – a passive cooling system that takes advantages of temperature stratification in air – should not face the windward direction [9].

Architectural designs for reduced heating and cooling loads and illumination costs, such as sun-facing glazing and sunshades and deflectors, have been commonly installed on today's high-performance buildings. Shown in Fig. 1 are the sun deflectors and sun lighting system developed and tested by the authors and co-workers. Their researches on this and related topics can be found in [10–12]



Figure 1: Sun deflectors and sun lighting system developed by the authors (at Kyung Hee University).

Sun deflectors and shades of different designs made from different materials can also be found in many architecture and green-building textbooks and magazines

(e.g., [4, 9]). These include fixed or movable overhangs and blinds, shingled glass facades, motorized louvers and awnings, light shelves that reflect sunlight onto the ceiling and then bounce it deep into the room, and so on. Planting trees around a building or growing vines over the walls and roof can not only reduce the cooling load in the summer but also lower the noise level. Building a wall may change the wind direction, thus positively transform the thermal qualities of a site [9] and may work as a sound barrier.

3.2 Smart windows

Electro-chromic and thermal-chromic windows have been investigated for years. The former became commercially available in 2006 [13]. The opacities of these so-called smart windows can be adjusted by varying the glazing temperature or the electric voltage applied to the glazing. New materials are under testing to improve the performance and reduce the costs of smart windows. Compared to motorized shades, louvers, or screens, smart windows have the advantages of quiet operation and more compact and aesthetic appearance. However the response times are long (typically 3 to 5 minutes [13]). When equipped with light or temperature sensors, a smart window can automatically adjust its opacity to allow the right amount of light to go through. Some researchers are now trying to integrate the self-cleaning feature (using special coatings to repel water and ultrasounds to shake off dust, for example) with variable opacity to make smart windows maintenance-free. Window coatings and retrofittable window films are low-cost alternates of solar-control windows.

3.3 Illumination

Energy used in lighting accounts for a large portion of energy use in buildings, especially for commercial buildings. According to the pie charts in [3], for average office building use in the United States, energy used in lighting is the largest

slice on these charts for climate zones 3 and 5 (north eastern and southern USA), and is second to space heating energy for climate zone 2 (midwest USA). A reduction in energy used in lighting therefore may offer great savings in building energy usage. One method is to install sensors and programmed light control systems to automatically dim or turn off the light when a building is not occupied, and to adjust the window shade position in accordance with the angle of the sun rays. Another way of reducing energy use for lighting is to switch to lamps or luminaries of better energy efficiency.

As incandescent light bulbs are to be phased out in the near future, more energy-efficient lighting devices and methods have been explored and became a hot research topic in recent years. Introduction to and comparison of different lamps and luminaries can be found in Bonda and Sosnowchik's book [4]. Fluorescent light tubes and CFLs (Compact Fluorescent Lamps) are widely installed in today's commercial buildings and residential houses. More recently LEDs (Light Emitting Diodes) have attracted a lot of attention and interest. Compared to CFL, LED is more energy efficient (a 3W LED will replace a 40 W halogen lamp as predicted in [4]), have an extremely long life span, and can emit colored light without the use of colored filters.

Because the light generated by LED is highly directional, LED is more suitable as a recessed or projection light source. Lexus was the first automobile company that replaced HID (high-intensity discharge) headlights of automobiles with LED. The color temperatures of HID and LED are very close, but LED has almost twice the lifespan. If not used as a projection or recessed light source, an optical diffuser must be added to direct the light into different directions. This may dim the light a bit and affect the cooling of LED.

In the early stages multiple-lamp LEDs were commonly used for illumination that required low-to-moderate lumens. More

recently single-lamp LEDs became more popular, but cooling of single-lamp high-power LEDs is a big challenge. Unlike the incandescent light bulbs, the core temperature of an LED typically should not exceed about 105 °C [14]. Forced-convection cooling is not preferred since cooling fans consume electricity, offsetting the electricity saved by switching from blackbody radiation to light-emitting diode design. Companies such as GELcore have studied LED cooling problems for years [14]. Huang's group [15] recently developed and tested various cooler designs for high-power LED lamps.

Natural convection cooling is more favorable, and can be found in most high-lumen LED lamps. Some cooler designs involve closely spaced metal plates which are effective only for natural convection in one direction (e.g., traffic lights). The authors are testing pin-fin arrays made from aluminium rods of different lengths and diameters (see Fig. 2).



Figure 2: Pin-fin array developed at the University of Utah for LED cooling.

Use of pin fins makes natural convection quite effective for different lamp orientations. Preliminary results of a 10-W LED lamp showed only a couple of degrees Celsius difference in fin temperatures when the lamp was orientated differently.

Solar illumination systems have gained increased popularity in recent years. Indirect and direct, concentrated and non-concentrated solar light has all been used as a supplementary light source for commercial buildings and residential houses. Fig. 3 shows a commercial solar tube that utilizes

indirect sun rays. The mini-dish optic-fiber solar system developed by the authors is shown in Fig.4.

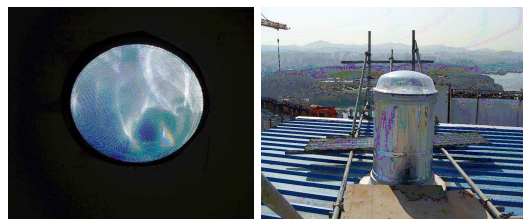


Figure 3: Solar tube for indoor illumination.

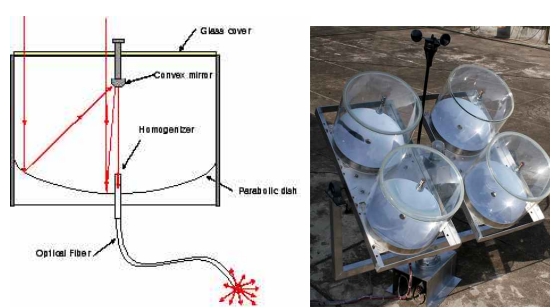


Figure 4: Mini-dish optic-fiber solar system (at Kyung Hee University).

A combined solar illumination-heating system is proposed by the authors to extend the application of the mini-dish optic-fiber system for spot (localized) heating and illumination. Because of the low absorptions of air, radiation heat transfer has been used to effectively transfer heat from a high- to a low-temperature region separated by a volume of gas without much attenuation. Radiant heaters thus are commonly used in large plants and factories, warehouses, and garages for spot heating. The proposed spot illumination/heating system is shown conceptually in Fig. 5. Solar energy collected by a mini dish (or Fresnel lenses if a planar collector is preferred or required) is transmitted using an optic fiber to a central energy storage/distribution unit. In the areas such as the lounge or hallways where illumination is needed, part of the reflective cladding of the optic fiber is removed to allow leakage of the light transmitted in the fiber. In the energy storage/distribution unit mirrors,

prisms, or lenses are used to focus and selectively send the sun rays emerged from the optic fiber to the desired location(s) for illumination. In addition, some of the solar energy can be used to heat up the phase-change fluid in the heat pipe, which provides localized heating without duct losses.

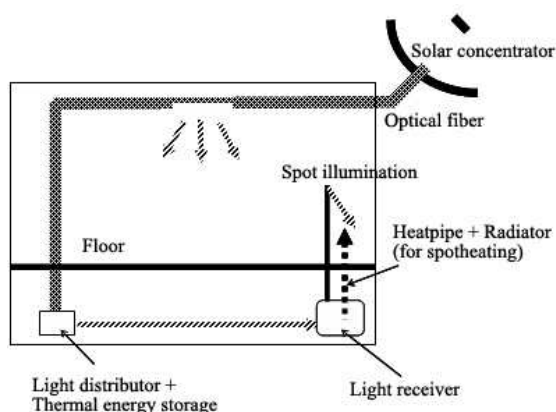


Figure 5: Use of the mini-dish optic-fiber system for localized heating and illumination.

Software and computer-control systems have been developed to track the sun for energy systems that require concentrated solar energy, and to automatically adjust the sunshades and deflectors for different seasons and times.

3.4 Efficient heating and air-conditioning systems:

A variety of innovative methods and techniques have been developed and tested lately to improve the energy efficiencies of building heating and air conditioning systems. In the past the average conversion efficiency of gas finances – a very popular choice for space heating – was about 80%. Owing to the soaring prices of natural gas in recent years, gas furnaces with 90% or higher efficiencies have replaced old, less efficient furnaces in many commercial buildings and residential houses. In theory very high furnace efficiencies can be achieved by increasing the heat transfer surface area. However the heat transfer rate

of a heat exchanger is often a logarithmic function of the required heat transfer area [16]. The considerable increases in furnace size and material and manufacturing costs for improving the gas furnace efficiency above 80% had made furnaces of high-efficiency less popular and affordable in the past. Improvements in heat exchanger designs render today's high-efficiency gas furnaces more affordable and not much larger than the low-efficiency ones.

Another important breakthrough in residential energy use is the rapid developments and improvements of micro CHP (combined heat power system). CHP is a cascade energy system similar to those to be discussed in Sec. 3.5. Micro CHP is generally considered as CHPs on a scale suitable for single-family residences [17]. A micro CHP can be installed where a gas furnace is located and provide both electricity and heat for space and water heating, and for the household appliances that operated on electric power. Many conferences and workshops have been held (e.g., [18]) and researches carried out recently to promote the use of micro CHP in residential houses. In April 2007 Honda and Climate Energy began the retail sales of their FreewattTM micro CHP. According to Climate Energy's test data, this micro CHP can produce 3.26 kW of heat and 1.2 kW of electric power. When replacing a typical 80% efficiency home heating system, the FreewattTM micro CHP can save an average of 30% energy cost.

Solar and geothermal energy have long been used for space and water heating [9]. Interests in these heating systems are surging due to the skyrocketing energy prices. Improvements in manufacturing techniques and materials made these old heating methods more affordable and energy efficient. Heat pipes housed in evacuated glass tubes can significantly reduce heat losses and achieve much higher operating temperatures and heat transfer rates than double- or triple-pane solar collectors. Plastic tubes are currently under testing to

replace glass tubes for reduced costs and better shattering resistance.

Rapid developments in MEMS (Micro ElectroMechanical Systems) have motivated the research on micro engines and heat pump clusters. It has been proposed to integrate tiny heat pumps of planar configuration into a compact heat pump system for spot cooling. This idea has not yet been realized because (1) efficient micro compressors are difficult to fabricate and operate due to the increase in frictional effects as the device size decreases, and (2) considerable heat leakage may occur if the heat source and sink of a small heat pump are too close to each other [19].

3.5 Cascade solar energy systems

The most important breakthrough in solar energy utilization in recent years was probably the high-efficiency solar cell. Multi-junction solar cells have achieved a conversion efficiency higher than 40%, and are aimed for more than 50% efficiency in the next decade. San Francisco International Airport installed a 20-kW array of PV (photovoltaic) panels in 2002 to provide electricity to one of the airport's supporting buildings. The system used commercial "peel-and-stick" PV laminates bonded to metal roofing pans and installed in modular units [20]. Today rooftop solar panels are very common in Germany, Spain, and several other European countries.

Hybrid or cascade solar systems that consist of different types of energy systems or converters have been developed and/or investigated. These energy-conversion systems may include photovoltaic, thermionic, and thermoelectric devices, and various heat engines such as Stirling engines or steam or gas turbines. The heat rejected from a thermionic or photovoltaic device in a cascade solar system can be used directly for space or water heating, or as the energy input for a low-temperature thermal or electrical system. Several PV/thermal system products are now commercially available. Some researchers recently

proposed a PV/thermal system design involving a thin plate-type heat pipe sandwiched between PV sheets. The compact design and interlocking feature of this invention make it convenient to add the PV/thermal system to existing roofs or use it as the roof of a new building.

Unlike solar energy, wind energy is a high-grade energy form and in theory can be 100% converted to other high-grade energy forms such as electricity. As was mentioned in [9], a small wind turbine can be one of the most cost-effective, home-based renewable energy systems and has the potential to lower a residential electric bill by 50 to 90%. The factors for selecting different small-scale wind power systems (grid-connected, stand-alone, and hybrid systems) were listed in [9]. However unlike PV panels, wind turbines and windmills can hardly be integrated into the structure of a building and therefore are not discussed in depth here. A review of the fuel cell is also skipped because hydrogen is needed for its operation. Hydrogen can be generated from high-temperature chemical reactions using concentrated solar energy. In this case the solar collector and the fuel cell system may become an integrated part of a building.

3.6 Innovative designs of building envelopes and construction modules

3.6.1 Soap bubble-filled building structures

In 1980s Richard Nelson in Canada received research grants and commercial partnerships to study soap bubbles for building insulation. The insulating values of soap foam as well as the flow dynamics and viscosity of soap foam were studied in these projects. The techniques to generate soap bubbles of desired rates and sizes were detailed in Nelson's early publications.

Based on Nelson's invention and test results, a Canadian company Agrispace has built soap bubble-filled greenhouses and manufactured modulated greenhouse structures in Canada since 1990s. Reports on the applications of this idea can be found

on the Internet (e.g., www.tdc.ca/bubblegreenhouse.htm) and in some HVAC journals (e.g., [21]). Most of these greenhouses were built in Canada.

Some people have claimed 80% plus savings in cost and preferred this invention to motorized curtains to provide shade in the summer. As was pointed out by Sissom [22], this technology is probably most suitable in extreme hot and cold climates, and in arid countries as well. Besides the thermal insulation application, this invention may be installed on a restaurant or cafeteria. The generation and movement of soap bubbles in the transparent envelope and the rainbow color reflection of soap bubbles would provide a fascinating and charming atmosphere.

3.6.2 Integrated solar desiccant cooling system

The places that need more energy for summer cooling are often the places where sunlight is abundant in the summer. Solar-driven cooling systems are therefore very attractive in these places. Information on solar space cooling can be found on the websites of US DOE Energy Efficiency and Renewable Energy (EERE), NRCan (Natural Resources Canada), and so on. Of the 3 types of cooling technologies that use solar thermal energy [23], absorption cooling is a very matured one. Vacuum tubes or concentrating collectors are often required and connected to the absorption chillers in this type of solar cooling systems.

Another solar cooling system that has gained increased attention is the combined heat engine/vapor compression system. It uses concentrated solar energy to run a heat engine for electricity generation. The electricity is then consumed by the compressor in a conventional vapor-compression refrigeration system. Due to the continuous improvements in solar heat engine technology, electrical power needed for vapor-compression cooling can be easily and inexpensively converted from solar energy using commercial solar heat engines.

The third solar cooling technology is desiccant cooling. Solar-driven desiccant cooling has been studied for a long time, and commercial products that can be easily integrated into a building structure are available (e.g., NovelAire). A double-skin, eco-dome design was recently proposed that integrated a solar-driven desiccant cooling system into the envelope of the dome. Pros and cons and candidates of desiccant cooling as well as other building cooling methods such as use of ice or chilled water for thermal energy storage, night precooling, and ground-source heat pumps, were discussed in details in most air conditioning books (e.g., [24]).

3.6.3 Smart construction modules

The authors have been investigating "smart" construction modules for years with an aim to improve building comfort and energy savings. A conceptual drawing of the module they invented is given in Fig. 6. The direction of heat flow, surface absorptivity, and thermal mass of the construction module all can be adjusted for maximum energy efficiency and/or maximum degree of comfort under various weather conditions.

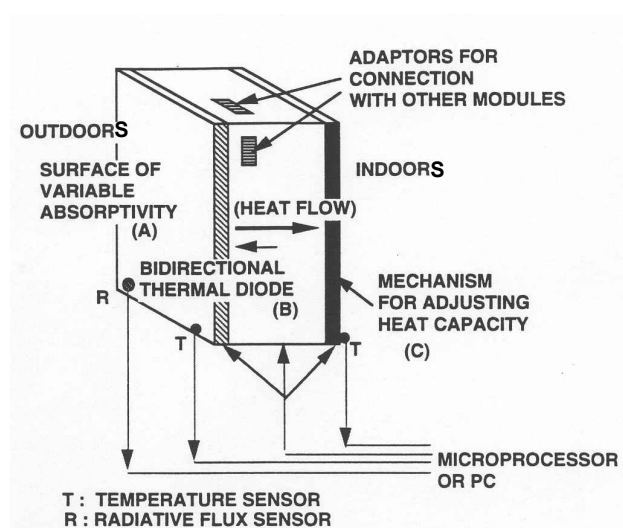


Figure 6: Smart construction module of variable direction of heat flow, surface absorptivity, and thermal capacitance.

The major component of the smart module is a bi-directional thermodiode. A photo of one the bi-directional thermodiodes invented by the authors and co-workers is shown in Fig. 7. Running the plastic tubes in this design through an existing wall and eliminating the glasswool between the collector and radiator plates, the wall can be turned into a smart wall for year-round energy savings. At present the authors and co-workers are testing different working fluids for improved performance and energy efficiency of the bi-directional thermodiode.

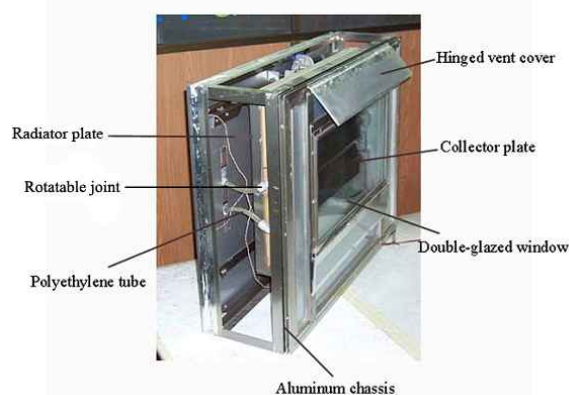


Figure 7: Photo of a bi-directional thermodiode

Operations of the module for winter heating and summer cooling are tabulated in Table 1. Solar energy is utilized in the winter for space heating. As a result the outdoor-facing surface is adjusted to be highly absorptive during the daytime and the direction of heat flow is from the outdoors to the indoors. Since a surface which absorbs radiation efficiently also emits radiation efficiently, the outdoor surface should change to highly reflective to reduce radiation loss at night in the winter.

Table 1. Operation of the Smart Module

	Winter Heating		Summer Cooling	
	Day	Night	Day	Night
(A) Variable direction of heat flow	From the outdoors to the indoors	Little heat leakage to the outdoors	Little heat leakage to the indoors	From the indoors to the outdoors
(B) Variable surface absorptivity	Highly Absorptive	Highly Reflective	Highly Reflective	Highly Absorptive
(C) Variable heat capacity	(Depends on indoor-outdoor temperature difference and the desired operation condition)			

The setting of the direction of heat flow and surface absorptivity are just the opposite for summer cooling application. The outdoor surface is highly reflective during the day for less solar heating, but changes to highly absorptive at night to transfer heat to the sky by radiation. The desired direction of heat flow of the diode for summer cooling is from the indoors to the outdoors.

A variety of designs to alter the surface absorptivity and thermal mass of the modules have been explored and discussed in Chen, Chun, and co-workers' publications (e.g., [25]). Operation of the mechanism that changes the thermal mass of the module depends on the weather conditions and the occupancy of the building. For winter heating, the thermal mass of the module should be set low when the building is occupied and a fast warm-up of the indoors is desired. A low thermal mass allows the module temperature to rise rapidly during heating. When the indoor temperature reaches a comfortable level, the heat capacity is adjusted high to store excess energy input for later use. When the outdoor surface is heated by solar energy but the building is not occupied, the module thermal mass should be set high for immediate storage of solar energy. For summer cooling, a large thermal mass is needed to hold a large amount of energy when the building is occupied and the outdoor air temperature is high. A small thermal mass, on the other hand, allows the indoor temperature to quickly drop when the outdoor temperature is low.

The best combination and adjustments of the direction of heat flow, thermal mass, and surface absorptivity should be determined and controlled by a PC (Personal Computer) for maximum energy efficiency and/or most comfortable indoor temperature.

Unlike solar house design which is part of the building and cannot be moved freely from one location to another, the module invented by the authors can be mass-manufactured and stored in one place and shipped to another place to be quickly assembled as building or shelter envelopes.

5. SUMMARY AND CONCLUSIONS

Recent design and development of energy-efficient buildings and sustainable architecture were reviewed in this paper. Most of the technologies developed for improving building energy efficiencies in different categories can be easily integrated to yield considerable savings in total energy consumption. Multifunction-capable designs such as micro CHP for dual-form energy generation and the bi-directional thermodiode that can be used for both winter heating and summer cooling were also reviewed and discussed.

The rapid developments in every aspect of energy-efficient building show great hope in the integration of green energy utilization, sustainable architectural design, and energy conservation for next-generation buildings and residential houses that consume no electrical or mechanical energy and have minimal impact on the environment.

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