IMPROVING INCREASED THERMAL CAPACITANCE AS A PASSIVE ENERGY MANAGEMENT SYSTEM WITH UNDERGROUND PIPING

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ABSTRACT

This paper evaluates the influence of underground piping on the performance of using increased thermal capacitance (ITC) as a passive energy management system on an office building. The building's cooling load will be decreased by circulating water from a storage tank through underground piping then through a piping system located in the building's ceiling. The cooling load of an ITC enhanced building with underground piping is compared to the cooling load of an ITC enhanced building without underground piping and a reference building without ITC at all. The reference building and the ITC enhanced building were simulated in Atlanta, GA, and New York, NY using the transient system simulation software TRNSYS. To improve the performance of the ITC piping system, a piping was buried 3 m to use the ground as a heat sink, i.e. transferring heat from the working fluid to the soil. The simulation results showed that ITC could reduce the overall cooling load for the summer months by almost 7%. ITC was ineffective for reducing the heating load.

INTRODUCTION

Energy consumption in the world is increasing at a drastic rate. According to the United States Energy Information Agency (EIA), commercial and residential buildings consumed about 40% of the energy consumption in the US (US Department of Energy, 2013a) with about 48% of the energy used in buildings being for heating and cooling (US Department of Energy, 2013b). The EIA expects the world's energy consumption to increase 56% by the year 2040 (US Department of Energy, 2013c). Radiant heating and cooling is identified as one of the technologies that can effectively reduce energy consumptions in buildings (ASHRAE, 2011a), (ASHRAE, 2011b). (Miriel et al, 2002) presented results for radiant heating and cooling experiment in a water ceiling panel in western France. They developed simulation models that allowed for yearlong simulations using TRNSYS (TRNSYS Manual, 2009) and verified by experimental data. They determined that the ceiling surface temperature needed to be maintained above 17°C to prevent condensation from the radiant ceiling due to high humidity. (Vangtook et al, 2007) presented results for using pipes with water for cooling in residential buildings in Thailand. They concluded that thermal comfort could be maintained with a cooling tower keeping the water temperature above 10°C to prevent condensation. (Venko et al, 2012) presented results on enhanced heat transfer for an active cooling wall in commercial buildings. In this study, an active wall was used in combination with fresh air supplied from a diffuser mounted at the top of the wall. The study determined that the forced convection from the diffuser provided superior heat transfer from the active wall when compared to the heat transfer due solely to natural convection. (Zhao et al, 2013) presented results of radiant floor cooling in a large building. The radiant floor cooling of a large building was found to provide better thermal comfort and required 20–30% less energy than a conventional forced air system. (Yang et al, 2013) presented results using a radiant cooled ceiling with a heat exchanger and conventional window air conditioner. A radiant cooling system was shown to reduce operating time and also reduce energy consumption by13–19%. (Stetiu, 1999) presented a study on the peak power savings using radiant cooling in commercial buildings in the US. He showed a radiant cooling system to save 30% on energy consumption and reduce the peak power demand by 27%. The savings were found to be climate-dependent.

In contrast with radiant cooling or heating systems, which use makeup water that has either been heated with a boiler or cooled with a chiller, Carpenter et al. (Carpenter et al, 2014) presented an analysis of using increased thermal capacitance (ITC) for passive energy management and showed that their proposed ITC systems can be a good potential application to reduce the building cooling load. The main concept of ITC is to reduce building thermal load by circulating water through a piping system located in the building walls or ceiling. The reduction of the thermal load is achieved by increasing the effective thermal capacitance at selected surfaces of the building, e.g., ceiling and walls. Water is circulated through pipes embedded in these surfaces and routed through a large storage tank in order to achieve the same effect of a massive capacitance. This is in contrast to a radiant heating and cooling system, where the objective is to provide the heating and cooling energy to maintain a set temperature. As an ongoing effort, this paper evaluates the influence adding underground piping to transfer energy to or from the system into the nearby soil using the soil as a heat sink or a heat source.

DESCRIPTION OF THE SIMULATION ENVIRONMENT

The reference building and building with ITC were both modelled in TRNSYS (Klein et al, 2010), a simulation program used in the fields of thermal energy engineering and building simulation. Figure 1 displays the dynamic model created in TRNSYS for the reference building.

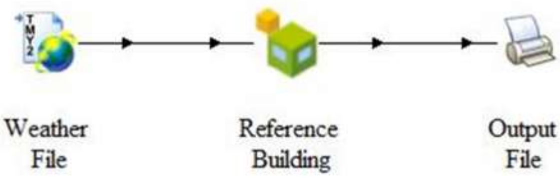

Figure 1 Reference building dynamic model

By utilizing a weather file, the dynamic model can estimate the reference building's heating and cooling loads. The model utilizes Typical Meteorological Year 2 (TMY) data (US Department of Energy, 2013d), which is a collection of weather elements over duration of several years such that typical weather data can be used in the simulation. The reference building was designed in TRNBuild (Klein et al, 2010), which is a conglomerate of TRNSYS (Klein et al, 2010) used to design buildings for simulation, and is called with the building icon called Type 56 Multizone Building Icon. The Type 56 component models the thermal behaviour of the building. TRNSYS calculates the cooling and heating loads during the simulation. The mathematical model of the components can be found in (TRNSYS 17, 2014). Once the baseline cooling and heating loads were determined, the reference building was modified to include the proposed ITC in the ceiling. This location was selected based on the results presented by Carpenter et al. (Carpenter et al, 2014) that indicted that locating the ITC in the ceiling shows better potential to reduce the building cooling load than in the walls. Figure 2 illustrates the TRNSYS dynamic model with the ITC added in the ceiling. This model was used for two different cases: first, the external pipe was perfectly insulated and exposed to ambient weather conditions. Then the pipe buried to simulate using the ground as a heat source or heat sink.

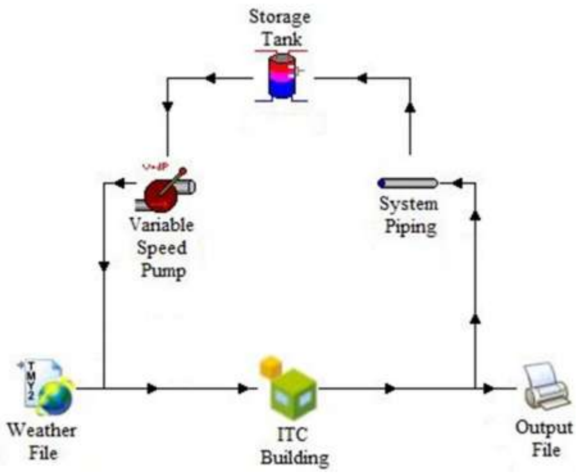

Figure 2 Dynamic model of TRNSYS with ITC either perfectly insulated or buried underground

For this case study, a piping system was installed into the ceiling to increase the thermal capacitance. The piping system was placed between insulation layer of the ceiling. Figure 3 shows a schematic of the piping system in the ceiling.

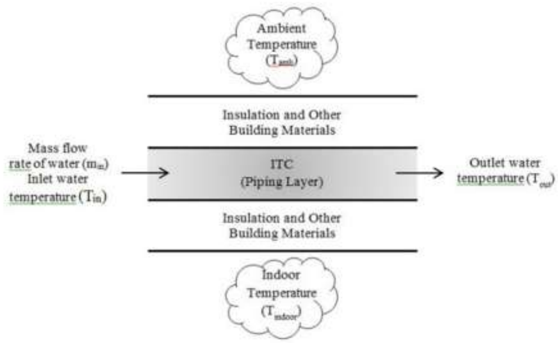

Figure 3 Schematic of ITC system in ceiling

The addition of a working fluid allows the addition or removal of energy to or from the zone depending on temperatures of the working fluid, zone air, and ambient air. By adding or removing energy to or from the zone through an increase in thermal capacitance, the amount of cooling or heating load required can be reduced. To further analyse this idea, the system shown in Figure 2 was implemented using an integrated model of a thermo-active building element in TRNSYS (Klein et al, 2010), which is an add-on feature available in TRNBuild (Klein et al, 2010). This add-on feature implements a fluid piping system into a building construction component. The mean fluid temperature in a pipe loop is based on the thermal resistance between the fluid and pipe shell. The interior and exterior wall surface temperatures are calculated based on the effect of conduction between pipes and construction material using a two-dimensional conduction analysis. For simulation of the ITC system, the proposed model also consists of a pump component and storage tank component implemented in TRNSYS with the purpose of circulating water through the ceiling and a storage tank. The pumping component chosen was a variable speed pump. The pump component controls the flow rate of the working fluid for the system; calculates electrical energy used by the pump, along with conveying the working fluid's temperature to the building component. The building component then calculates the water temperature change through the building's pipes in the ceiling and transmits the working fluid's exit temperature and flow rate to the pipe component. The pipe component calculates the water temperature change through the pipes and transmits the working fluids pipe exit temperature to the tank. For the basic ITC case, the pipes were exposed to ambient weather conditions but are perfectly insulated. For the underground piping case, the pipes were made of PVC and buried 3 m into the ground. In both cases the storage tank component selected was a thermally insulated vertical storage tank with a single inlet as well as a single outlet, located outside the building, and exposed to ambient weather conditions.

RESULTS

This section presents the results obtained using the models described in Section 2. Case 1 found a baseline heating and cooling load by simulating the reference building without ITC. Case 2 added an ITC system to the reference building with insulated external pipe in the air. Case 3 added an ITC system to the reference building with the external piping uninsulated and buried 3 m underground.

3.1 Reference building

The reference building chosen was a hypothetical square office building with a surface area of 196 m^2 (14 m x 14 m) and a wall height of 3.048 m, with a flat roof and windows occupying 20% of the wall space. This is a typical size for a small office building. Table 1 presents the material properties for the walls, with Table 2 showing the same properties for the roof. Table 3 displays the material properties for the floor.

Table 1
Material properties for walls

Material	Thickness (m)	Conductivity (W/m·K)	Capacity (kJ/kg·K)	Density (kg/m^3)
Plaster Board	0.010	0.160	0.84	950
Fiberglass Insulation	0.061	0.040	0.84	12
Concrete Block	0.200	0.510	1.00	1400

Table 2
Material properties for roof

Material	Thickness (m)	Conductivity (W/m·K)	Capacity (kJ/kg·K)	Density (kg/m^3)
Plaster Board	0.010	0.160	0.84	950
Fiberglass Insulation	0.160	0.040	0.84	12
Concrete Block	0.200	0.510	1.00	1400
Roof Decking	0.019	0.140	0.90	530

Table 3
Material properties for the floor

Material	Thickness (m)	Conductivity (W/m·K)	Capacity (kJ/kg·K)	Density (kg/m^3)
Timber Flooring	0.025	0.140	1.2	650
Fiberglass Insulation	0.112	0.040	0.84	12
Concrete Slab	0.080	1.130	1.00	1400

For this analysis, the cooling thermal set point was set to 24°C with the heating thermal set point set to 20°C. The lighting power density was assumed to be 10 W/m^2 with the lights scheduled to turn on at 8 AM and switch off at 5 PM. For this analysis 14 occupants worked a nine hour day from 8 AM to 5 PM, Monday through Friday. The occupants were working on computers with a power density of 16 W/m^2. On the weekends, the building is unoccupied and everything is turned off. The initial reference building was simulated using weather data for Atlanta, GA and New York, NY for a year.

Figure 4 displays the cooling load, estimated in TRNSYS, along with the indoor zone temperature and ambient temperature for a week around July 21st, for Atlanta, GA. Figure 5 displays the cooling load, estimated in TRNSYS, along with the indoor zone temperature and ambient temperature for a week around July 21st, for a building located in New York, NY. In Figure 4 and Figure 5, a week of time was chosen so the temperature profiles could clearly be appreciated.

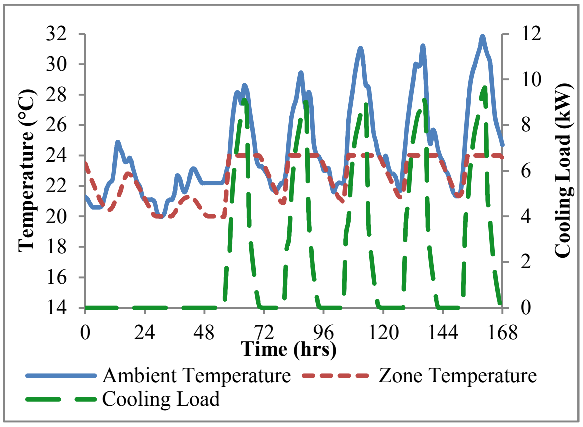

Figure 4 Reference building cooling load, ambient and zone temperatures for a week in July located in Atlanta, GA

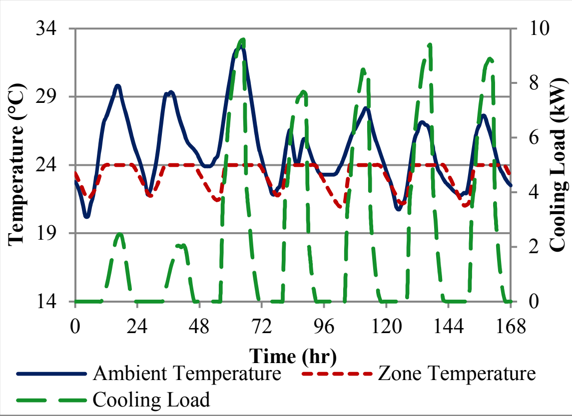

Figure 5 Reference building cooling load, ambient and zone temperatures for a week in July located in New York, NY

As is shown in Figure 4 and Figure 5, the cooling load varies with the ambient temperature, and the indoor zone temperature remains around 24 °C throughout the day and sinks at night. Due to internal gains in the building, from people, lighting, and equipment, cooling is required even if the ambient temperature does not reach the set point temperature. On weekends, the cooling load will be lower due to no internal loads being present.

Figure 6 shows the monthly heating and cooling loads for the reference building simulated in Atlanta, GA. Due to large internal heat gains solar radiation through the southern facing windows, cooling is required year round. During the summer months, no heating is required. July and August require the most energy for cooling while January and December require the most energy for heating. The total energy required for cooling is 13,489 kWh with the total energy required for heating is 4,566 kWh.

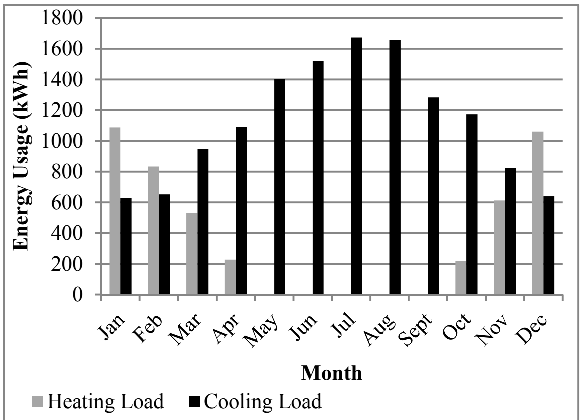

Figure 6 Reference building's monthly heating and cooling energy required in Atlanta, GA

Figure 7 displays the monthly heating and cooling loads for the reference building simulated in New York, NY. Similar to Figure 6, no heating is required for the summer months. July and August require the most energy for cooling while January and December require the most energy for heating. The total energy required for cooling is 11,205 kWh with the total energy required for heating is 7,333 kWh.

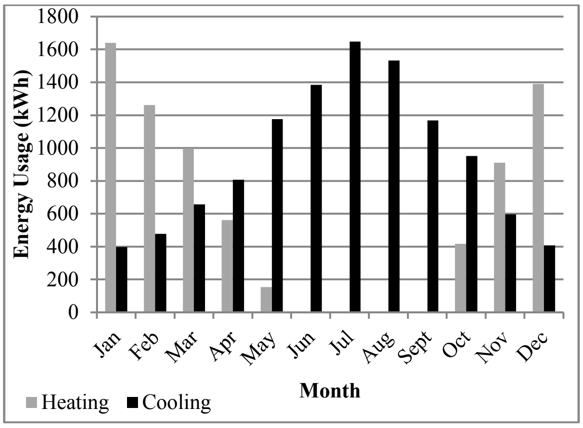

Figure 7 Referenc building's monthly heating and cooling energy required in New York, NY

Cooling Load Comparison

After finding the monthly baseline heating and cooling loads for the reference building located in Atlanta, GA, and New York, NY, an ITC system (a piping system that circulates a working fluid) was placed within the insulation layer of the ceiling, due to TRNSYS calculations of fluid mass flow rate within the piping. The pipes within the building are located 0.06 m from the internal surface. Table 4 shows the design parameters of the piping system within the ceiling used in this analysis. The working fluid chosen for this analysis is water. In Case 2 the external pipes are considered perfectly insulated. Table 5 displays the external piping specifications for the buried piping in Case 3. Case 3 buries the external pipes 3 m underground while also removing the insulation to allow conduction between the ground and piping to occur. At that depth ground temperature does not fluctuate nearly as much as sky temperature and stays between 15 °C and 25 °C (Florides et al)

Table 4
Internal piping system design parameters

Pipe Material	Pipe spacing (m)	Outside diameter (m)	Pipe wall thickness (m)	Conductivity (W/m K)
Copper	0.2	0.02	0.004	401

Table 5
External piping system specifications

Pipe Length (m)	Outside diameter (m)	Pipe wall thickness (m)	Conductivity (W/m K)
28	0.02	0.004	0.42

Figure 8 shows the monthly cooling energy required for the reference building, the basic ITC building, and the ITC building with underground piping simulated in Atlanta, GA. The basic ITC building and reference buildings cooling loads are approximately the same while the building with underground piping has a significant reduction in the cooling load. The reduction of the cooling load in the underground piping case increases in the summer months with the largest reduction being in July with the cooling energy being reduced by 166 kWh for the month. The ITC system with underground piping is about to reduce the cooling energy required by over 8% for the summer months. The basic ITC case reduced the cooling energy required by 0.6% for the year while the underground piping reduces the cooling energy required by 7.1% for the year. The basic ITC case is unable to reduce the cooling load due to water temperature in the storage tank being increased from gaining the energy while the underground piping case can continue to be effective due to energy being transferred to the ground.

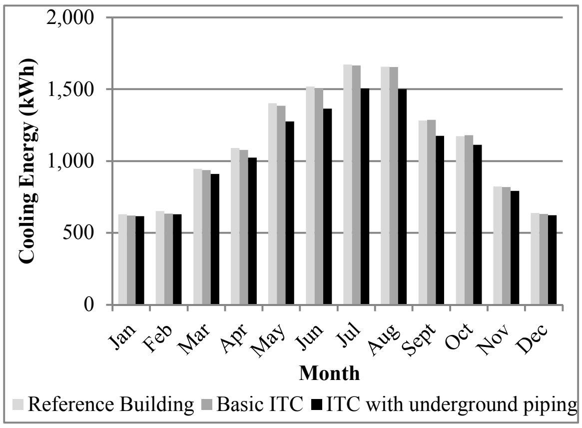

Figure 8 Cooling energy comparison for buildings simulated in Atlanta, GA

Figure 9 displays the monthly energy cooling required for the reference building, the basic ITC building, and the ITC building with underground piping simulated in New York, NY. Similar to the simulation in Atlanta, GA, the basic ITC case does not reduce the cooling energy required. Also similar to Atlanta the case with underground piping significantly reduces the energy consumption for cooling. The large energy reduction again occurs in July with the total reduction being 162 kWh. The ITC system with underground piping is about to reduce the cooling energy required by over 6.5% for the summer months. The basic ITC case reduced the cooling energy required by 0.6% for the year while the underground piping reduces the cooling energy required by 6.0% for the year.

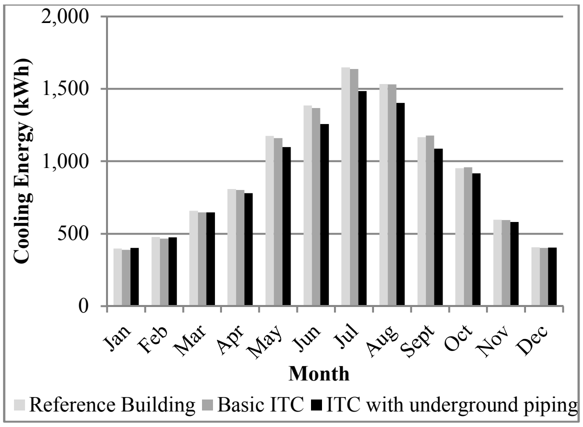

Figure 9 Cooling energy comparison for buildings simulated in New York, NY

In both geographical locations, the use of underground piping significantly improves the result of using ITC to reduce the cooling energy required.

Heating Load

The heating load for each case was also simulated for all six cases in two different locations. Figure 10 shows the monthly heating energy required for the reference building, the basic ITC building, and the ITC building with underground piping simulated in Atlanta, GA. The addition of ITC to the building does not help with reducing the heating energy required and in several months actual causes more energy to be required. In the case of the ITC with underground piping, this is explained by the ground temperature at 3 m deep being cooler than the heating set point within the building. This causes the ground to act as a heat sink year round, which means that during the winter heat transfers from the underground pipes into the ground. The working fluid is cooler than the indoor air temperature, which increases the heating load due to heat being transferred from the indoor air to the working fluid. In the case of the basic ITC the working fluid temperature drops as the ambient temperature drops due to energy being released to the building or outdoor from the pipes within the building. The basic ITC case decreases the heating energy required by 0.5% for the year. The ITC case with underground piping actually increases the heating energy required by 2.2%.

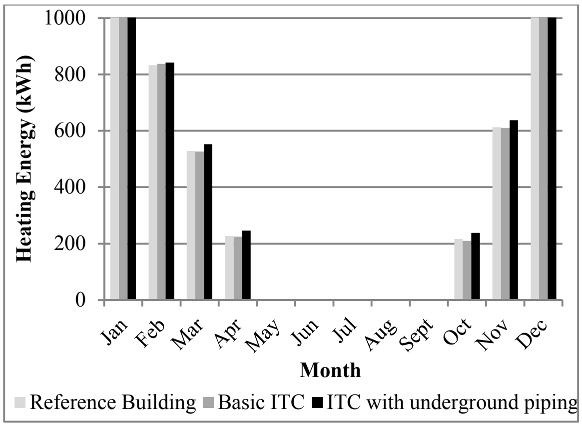

Figure 10 Heating energy comparison for buildings simulated in Atlanta, GA

Figure 11 shows the monthly heating energy required for the reference building, the basic ITC building, and the ITC building with underground piping simulated in New York, NY. Similar to the results for Atlanta, GA, neither case helps reduce the heating energy consumption. In the basic ITC case, the total heating energy consumption decreases by 0.2%. For the ITC with underground piping case, the heating energy consumption increases by 0.6%.

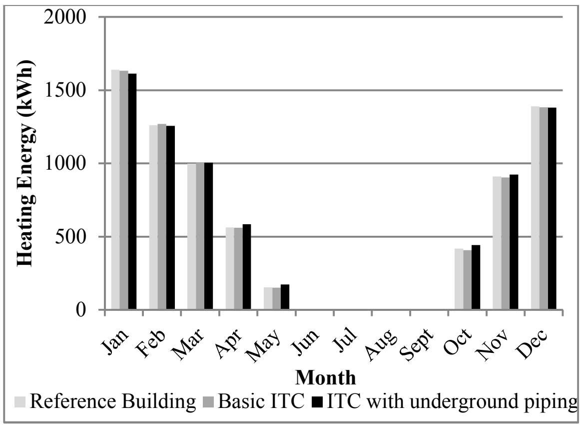

Figure 11 Heating energy comparison for buildings simulated in New York, NY

The use of ITC to reduce heating energy consumption is not effective. To use ITC to reduce the heating energy usage, a heat source for the water will be required. Depending on the heat source, the heating could be free (i.e. solar radiation), use electricity (i.e. heating strips), or use another method of heating the water.

CONCLUSION

This analysis investigated the use of underground piping to enhance the effect of ITC on an office building cooling and heating energy requirements. The addition of underground piping to the ITC reduced the cooling load by more than 6% for the year. The use of ITC for reducing the heating load was ineffective with just the basic ITC system and actually increased the heating energy required with the addition of underground piping. Due to the soil being cooler than the heating and cooling set points of the building, the ground acts as a heat sink year round.

Future research should include investigating using solar panels as a heat source for heating the working fluid or using night-time air as a heat sink with the use of solar panels to reduce the cooling load. In addition, a cost analysis of the implementation an ITC system should be done and a study of even more geographical locations to understand the effect of ambient conditions on the effectiveness of an ITC system. Implementation costs should be similar to other radiant heating and cooling systems since in both systems piping will have to be installed. However this system will include a storage tank while the radiant systems will not.

REFERENCES

ASHRAE Handbook, 2011. ASHRAE Handbook—HVAC Applications, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA.

ASHRAE, 2011b. Advanced Energy Design Guide for Small to Medium Office Buildings, American Society of Heating, Refrigerating, and Air-Conditioning Engineers(ASHRAE), Atlanta, GA.

Carpenter, J., Mago, P., Luck, R., Cho, H. 2014. Passive energy management through increased thermal capacitance. Energy and Buildings, 75, 465-471.

Klein. F S.A., et al., 2010. TRNSYS 17: A Transient System Simulation Program, Solar Energy Laboratory, University of Wisconsin, Madison, USA, http://sel.me.wisc.edu/trnsys.

Miriel, J.,Serres, L., Trombe, A. 2002 Radiant ceiling panel heating cooling systems experimental and simulated study of the performances, thermal comfort and energy consumptions, Applied Thermal Engineering, 22, 1861–1873.

Stetiu, C. 1999. Energy and peak power saving potential of radiant cooling systems in US commercial buildings, Energy and Buildings, 30, 127–138.

TRNSYS 17 Manual, 2009 Solar Energy Laboratory, University of Wisconsin, Madison, USA, http://sel.me.wisc.edu/trnsys

TRNSYS 17 Mathematical Reference. 2009. Solar Energy Laboratory, University of Wisconsin, Madison, USA, http://sel.me.wisc.edu/trnsys.

U.S. Department of Energy, 2013a. Energy Information Administration, EIA projects world energy consumption will increase 56% by 2040, U.S. Department of Energy, Available from: http://www.eia.gov.

U.S. Department of Energy. 2013b. Energy Information Administration, Frequently asked questions, How much energy is consumed in residential and commercial buildings in the United States, U.S. Department of Energy, Available from: http://www.eia.gov.

U.S. Department of Energy 2013c. Energy Information Administration, Heating and cooling no longer majority of U.S. home energy use, U.S. Department of Energy, Available from: http://www.eia.gov.

U.S. Department of Energy, 2013d Brief Summary of the TMY2s, National Renewable Energy Laboratory, http://www.nrel.gov/rredc.

Vangtook, P., Surapong, C. 2007. Application of radiant cooling as a passive cooling option in hot humid climate, Building and Environment, 42, 543–556.

Venko, S., Vidrih, B., Pavlovic, E.,Medved, S. 2012. Enhanced heat transfer on thermos active cooling wall, Journal of Mechanical Engineering, 58, 623–632.

Yang, C.M., Chen, C.C., Chen, S.L. 2013. Energy-efficient air conditioning system with combination of radiant cooling and periodic total heat exchanger, Energy, 59, 467–477.

Zhoa, K., Xiao-Hua, L., Jiang, Y. 2013. Application of radiant floor cooling in a large open space building with high-intensity solar radiation, Energy and Buildings, 66, 246–257

Florides, G., Kalogirou, S. Annual Ground Temperature Measurements at Various Depths