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Passive Energy Management through Increased Thermal Capacitance

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Passive energy management through increased thermal capacitance

By

Joseph Paul Carpenter

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in the Department of Mechanical Engineering

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Passive energy management through increased thermal capacitance

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Energy usage within the world is increasing at a drastic rate. Buildings currently consume a major amount of the total energy used within the United States, and most of this energy usage supports heating and cooling. This demand shows that new passive energy management systems are needed. The use of Increased Thermal Capacitance (ITC) is proposed as a new passive energy management system. To increase thermal capacitance, a piping system is either added into a building's walls or ceiling. In this paper, a building with ITC added is compared to a similar building without ITC using the simulation program TRNSYS. Along with a comparison between the walls and ceiling, several parameters are analyzed for their effect on the performance of the ITC. ITC was found to be effective especially when located in the ceiling, with the location, specific heat and tank size being the most important factors.

DEDICATION

I would like to dedicate this research to my parents, James and Elizabeth Carpenter.

ACKNOWLEDGEMENTS

I would like to thank the people who have assisted in the development of this thesis. First of all, I would like to thank Dr. Pedro J. Mago, my advisor, for his expending time and effort to guide and assist me throughout my master's program. I would also like to share my appreciation to the other members of my committee, Dr. Rogelio Luck and Dr. Heejin Cho, for the time and direction they provided. Lastly, I would like to thank Mrs. Amy Barton for her time and effort with the writing of my thesis.

TABLE OF CONTENTS

CHAPTER

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

1.1 Importance of Research

With worldwide energy consumption increasing at a drastic rate, low-energy cooling and heating systems are needed. According to the United States Energy Information Agency (EIA), the world's energy consumption is expected to increase 56% by the year 2040 [1]. Also according to the EIA, commercial and residential buildings consume about 40% of the energy consumption in the US [2], with about 48% of the energy used in buildings supporting heating and cooling [3]. These statistics can be seen in Figures 1 through 3. In Figure 1.1 one it can be seen that 40% of the total energy consumption in the United States is for electricity. Figure 1.2 shows the amount of electricity usage for each sector for the month of October 2013. As can be seen in the figure, most of electrical consumption is used in commercial and residential buildings. Figure 1.3 displays the energy usage by type in buildings, which shows that the space heating consumes the most energy in buildings. Although the energy usage for space heating is decreasing, most of the decrease is due to people moving to warmer climates [3]. This demand presents the opportunity to reduce energy consumption. By reducing the energy usage for heating and cooling in buildings, the total energy usage will be decreased. One way to decrease the cooling and heating loads is through passive energy management. Passive energy management is using little to no energy for cooling.

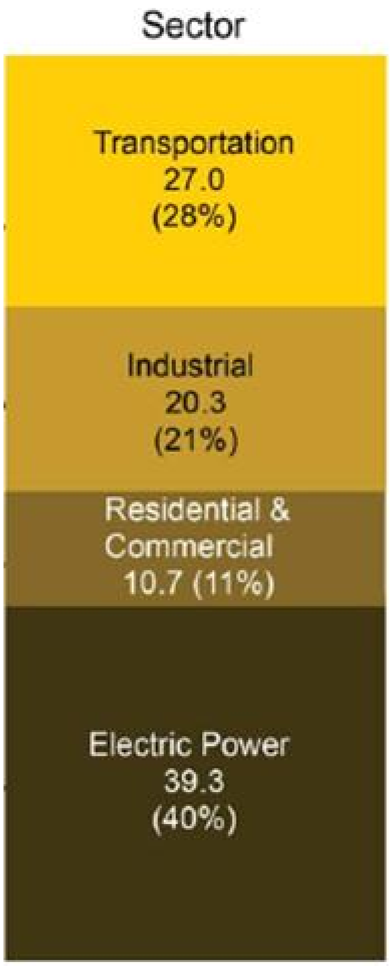


Figure 1.1 Energy consumption by sector [1]

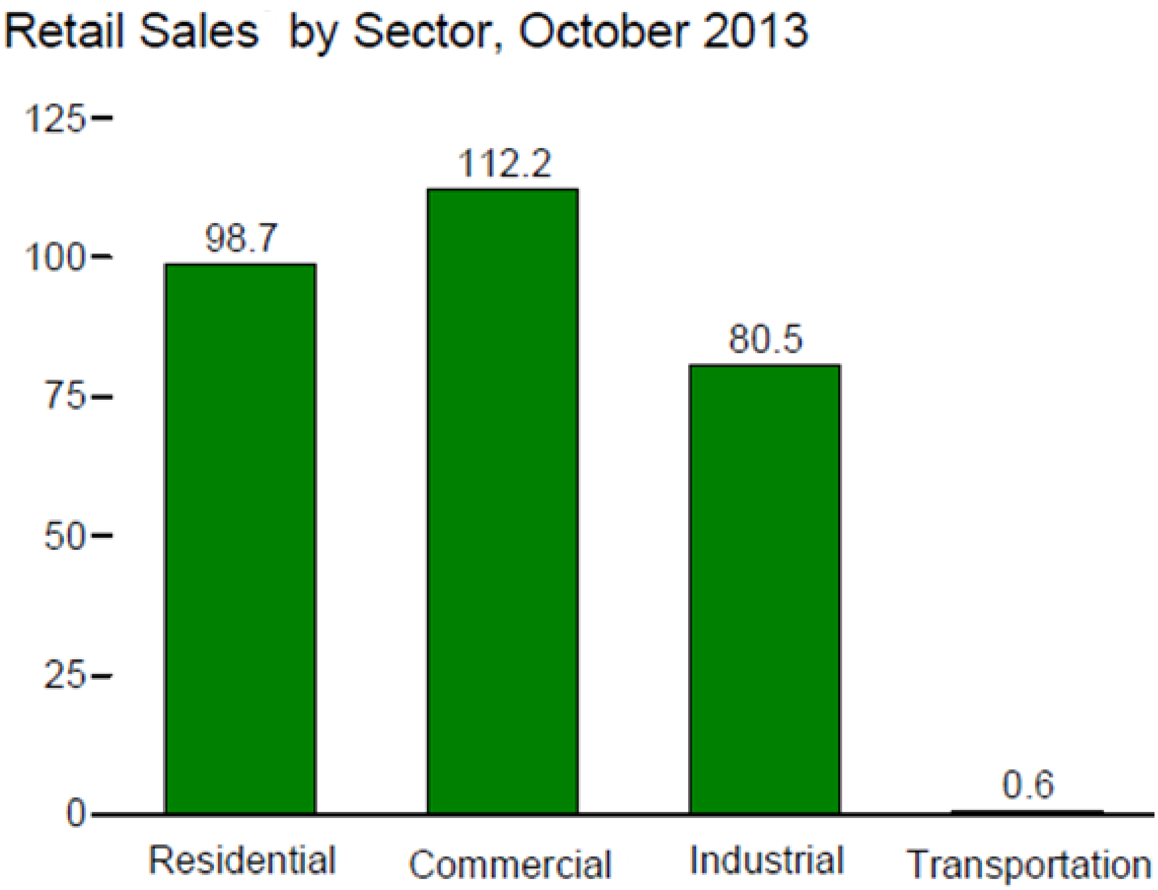


Figure 1.2 Electricity consumption in billion kWh [2]

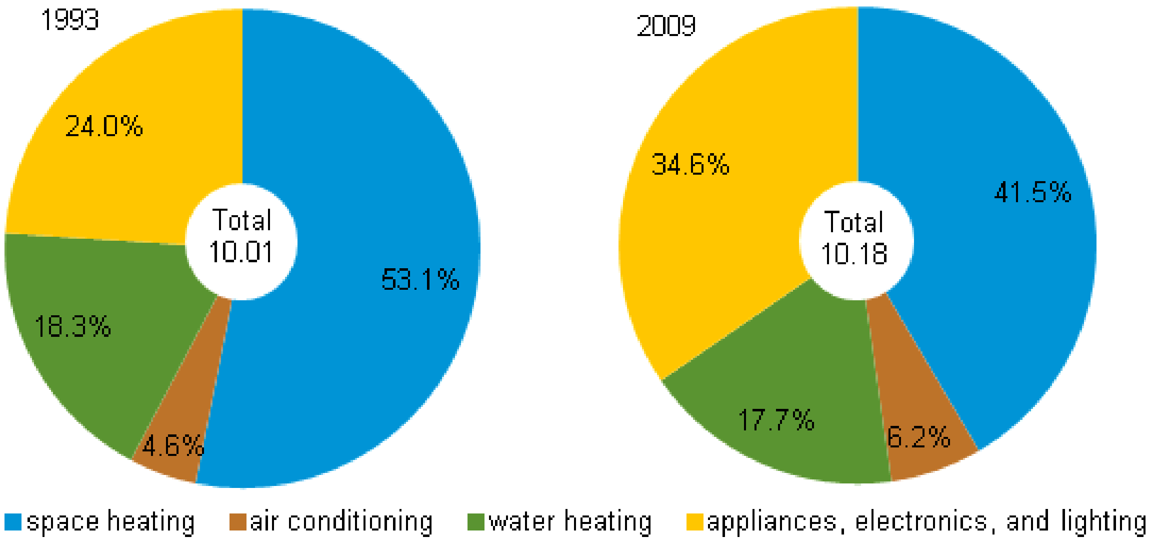


Figure 1.3 Energy consumption in buildings [3]

1.2 Literature Review

One way to reduce total building energy consumption is to increase the efficiency of the building's energy components. An alternative way to achieve energy usage reduction and/or energy cost reduction in buildings is to reduce the total energy load or peak load using active and/or passive systems. Thus less energy is required for the building's energy components to maintain a quality working and living environment.

Along with increased interest in the demand side energy management [4-6], to save costs in energy generation and plant construction and increase gird resilience, many studies have been conducted to reduce or shift peak load in buildings (e.g., [7-11]). Lee and Braun [7] proposed a model-based approach to minimize peak cooling load using building thermal mass and demonstrated that their proposed method can result in about 30% reduction in peak cooling loads for a particular building. Applications of building thermal energy storage have been investigated to shift peak building thermal loads [8-11]. Rabi and Norford [12] explored thermostat control strategies to reduce cooling load during the peak period by sub-cooling a building at night.

Different means of reducing overall building energy consumption also have been explored by several researchers [13-21]. Yang and Li [13] performed a quantitative analysis to reduce cooling load using thermal mass and night ventilation using the building time constant information. Various building energy components, such as green and vegetation roofs [14-16], insulation material [17,18], and windows [19,20], have been considered to decrease thermal loads in buildings by increasing thermal conductivities. Sadineni et al. [21] provided a review of building envelope components that are used as passive building energy saving technologies.

Another way to control indoor temperatures is radiant heating and cooling, which is identified as one of the technologies that can effectively reduce energy consumption in buildings [22, 23]. Radiant heating and cooling is using piping within a building's structure to maintain thermal comfort levels. Studies of radiant cooling and heating have been conducted by several authors, such as Miriel et al. [24], Vangtook et al. [25], Venko et al. [26], Zhao et al. [27], Yang et al. [28], and Stetiu [29], among others.

Miriel et al. [24] presented results for a radiant heating and cooling experiment in a water ceiling panel in western France. Simulation models that allowed for yearlong simulations were developed for TRNSYS [30] and validated by experimental data. They found that radiant ceiling panels could be used for heating and cooling with good thermal insulation but that the building's heating and cooling loads must be low. They also determined that the ceiling needed to be maintained at a minimum temperature of 17°C to prevent condensation from the radiant ceiling due to high humidity. Vangtook et al. [25] presented results for using pipes with water for cooling in residential buildings in Thailand. They concluded that with low load requirements thermal comfort could be maintained with a cooling tower to keep the water temperature at 10°C to prevent condensation. They also found that if further cooling was required that pre-cooling ventilation air with active cooled water would achieve thermal comfort better than conventional air-conditioning. Venko et al. [26] presented results on enhanced heat transfer for an active cooling wall in commercial buildings. They found that natural convection is noiseless, but difficult to control and adapt to current cooling load due to the dependency of natural convection on temperature differences between the walls and air. 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. [27] presented results of radiant floor cooling in a large building. They developed a simple model to predict the performance of radiant cooling floors with solar radiation and found that the cooling capacity of the radiant floor increased with high-intensity solar radiation. They also found that a sheltered floor's cooling capacity was much lower than that of an unsheltered floor. Finally they found that 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. [28] 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 reduced energy consumption by 13-19%. Along with reduced energy consumption, the amount of CO_2 production would be reduced. Also the study showed that the payback period from energy cost saved would be about 3 years. Stetiu [29] presented a study on the peak power savings using radiant cooling in commercial buildings in the US. He found that different ventilation strategies along with different parameters of a building's conditioning system are needed for different climates. He also showed that a radiant cooling system can be used anywhere in the US without the concern of condensation. A radiant cooling system was shown to save 30% on energy consumption and reduce the peak power by 27%. However, the savings were found to be climate-dependent.

Feustal et al. [31] did a preliminary assessment of radiant cooling and showed that radiant cooling could reduce peak power requirements and reduce total energy usage for cooling. They also determined that due to the limited cooling power of radiant cooling systems, the design of buildings had to be carefully done with special consideration to reducing the peak cooling required. Venko et al. [32] presented an experimental study on mixed convection with a cooled vertical wall and found that mixed convection improved the effectiveness of the radiant system. They found the major problem with alternate cooling methods was the initial investment cost of alternatives to conventional air conditioning were much higher. They also found that the effect of these systems were limited due to low convective heat transfer. So to be effective large surfaces are needed to cool the rooms, which were beyond cost efficiency or architectural design. Yin et al. [33] conducted an investigation on performance and condensation of three different types of radiant cooling panels and showed that with proper control strategies, radiant cooling was effective and condensation was avoidable. They found that the performance of radiant cooling panels improved with a larger temperature gradient and also found that gypsum cooling panels worked better than metal or pure tube panels and resulted in less condensation problems.

Tian and Love [34] showed that a radiant floor system with a conventional air conditioning system can reduce energy usage up to 80%. They also found that the thermal quality of the building envelope played a significant role on the performance of radiant cooling. Finally they found that it is possible to design a very energy-efficient building. Sanusi et al. [35] examined using the ground as a heat sink with a radiant system for cooling in low-energy buildings. They found that the greatest temperature reduction occurred within a buried pipe at depth of 1 m underground. They also found potential in using Earth Pipe for providing low energy cooling. Chowdhury et al. [36]

explained that a radiant system is a better alternative than pre-cooling or economizer usages to conventional cooling in a subtropical climate. They also found that pre-cooling or economizer did satisfy the current thermal-comfort standards. They also found that low-energy cooling systems can be introduced into office buildings and maintain thermal comfort.

Imanari et al. [37] found that in Tokyo, a radiant cooling panel reduced energy consumption up to 10%. They found that the radiant cooling panel system created a superior radiant environment when cooling and also creates a smaller vertical temperature variation when heating. They also found that the radiant ceiling was preferred by subjects to the conventional heating and cooling system. Sattari and Farhanieh [38] presented a parametric study on radiant floor heating using finite element analysis and found that the type and thickness of the cover were the most important design parameters. They also found that pipe type, pipe diameter, and number of pipes had very little effect on the performance of a radiant floor system. They found that from a design point of view, the optimum floor heating system includes the minimum number of pipes needed to supply a specific hot water flux and consist of a cover with good radiation emission behavior.

The proposed concept is similar to the concept of radiant floor heating and cooling popular in the US [39] to control the cooling and heating load in a building. The main difference is that the radiant heating and cooling system is aimed at increasing the comfort level of the occupants while the proposed system aims to reduce the energy required to satisfy the thermal load of the building.

1.3 Objective

The main objective of this research is to explore the potential of using Increased Thermal Capacitance (ITC) as a passive energy management aimed at reducing the building thermal load. This study investigates the potential of using passive energy management through ITC on the building cooling load by circulating water through a piping system located in the building walls or ceiling. To achieve this objective, the following milestones had to be accomplished:

1. Perform a literature review on the proposed subject.
2. Simulate a reference building with and without the addition of ITC in the walls and ceilings.
3. Analyze the effect of the window-to-wall-ratio on the performance of the ITC implementation on the walls.
4. Analyze the effect of several flow parameters on the performance of the proposed ITC which include the tank size, the mass flow rate of the working fluid, and initial working fluid temperature.
5. Analyze the effect of several design parameters on the performance of the proposed ITC which include the pipe material, pipe wall thickness, location of pipe in the ceiling, and the specific heat of the working fluid.

CHAPTER II

PRELIMINARY STUDY

This chapter investigates the potential of using passive energy management through ITC on the building cooling load by circulating water through a piping system located in the building walls or ceiling and then through a water storage tank. The cooling load obtained from the application of the ITC on the building walls and the ceiling is compared with the cooling load of a reference building without ITC. A reference building, which is located in Atlanta GA, and a building with ITC were simulated using a transient building simulation software, TRNSYS, for the month of May. Several of the flow parameters that affect the performance of the proposed ITC are also analyzed, including the tank size, the mass flow rate of the working fluid, and initial working fluid temperature. In addition, the effect of the window-to-wall-ratio was analyzed for the ITC case in the walls.

2.1 Description of the Simulation Environment

To establish the benefits of using ITC, it is first necessary to create a reference building model to use as a baseline for comparison. Both the reference building and the building with ITC are modeled in TRNSYS [30], which is a simulation program primarily used in the fields of thermal energy engineering and building simulation. Figure 2.1 shows the dynamic model generated in TRNSYS for the reference building. This model, along with the input weather data, is used to estimate the cooling and heating loads of the reference building. The building icon is called Type 56 Multizone Building, which can model thermal behavior of a building. Typical meteorological Year 2 (TMY2) weather data was used in the simulation. TMY2 weather data is a collection of solar radiation and other meteorological elements for various locations in the United States based upon weather over multiple years [40]. During the simulation, TRNSYS calculates the heating and cooling loads (i.e. the energy required for cooling) for the building model.

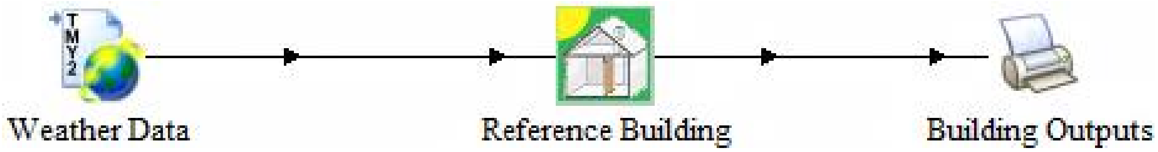


Figure 2.1 Reference building model in TRNSYS

The effect of ITC was determined by modifying the reference building to include proposed ITC in either the walls or the ceiling. Figure 2.2 illustrates the dynamic model of a building with the ITC added in either the walls or the ceiling. For this case, a piping system was inserted into the walls or the ceiling to increase the thermal capacitance of these surfaces. A schematic of the wall with the piping system is shown in Figure 2.3. This figure illustrates how the piping system is placed between the outer and inner material of the wall. Depending on the type of working fluid used, ambient, and zone temperatures, the working fluid can either add or remove energy from the zone,. Adding or removing energy from the zone through increased thermal capacitance (due to the liquid in the pipes and in the storage tank) can reduce the amount of heating or cooling required, respectively. To establish the merit of this idea, a system presented in Figure 2.2 was implemented using an integrated model for thermo-active building elements (e.g. walls and ceilings) in TRNSYS [30]. This thermo-activated building element model is an integrated add-on feature available in Type 56 Multizone Building and is composed of a fluid piping system into a building construction element. The mean fluid temperature in a pipe loop is calculated based on the thermal resistance between the fluid and the pipe shell. The interior and exterior wall surface temperatures are calculated based on the effect of conduction between pipes and building construction material using a two-dimensional conduction analysis. Along with this thermo-activated building, the proposed model also consists of a single speed pump and a vertical tank connected to the building with the purpose of circulating water through the walls or the ceiling. The pump component in the TRNSYS simulation was used to control the working fluid flow rate for the entire system as well as to transmit information such as water temperature and flow rate to the building component. The mathematical model of the different components used in the model can be found in [30]. The building component calculates the water temperature change through the pipes in the walls and then conveys this data to the tank. A thermally insulated vertical tank with a single inlet and a single outlet was selected as the water storage tank. The insulated tank was placed outside the building and exposed to ambient weather conditions.

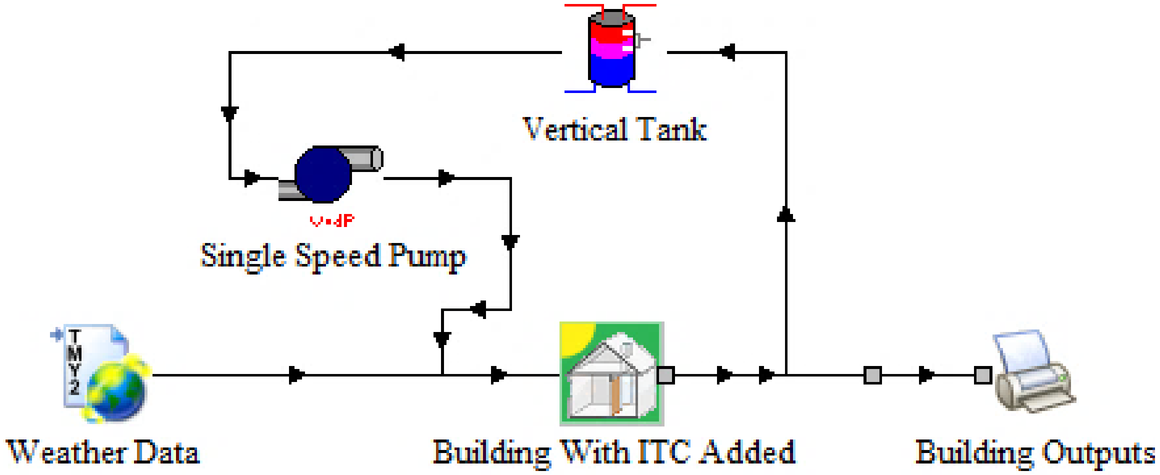


Figure 2.2 Schematic of the TRNSYS model with ITC on the walls or ceiling

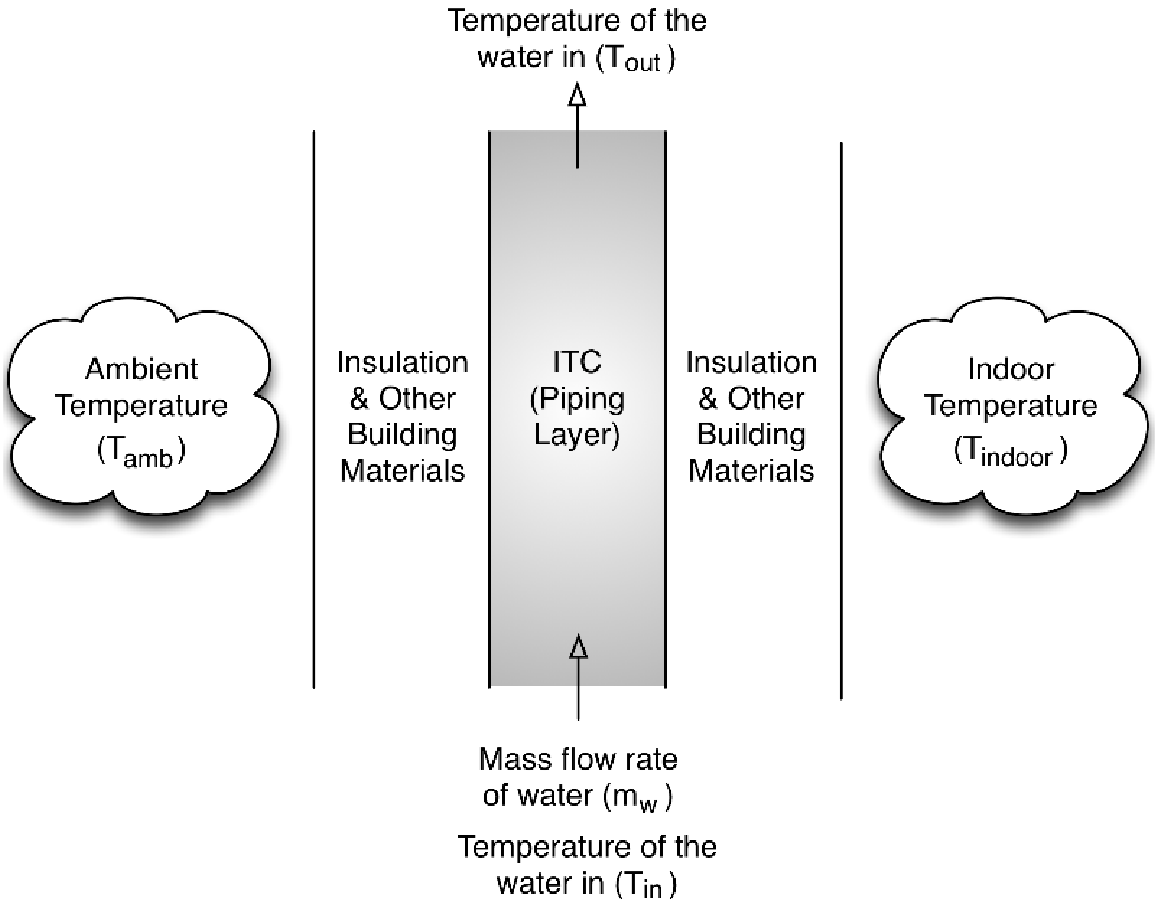


Figure 2.3 Schematic of piping layer in building

Figure 2.4 shows an isometric view of the entire ITC system placed in the ceiling. The working fluid begins in the tank and flows through the pump before entering the ceiling at the top of the wall. The system for the walls would be similar to the ceiling except for the system would continue through each wall and exit at a corner.

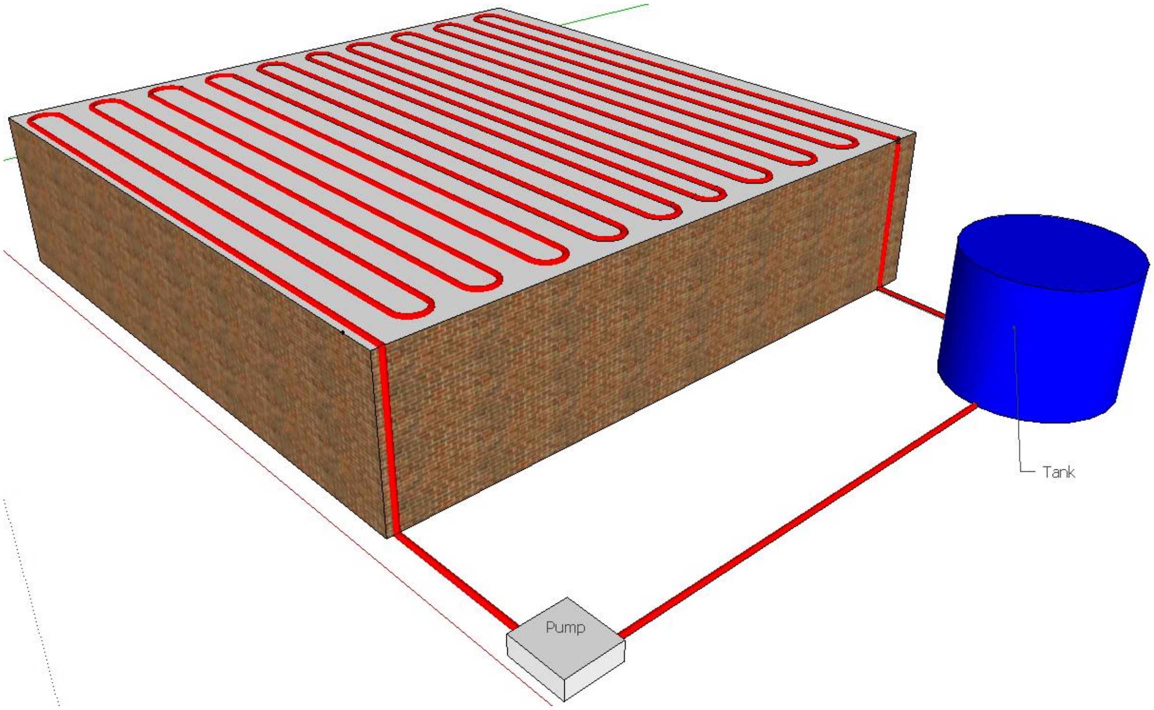


Figure 2.4 Isometric view of ITC system in ceiling

2.2 Results

This section presents the results obtained using the models described in Section 2. Initially, a reference building was simulated to determine the cooling load. Next, the same reference building with ITC added to the walls and then to the ceiling was simulated to investigate the potential benefits from passive energy management through ITC.

2.2.1 Reference building

To establish the potential merit of ITC without introducing additional complexities due to architectural details, a very simple reference building was assumed for this investigation. Thus, at the beginning of this study, the hypothetical reference building was chosen to be a rectangular room with a surface area of 14 m x 14 m, wall height of 3.048 m, and a flat roof without windows. No windows were used initially to allow the most piping possible to be used in the walls. The model for this initial reference building was simulated using the weather data for Atlanta, GA [40] during the month of May. The thermal set points were 21°C and 24°C for heating and cooling, respectively. The lights were scheduled to switch on at 6 AM and be cut off at 6 PM. The lighting power density was assumed at 10 W/m^2. No occupancy was used for this study. The thickness, thermal conductivity, capacity and density of the materials used in the walls are presented in Table 2.1. Table 2.2 shows the material properties for the floor, which also includes a massless layer with a resistance of 25.075 ($m^2 \cdot K/W$), which is one of the predesigned floors available in TRNSYS. The material properties of the roof are shown in Table 2.3. Figure 2.5 shows the cooling load, estimated in TRNSYS, for a week in May, along with the ambient temperature and the indoor zone temperature.

Table 2.1 Building materials for the wall

Material	Thickness (m)	Conductivity (W/m·K)	Capacity (kJ/kg·K)	Density (kg/m^3)
Cinder Block	0.203	0.919	1	1500
Foam Glass Insulation	0.12	0.044	1	100
Gypsum Wall Board	0.013	0.289	1	600

Table 2.2 Building materials for the floor

Material	Thickness (m)	Conductivity (W/m·K)	Capacity (kJ/kg·K)	Density (kg/m^3)
Hardwood Floor	0.203	0.025	1.2	650

Table 2.3 Building materials for the roof

Material	Thickness (m)	Conductivity (W/m·K)	Capacity (kJ/kg·K)	Density (kg/m^3)
Plaster Board	0.01	0.16	0.84	950
Fiber Glass Insulation	0.12	0.04	0.84	12
Roof Decking	0.019	0.14	0.9	530

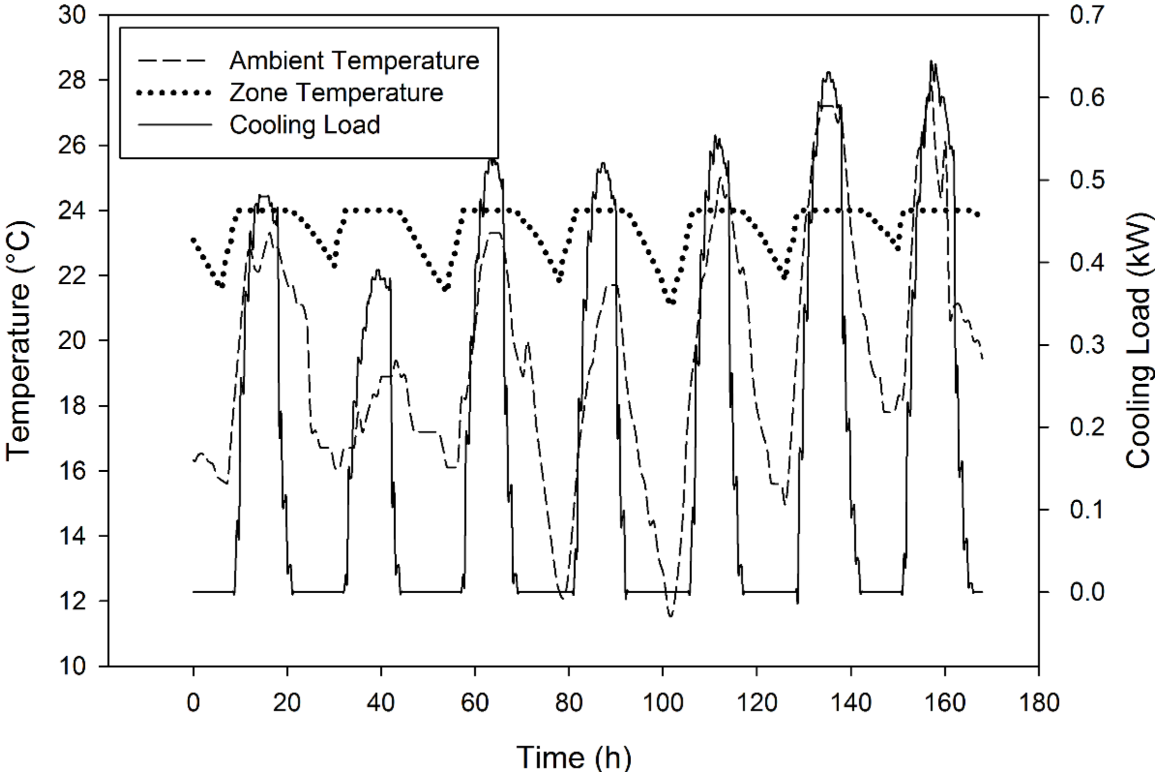


Figure 2.5 Reference building cooling load, ambient and zone temperature for a week in May

Figure 2.5 shows that the cooling load fluctuates with the ambient temperature (e.g. as the ambient temperature rises, the amount of cooling load required increases). The zone temperature remains around 24°C for the week considered, which is the higher limit of the set-point temperature used in the simulations.

2.2.2 ITC added to the walls and ceiling

Once the reference building was analyzed, an ITC (a piping system that circulates water) was placed at the center of the insulation layer in either the walls or the ceiling for comparison to the reference building. The specifications of the piping system used in this paper are shown in Table 2.4.

Table 2.4 Piping system specifications

Pipe Material	Pipe Spacing (m)	Outside Diameter (m)	Pipe Wall Thickness (m)	Conductivity (W/m·K)	C_p of water (kJ/kg·K)
Copper	0.2	0.02	0.002	401	4.18

This section describes the different scenarios that were analyzed. Case 1 considers the reference building described in Chapter 2.1. Case 2 considers a similar configuration of the reference building with ITC placed in each of the four walls and connected in a series configuration entering in the south wall, then west wall, then north, and exiting out the east wall, but not in the ceiling. Finally, Case 3 considers the reference building with ITC in the ceiling but not in the walls. Cases 2 and 3 use the piping layer described in Table 2.4. The parameters used for Case 2 and 3 to simulate the ITC performance in the walls or ceiling are water with a mass flow rate of 500 kg/h, a tank size of 3.785 m^3 (1,000 gal), and initial water temperature of 22°C. The flow rate is the standard set for shower heads by the EPA Act of 1992 [41], with the tank size being selected as typically available size tank. The initial water temperature was assumed as the average ambient ground temperature for the entire year. For this simulation, the mass flow rate was kept constant throughout the day, for simplicity.

Figure 2.6 shows the cooling load for a week in May for the three cases considered in this paper. This figure illustrates that the use of ITC in the walls (Case 2) is able to reduce the peak cooling load from 0.75 kW to 0.72 kW, while for Case 3, the use of ITC in the ceiling reduces the peak load from 0.75 kW to 0.63 kW. The overall reduction of the cooling load for the month of May is 7.3% and 11.1% for Case 2 and

Case 3, respectively. The energy required to operate the pump is already factored in the net cooling load calculations. This net reduction of energy can be directly translated into operating cost (cooling cost) reduction.

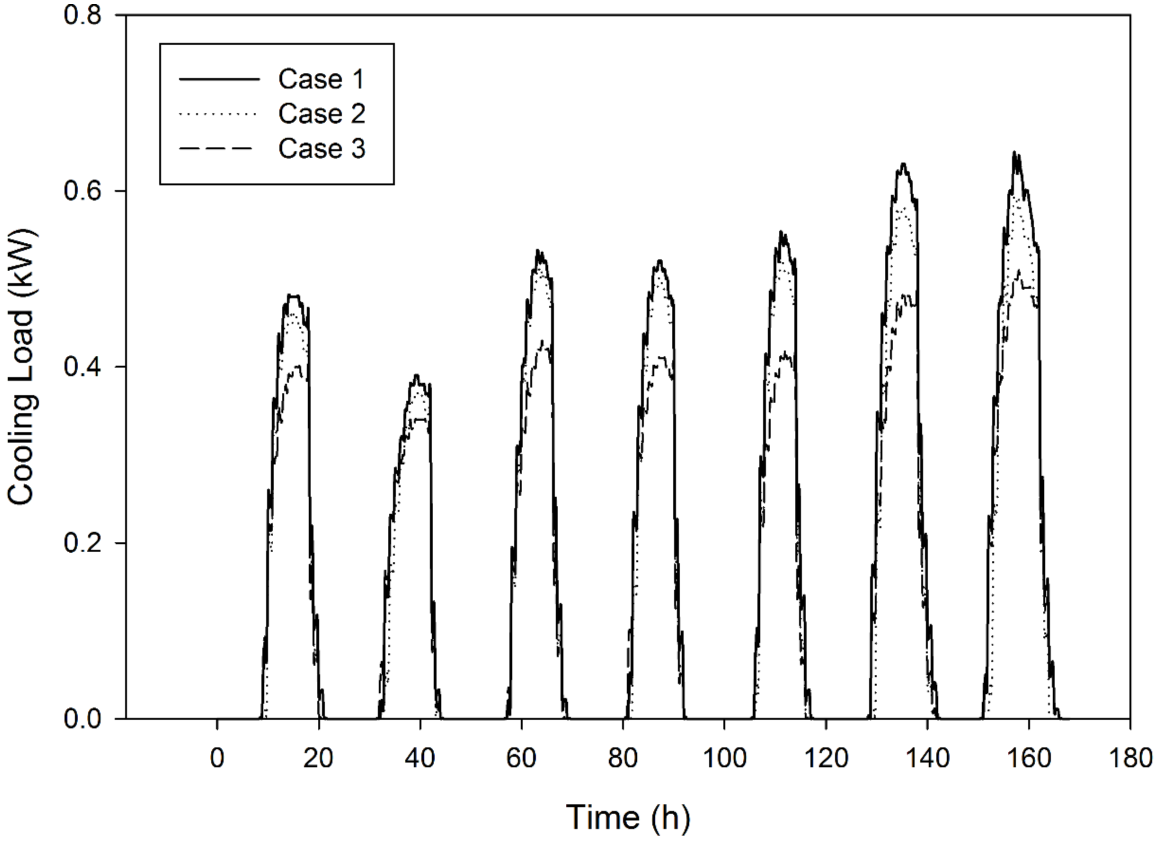


Figure 2.6 Cooling load comparison for a week in May for the three cases evaluated in this paper.

2.2.3 Effect of different flow parameters on the overall performance of the ITC

This section considers the effect of different parameters on the potential of ITC to reduce the cooling load of the building. The parameters considered are storage tank size, water mass flow rate, and the initial temperature of the water in the tank.

2.2.3.1 Storage tank size

The first parameter to be studied is the size of the storage tank. For this analysis, tank sizes of 1.893 m^3 (500 gal) (Size 1), 3.785 m^3 (1,000 gal) (Size 2- the base case from Section 3.2), and 5.678 m^3 (1,500 gal) (Size 3) were used. The values for the rest of the parameters were kept the same as for Case 2 in Section 3.2. Figure 2.7 shows how the cooling load varied with different tank sizes for the first week in May. For the results obtained for the month of May, Tank 1, which is the smallest, has the largest peak for the cooling load for all the cases. For Tank Size 1 the peak load was 0.74 kW (not shown in Figure 2.7). For Tanks Size 2 and Size 3, the peak load is slightly reduced to 0.72 kW for the evaluated month. The total reductions in the cooling load with respect to the reference case for the month of May are 4.2%, 7.3%, and 9.8%, for Tank Sizes 1, 2, and 3, respectively. These reductions already include the power required for the pump. These results clearly indicate that a larger tank is able to provide higher reduction of the cooling load. This variation on the cooling load reduction can be explained by the thermal capacitance of the storage tank; specifically a smaller tank indicates a smaller thermal capacitance, resulting in a larger variation in the temperature of the water in the tank when compared to that of the largest tank.

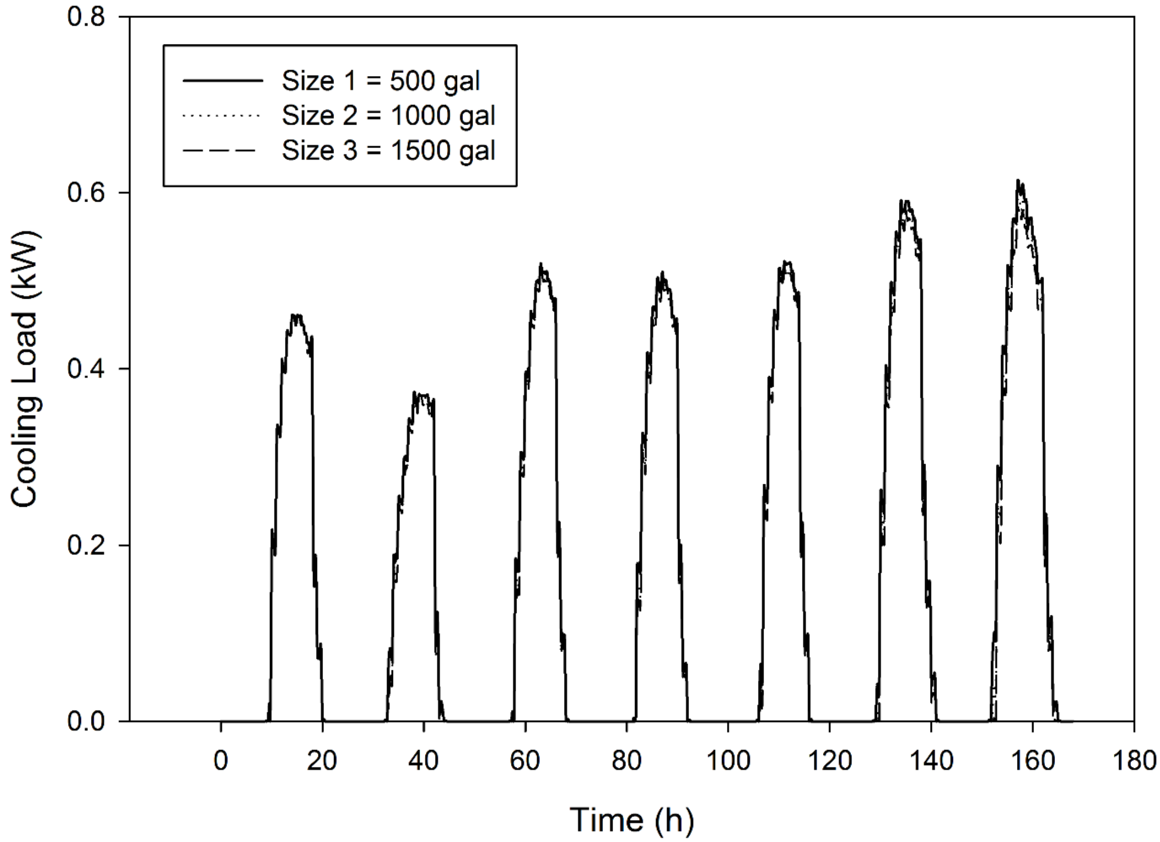


Figure 2.7 Cooling load based on tank size

2.2.3.2 Mass flow rate

The next parameter analyzed was the water mass flow rate. Mass flow rate decreases the resistance to heat flow into or out of the ITC. Similar to the previous case, the tank size evaluation, the values for the other parameters were kept the same as for Case 2 in Chapter 2.2.2. The mass flow rates were set at 100 kg/hr (Flow 1), 500 kg/hr (Flow 2), and 1,000 kg/hr (Flow 3). Figure 2.8 shows the results of this evaluation for the first week in May. The results indicate that for all flow rates, the peak load was about 0.72 kW for the month of May (not shown in Figure 2.8); therefore it can be concluded that the peak cooling load is not significantly affected by varying the flow rate within the evaluated range. However, Flows 1, 2, and 3 reduce the cooling load by 8.9%, 7.3%, and 4.6% respectively, with respect to the reference case. Therefore, the results illustrate that smaller mass flow rates provide better performance in terms of cooling load reduction. These results indicate that as the flow rate in the ITC is increased, the power required for pumping outweighs the gains from cooling load reduction.

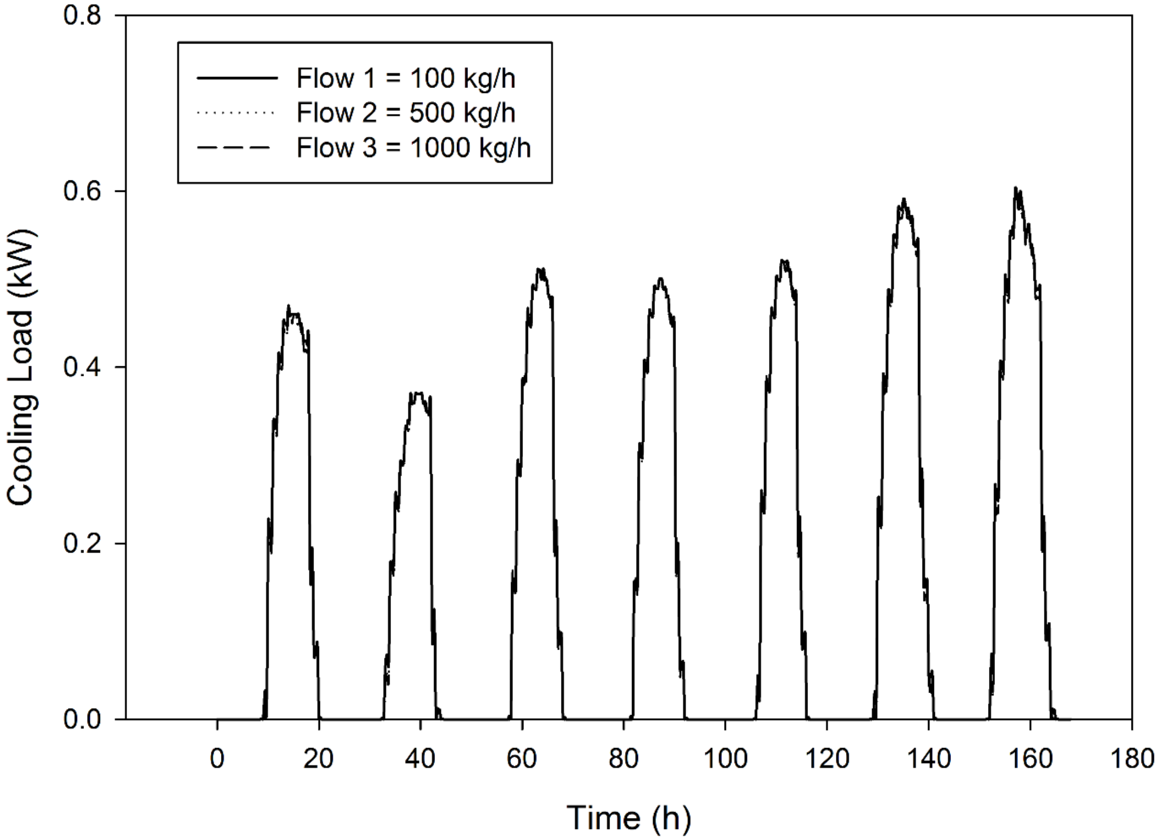


Figure 2.8 Cooling load required based on mass flow rate

2.2.3.3 Temperature

The next analysis was varying the initial temperature of the water. The colder the initial temperature, the larger the temperature gradient between the pipes and the building, which should allow more energy to be removed from the building by the water. For this analysis, initial temperatures of 20°C (Temp 1), 22 °C (Temp 2), the reference case from Section 3.2, and 24 °C (Temp 3) were chosen. Figure 2.9 shows the results of the effect of the initial water temperature for the first week of May. Results indicate that Temp 1, Temp 2, and Temp 3 have approximately the same peak load of 0.72 kW (not shown in Figure 2.9). The overall cooling load for the month of May is reduced by 7.6% for Temp 1, 7.3% for Temp 2, and 7.1% for Temp 3 with respect to the reference case. As expected, the lower temperatures provide significant cooling in the first week, but by the second week of May, the temperature in the tank is the same for all three temperatures.

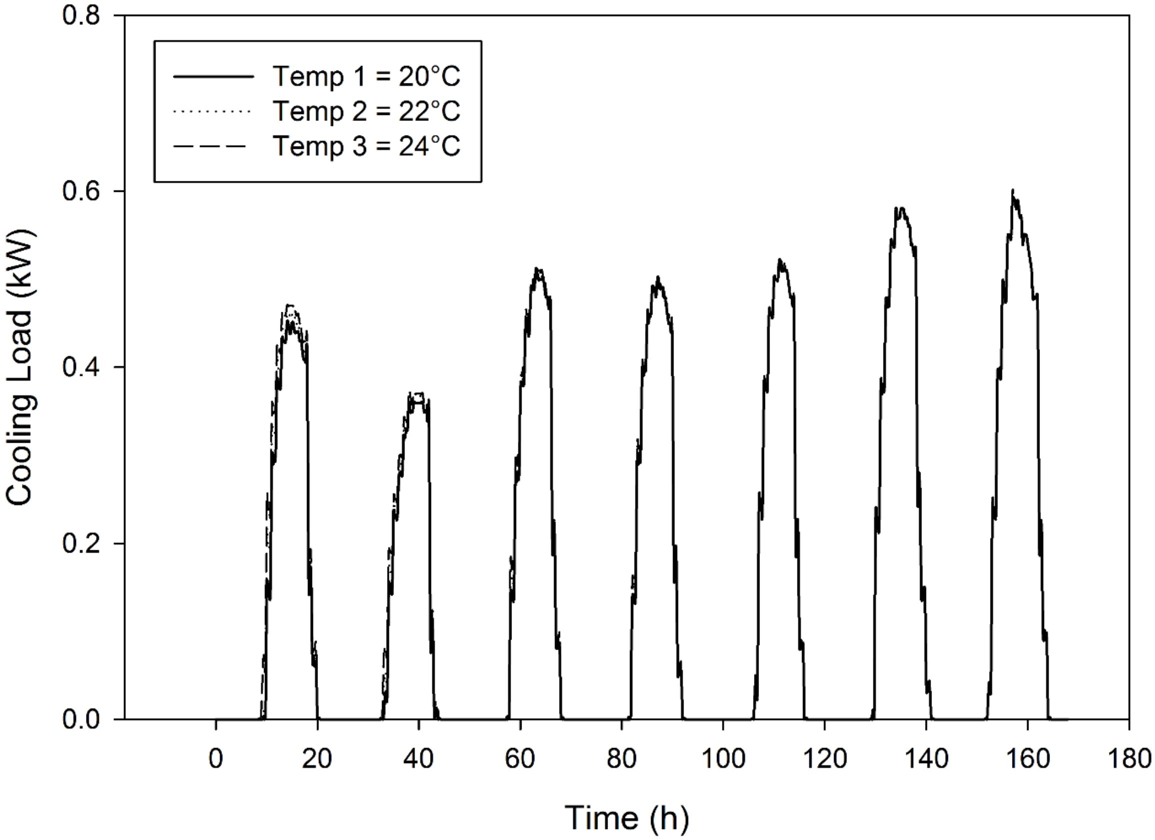
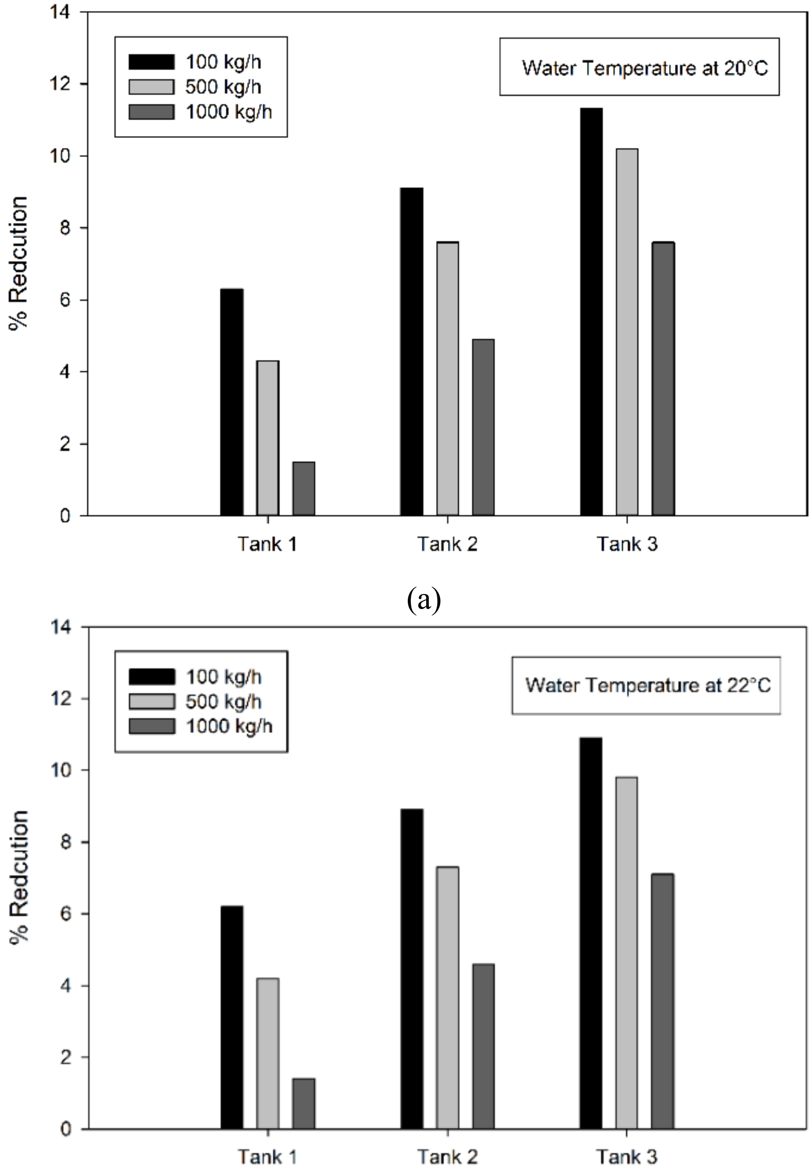


Figure 2.9 Cool load required based on initial temperature

2.2.4 Comparison of the use of the ITC in walls and ceilings

The same analysis presented in Section 3.3 for Case 2 was performed for Case 3 (ITC on the ceiling), and the results are discussed below. Figure 2.10 displays the percentage of cooling load reduction for all the parameter variations considered for Case 2, while Figure 2.11 displays the percentage of cooling load reduction for Case 3.

As can be seen in Figure 2.10, the ITC implementation on the walls was able to reduce the cooling load for all cases. Figure 2.10(a), Figure 2.10(b), and Figure 2.10(c) illustrates that for the same initial temperature of the water in the tank, the largest tank is able to provide the highest reduction of the cooling load. In addition, it can be observed that for the same tank size, improved cooling load reduction is achieved for lower water mass flow rates. The highest reduction in the cooling load (11.3%) was obtained when the mass flow rate was 100 kg/s, with an initial temperature of 20°C for the largest tank (Tank 3). For Tanks 1 and 2, the proposed system was able to reduce the cooling load between 1.5% and 9% for the different combinations. For the smaller tank, the highest reduction was about 9.1%, and it was obtained when the mass flow rate was 100 kg/s for an initial water temperature of 20°C.



(a)

(b)

Figure 2.10 Reduction of cooling load with ITC on the wall

(a) water temperature of 20°C, (b) water temperature of 22°C, (c) water temperature of 24°C

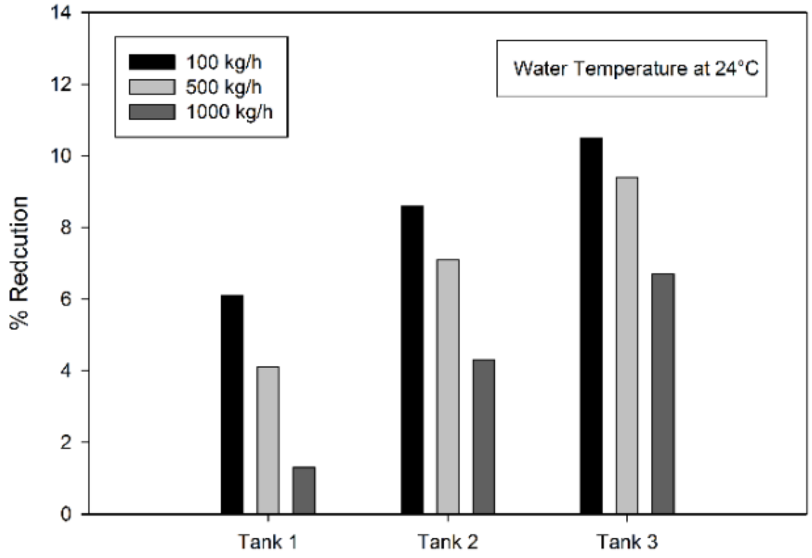
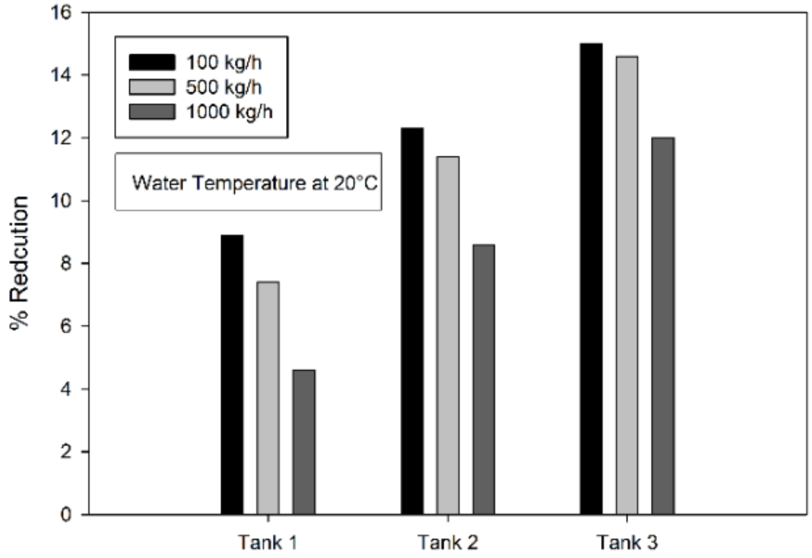


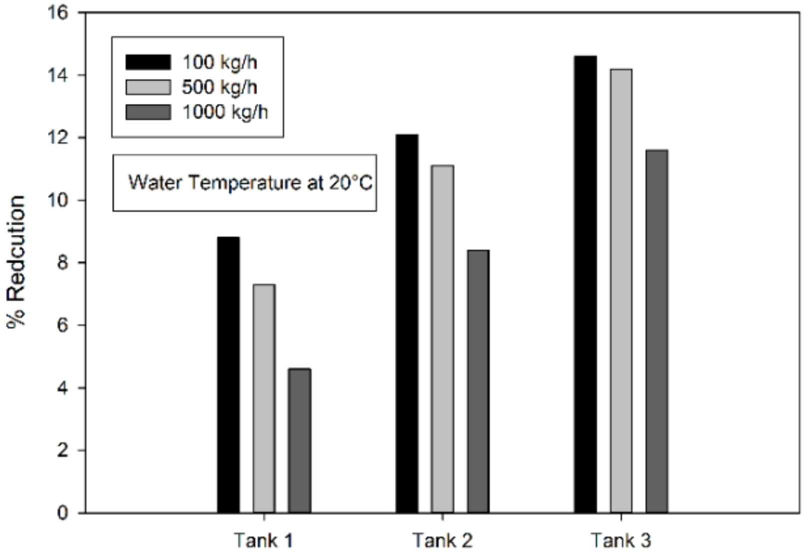
Figure 2.10 (continued)



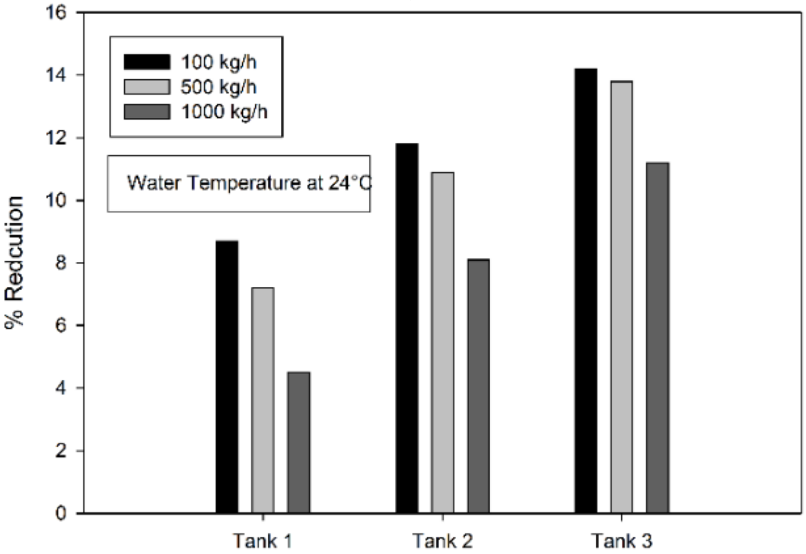
(a)

Figure 2.11 Reduction of cooling load with ITC on the ceiling

(a) water temperature of 20°C, (b) water temperature of 22°C, (c) water temperature of 24°C



(b)



(c)

Figure 2.11 (continued)

Figure 2.11 indicates that the ITC implementation on the ceiling was able to reduce the cooling load for all cases. Similar to the results presented in Figure 2.10, Figure 2.11(a), Figure 2.11(b), and Figure 2.11(c) show that for the same initial temperature of the water in the tank, the largest tank is able to provide the highest reduction of the cooling load. Again, it can be observed that for the same tank size, improved cooling load reduction is achieved for lower water mass flow rates. The highest reduction in the cooling load (15%) was obtained when the mass flow rate was 100 kg/s with an initial temperature of 20°C for Tank 3. For Tanks 1 and 2, the proposed system was able to reduce the cooling load between 4% and 13% for different cases. For these two cases, the highest reduction was about 12.3%, and it was obtained when the mass flow rate was 100 kg/s for an initial water temperature of 20°C.

Comparing the results presented in Figure 2.10 and Figure 2.11, it can be concluded that the implementation of ITC on the ceiling shows more potential to reduce the cooling load for the evaluated month.

2.2.5 Effect of the window-to-wall ratio

The effect of the window-to-wall ratio in the building can significantly affect the cooling load of the building. It is important to remind the reader that the results presented above are for a building with no windows. Therefore, this section examines the effect of adding windows to the building on the performance of the ITC. The same analysis presented in Section 3 for Case 2 is replicated but this time adding windows to the building. By adding windows to the walls, the area available for the piping system inside each wall is reduced, affecting the potential of the proposed ITC to reduce the cooling load of the building. For this analysis, a tank size of 3,785 L water at an initial temperature of 20°C, and a mass flow rate of 500 kg/h were used. Different scenarios in which between 5% and 30% of the wall's area is covered by windows are analyzed in this section. The reduction of the cooling load from the ITC with respect to the reference case with the same window-to-wall ratio is compared and presented in Figure 2.12. It is important to note that the same types of windows are used in the scenarios being compared. Thus the heat transfer efficiency of the windows would affect both scenarios in the same manner.

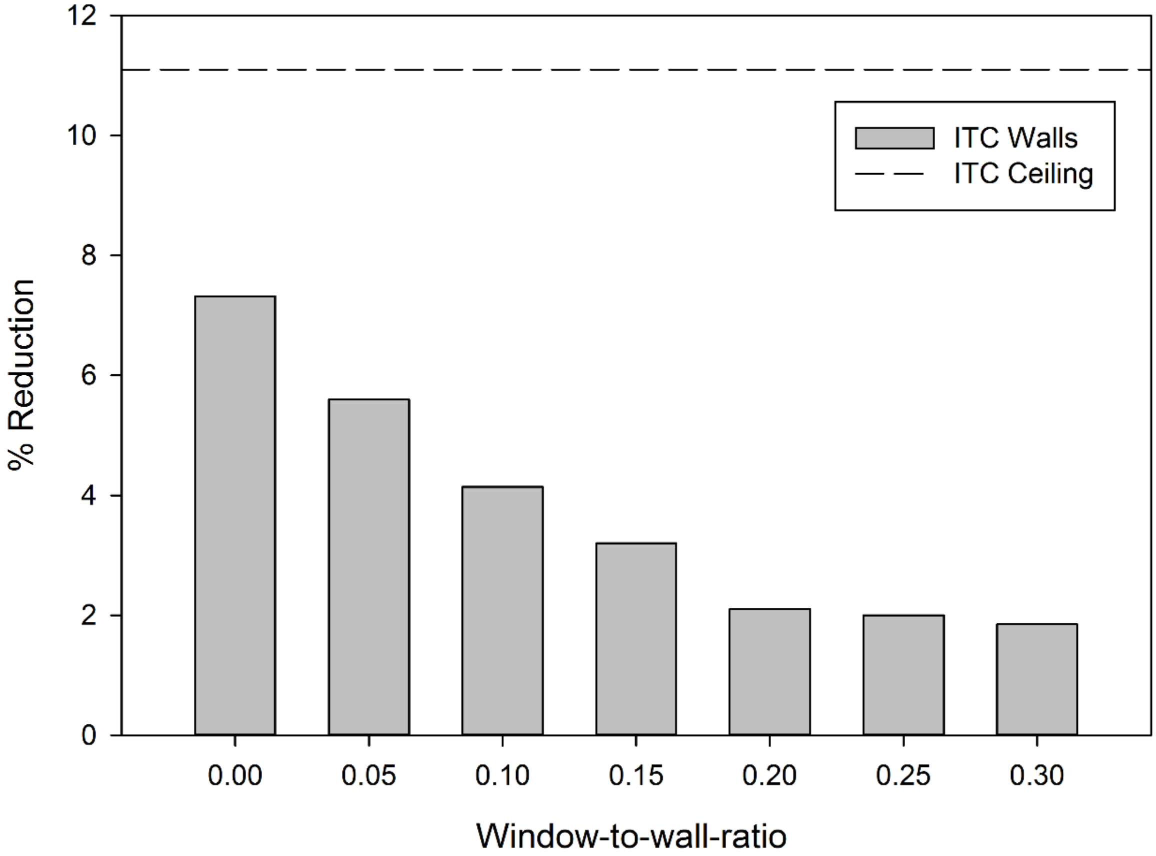


Figure 2.12 Effect of the window-to-wall ratio on the potential of ITC to reduce the building cooling load

As can be seen in Figure 2.12, the potential to reduce the cooling load decreases with increased window-to-wall-ratio. For a window-to-wall-ratio of 0.1 the ITC is able to reduce the cooling load by 4.1%, which is a decrease compared with the case of no windows (7.3%). The reduction of cooling load decreases to 1.9% for a window-to-wall-ratio of 0.3. This can be explained since the overall area for placing the piping of the ITC system is reduced. The dashed line shown in Figure 2.12 represents the reduction of the cooling load obtained when the ITC is used in the ceiling (Case 3) obtained in Section 3.2 (11.1%). This figure clearly emphasizes one of the advantages of using the ITC in the ceiling instead of the walls. Realistically, a building will have windows; therefore, the ITC in the walls may not be that effective as compare with the ITC in the ceiling.

2.3 Conclusion

This chapter investigated the potential of using passive energy management through ITC on the building cooling load by circulating water through a piping system located in the building walls or ceiling. The cooling load obtained from the application of the ITC on the building walls and the ceiling was compared with the cooling load of a reference building without ITC. A building with and without ITC was simulated in TRNSYS for the month of May using the weather data of Atlanta, GA. Several parameters, such as the effect of the tank size, the mass flow rate of the working fluid, and initial working fluid temperature were also analyzed to evaluate the performance of the proposed ITC. In general, for the analyzed cases, the implementation of ITC in the walls has the potential of reducing the cooling by around 7% for a building with no windows and by about 11% when the ITC is implemented in the ceiling. In addition, the effect of the window-to-wall-ratio was analyzed for the ITC case in the walls. It was found that as the window-to-wall ratio increases, the amount of the ITC's potential cooling energy savings decreases. In general, the analysis results indicate that the application of ITC reduces the cooling load, with an application in the ceiling being the best scenario. This paper showed that the use of passive energy management through ITC has a good potential application to reduce the building cooling load and therefore the energy required to operate the building.

CHAPTER III

PARAMETRIC ANALYSIS OF PASSIVE ENERGY MANAGEMENT THROUGH INCREASED THERMAL CAPACITANCE

This chapter evaluates the influence of several parameters on the potential of using ITC as a passive energy management system to decrease the building cooling load by circulating water from a storage tank through a piping system located in the building's ceiling. The cooling load of the ITC-enhanced building is compared to the cooling load of a reference building with no form of ITC. TRNSYS is used to simulate both the ITC enhanced building and the reference building for the month of May in the city of Atlanta, GA. Then several design parameters that affect the performance of the ITC are analyzed, including the pipe material, pipe wall thickness, location of pipe in the ceiling, and the specific heat of the working fluid.

3.1 Description of the Simulation Environment and Building

This chapter will use the same building as described in Chapter 2 with the exception that the roofing insulation layer thickness was increased from 0.12 m to 0.16 m, due to requirements in the simulation software. The simulation environment will be similar to the environment used in Chapter 2, with only the reference building and building with ITC in the ceilings being simulated based on results obtained in Chapter 2.

3.2 Results

This section presents the results obtained using the models described in Chapter 3.1. First, a reference building was simulated to determine the building's cooling load. Then, the same reference building with ITC added to the ceiling was initially simulated to establish the benefits of passive energy management through ITC in the updated building. After the benefits were established, several parameters that may influence the benefits obtained from ITC are evaluated. These parameters include the pipe material, pipe wall thickness, location of pipe in the ceiling, and the specific heat of the working fluid.

3.2.1 New Reference building

The new reference building with the insulation layer thickness was simulated to establish a new baseline for comparison. Figure 3.1 displays the cooling load, estimated in TRNSYS, along with the indoor zone temperature and ambient temperature for the first week in May, with a week time period chosen so the temperature profiles could clearly be appreciated. As is shown in Figure 3.1, the cooling load varies with the ambient temperature, and the indoor zone temperature remains around 24 °C throughout the day and sinks at night, similar to the results shown for the reference building in Chapter 2.

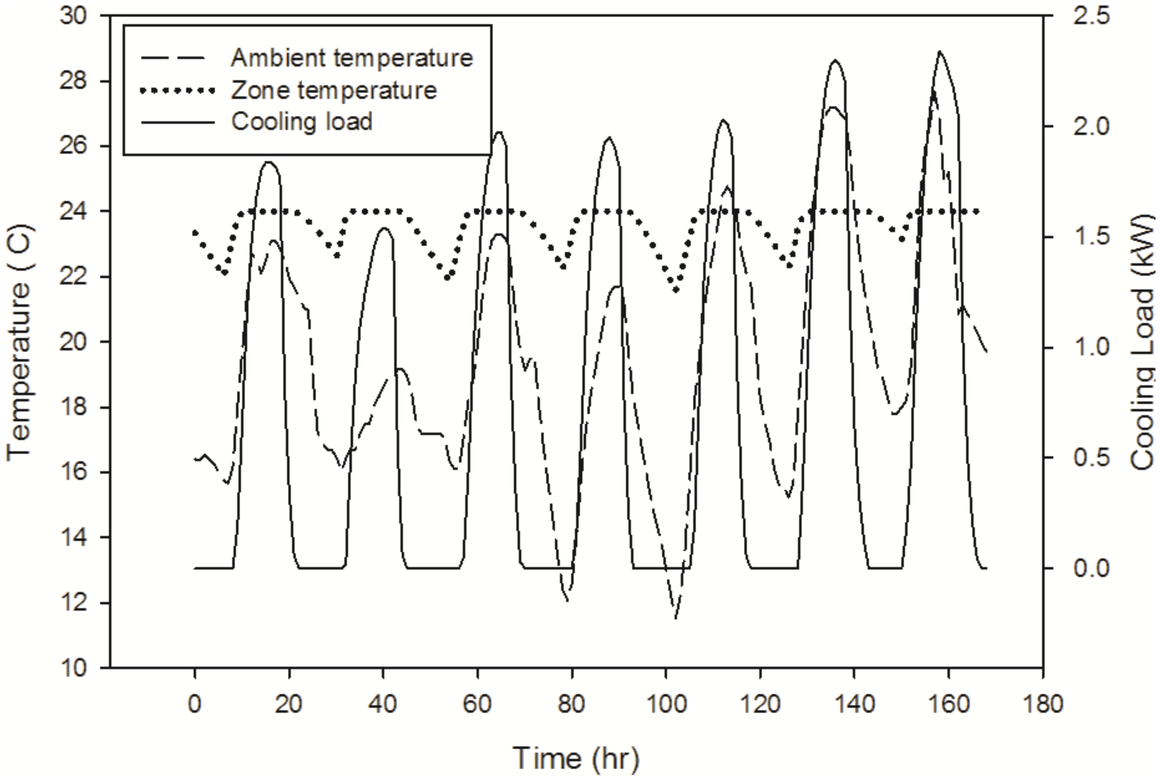


Figure 3.1 New reference building cooling load, ambient and zone temperature for a week in May

3.2.2 ITC added to the ceiling

Once the reference building was analyzed, the ITC was placed in the insulation layer of the ceiling for comparison with the reference building. This section compares the new reference building described in Chapter 3.1 (Case 1) with a similar configuration with ITC placed in the ceiling of the new reference building (Case 2). To simulate Case 2, the TRNSYS model described in Chapter 2 with a mass flow rate set at 150 kg/h, a tank size of 3.785 m^3 (1,000 gal), and an initial working fluid temperature of 20 °C was used. Table 3.1 shows the information of the piping system used to simulate Case 2. For this case, the piping was positioned at the center of the insulation layer in the ceiling.

Figure 3.2 presents a comparison of the cooling load required for a week in May between the Case 1 and 2.

Table 3.1 Piping system specifications for new building

Pipe Material	Pipe Spacing (m)	Outside Diameter (m)	Pipe Wall Thickness (m)	Conductivity (W/m·K)	C_p of water (kJ/kg·K)
Copper	0.2	0.022	0.002	401	4.18

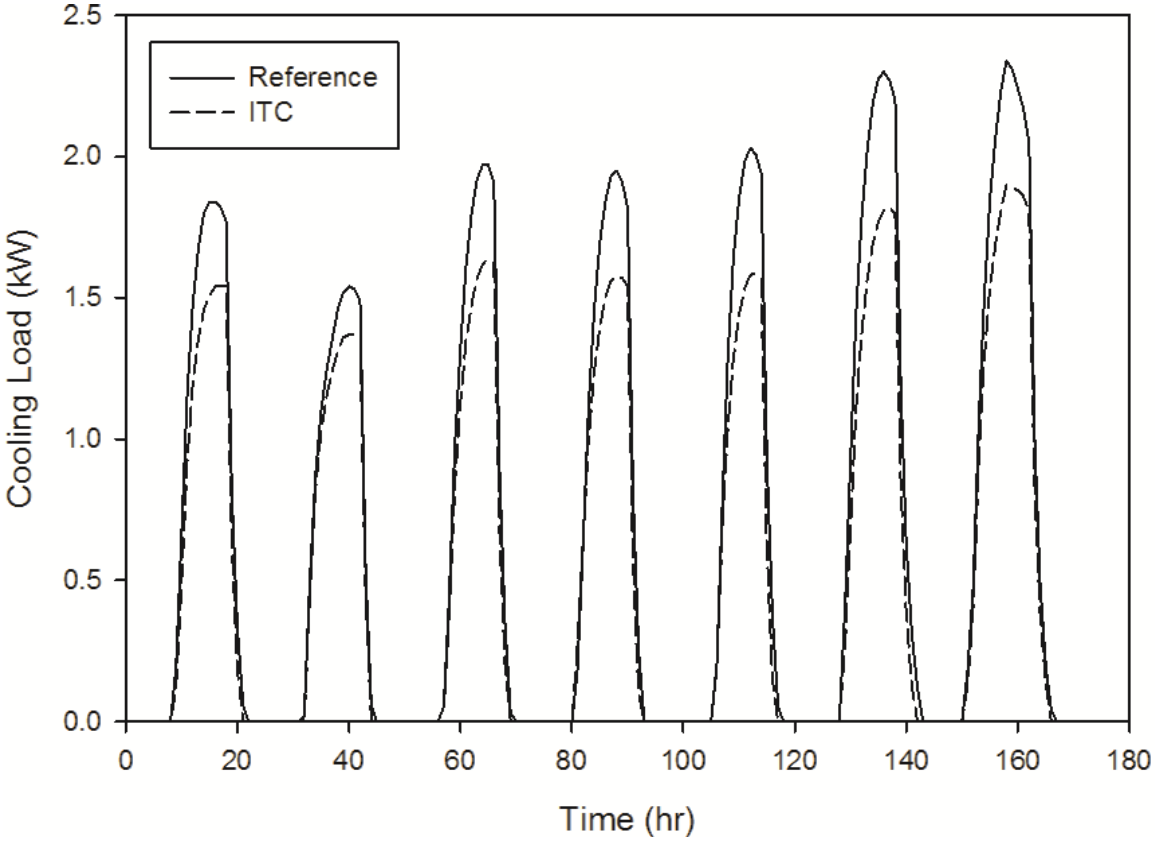


Figure 3.2 Cooling load comparison for a week in May for the two cases evaluated in this paper

Figure 3.2 shows that the peak cooling load for each day of the selected week is reduced with the addition of the ITC system in the ceiling. The peak load for the month is reduced from 2.74 kW to 2.36 kW (which is not shown in the figure) with the total cooling load being reduced by 11.6%. The energy required for pumping the working fluid is included in the net cooling load calculations. By reducing the amount of energy needed for cooling, the net operating cost is also reduced.

3.2.3 Effect of different design parameters on the overall performance of the ITC

This section considers the sensitivity of different parameters on the benefits of using ITC to reduce the cooling load of a building. The parameters considered are pipe material (thermal conductivity), pipe wall thickness, location of the piping system in the ceiling insulation, and the specific heat of the working fluid.

3.2.3.1 Pipe material

The first parameter to be analyzed is the thermal conductivity of the pipes. A higher thermal conductivity should increase the amount of energy added to or removed from the building. The thermal conductivity was varied between 1 W/m·K, which is close to the thermal conductivity of PVC, and 400 W/m·K, which is close to the thermal conductivity of copper. All other parameters were kept the same as described in Chapter 3.2.2. Figure 3.3 shows the amount of cooling load reduction due to thermal conductivity for the month of May. The reduction varies from about 11.52 % at 1 W/m·K to 11.62 % at 10 W/m·K. However, these results indicate that the thermal conductivity of the pipes does not have a strong influence on the ITC performance and therefore on the total cooling load reduction. The small amount of change based on thermal conductivity is due to the insulation’s thermal resistance being much larger than the piping’s thermal resistance. The insulation’s thermal resistance is approximately 10 times greater than the piping’s resistance; thus the greatest temperature change is through the insulation layers. This causes the temperature distribution through the piping layer to be similar with regards to piping material. This finding is similar to the results presented by Sattari and Farhanieh [38].

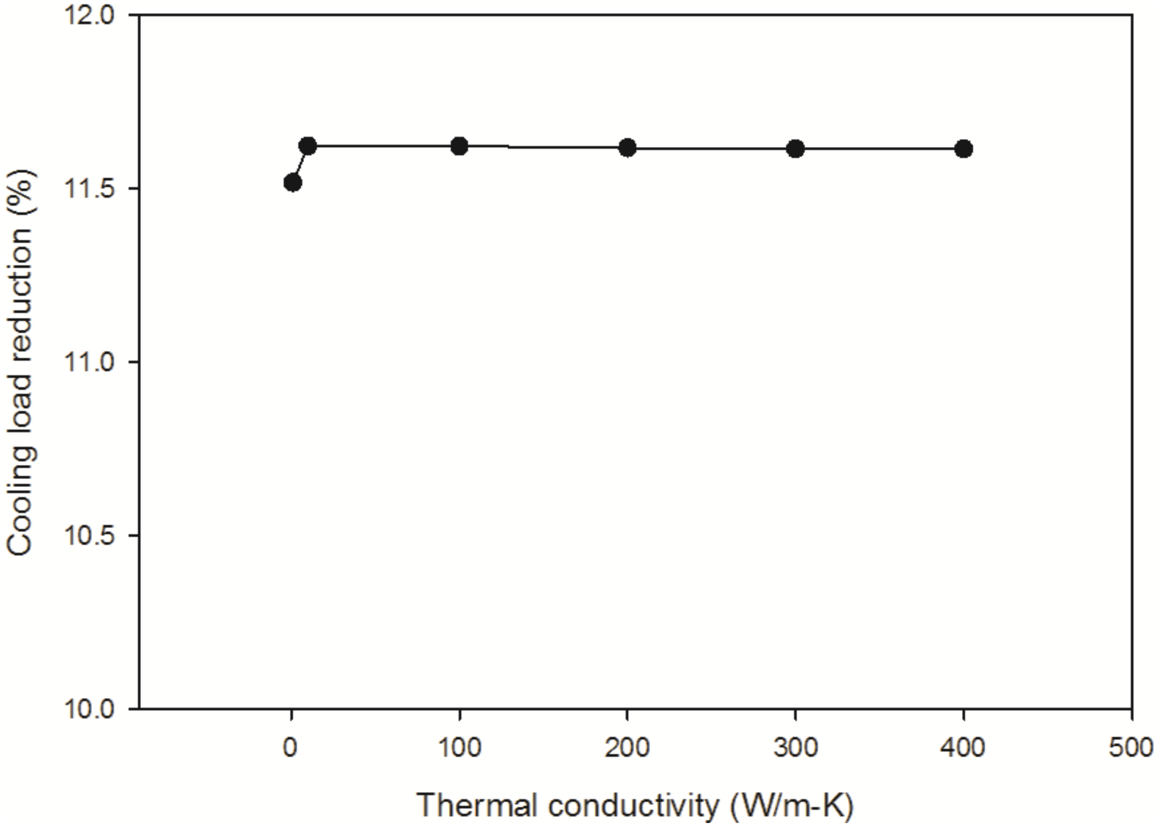


Figure 3.3 Effect of pipe thermal conductivity on performance of ITC

3.2.3.2 Pipe wall thickness

Next pipe wall thickness was analyzed by varying the outer diameter of the pipes. Pipe wall thickness increases the resistance of heat flow into or out of the ITC. The wall thickness was varied from 0.0016 m (1/16 in) to 0.0064 m (1/4 in). Similar to the thermal conductivity evaluation, the values of the other parameters were kept the same, as described in Chapter 3.2.2. Figure 3.4 shows the cooling load reduction based on pipe wall thickness for the month of May. The potential to decrease the cooling load increases linearly with increasing the pipe wall thickness. The cooling load reduction varies from 11.43% at 0.0016 m (1/16 in) to 12.03% at 0.0064 m (1/4 in). This can be explained by the critical radius, where the inner radius is smaller than critical radius of conduction to convection. This causes a reduction in the total thermal resistance so that the heat transfer rate increases with a larger pipe wall thickness.

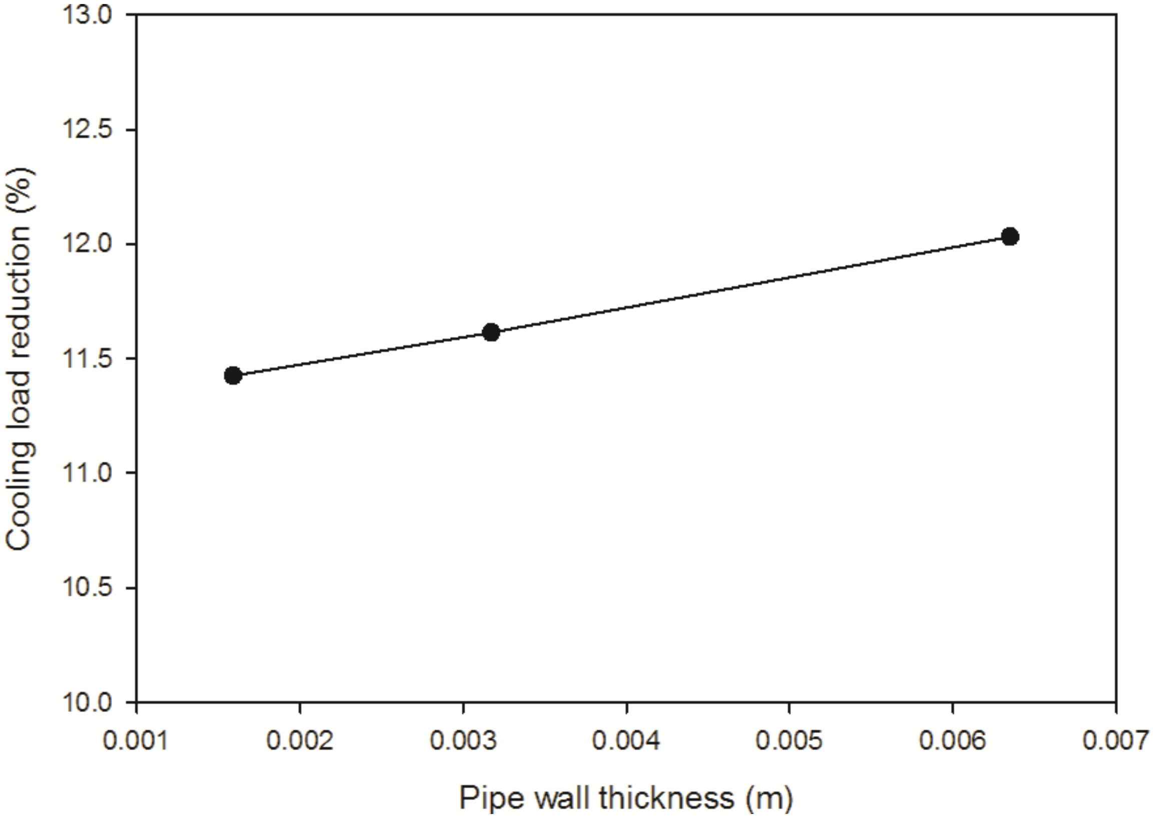


Figure 3.4 Effect of pipe wall thickness on performance of ITC

3.2.3.3 Location of the ITC in the ceiling

The next parameter analyzed is the location of the ITC layer in the ceiling. By changing the location of the piping system inside the insulation layer more heat can be drawn from either inside the house or outside the house. The location of the piping system inside the insulation is shown in Figure 3.5.

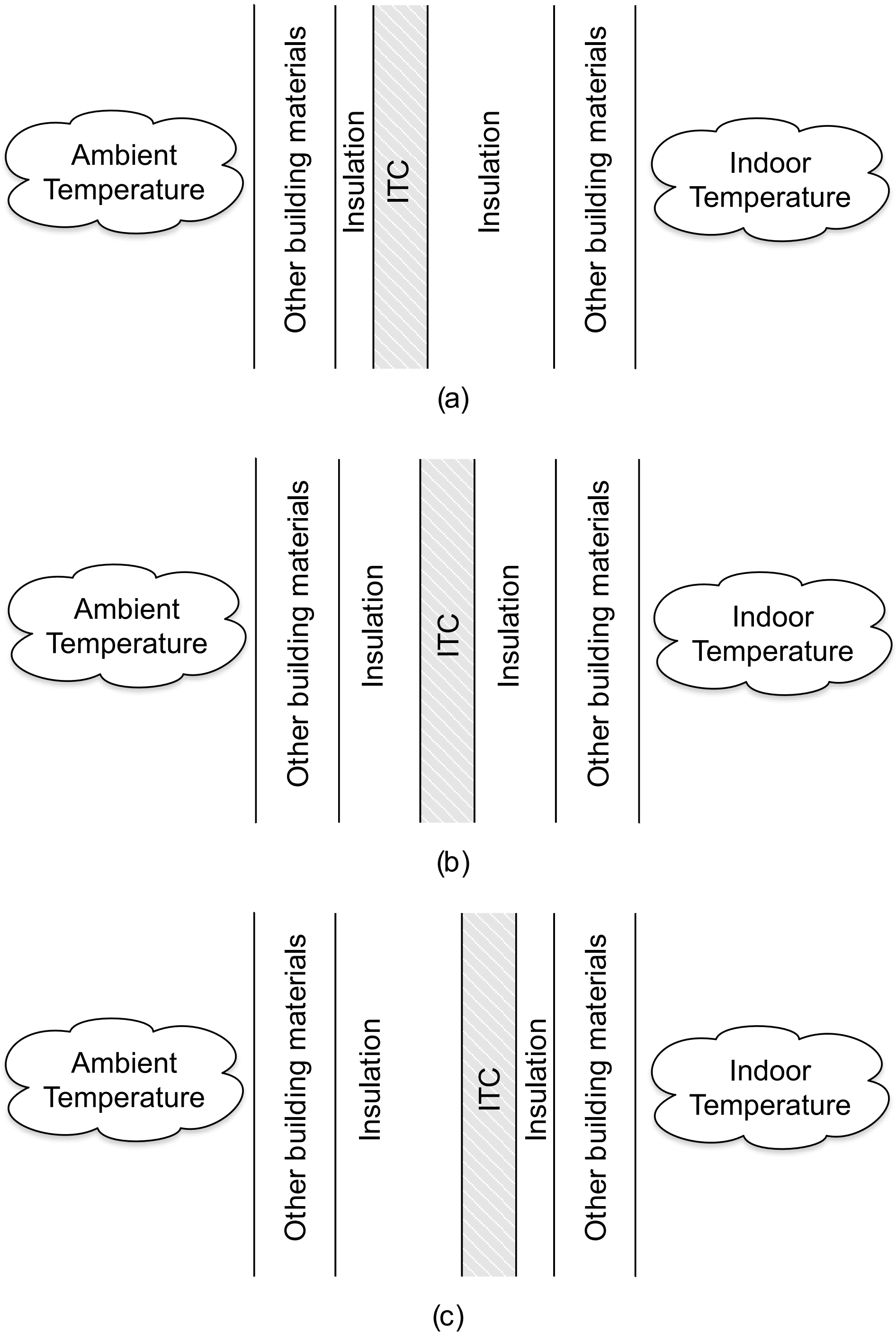


Figure 3.5 Model of location of pipe in insulation layer

In Figure 3.5(a), the piping system is closer to the exterior, in Figure 3.5(b), the piping system is in the center, and in Figure 3.5(c), the piping system is closer to the interior. The values of the other parameters were the same as described in Chapter 3.2.2. Figure 3.6 shows the cooling load reduction based on pipe location in the insulation layer for the month of May. Figure 3.6 illustrates that the locating the piping system closer to the interior of the building provides more benefits in terms of cooling load reduction. The cooling load is reduced from 9.10% at 0.06 m, which represents the ITC located closer to the exterior, to 14.05% at 0.1 m, which represents the ITC located closer to the interior. . This maintains a lower fluid temperature in the ITC, which allows the ITC to provide more benefits throughout the evaluated month.

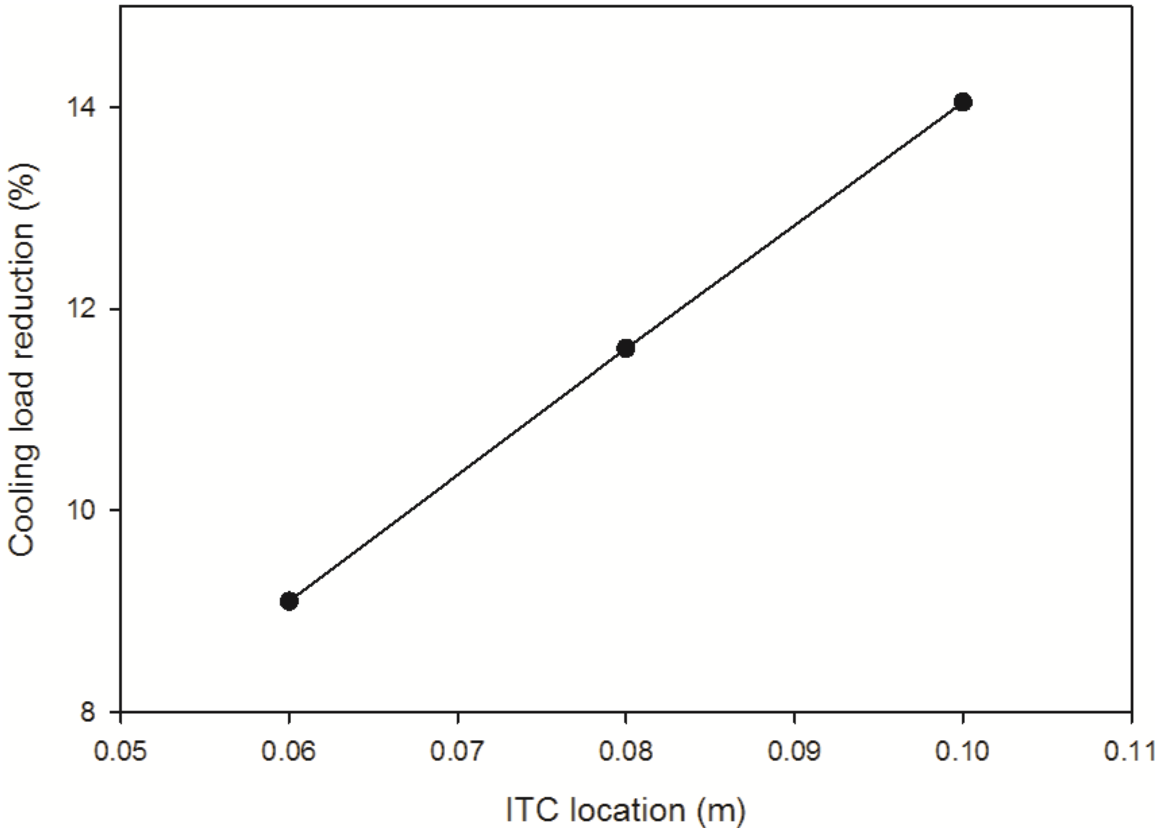


Figure 3.6 Effect of pipe location in insulation on performance of ITC

3.2.3.4 Specific heat of working fluid

The next parameter to be analyzed is the type of working fluid used in the ITC. In this paper, this is evaluated by varying the specific heat of the working fluid to determine the effect on the ITC performance. By increasing the specific heat of the working fluid, the total capacitance of the ITC should increase. The specific heat is varied from 3 kJ/kg·K to 10 kJ/kg·K, below and above the specific heat of water (4.18 kJ/kg K). The other parameters will be the same, as described in Chapter 3.2.2. Figure 3.7 shows the cooling load reduction based on the specific heat of the working fluid for the month of May as the specific heat of the working fluid increases, the amount of cooling load required decreases. The cooling load reduction goes from 10.83% at 3 kJ/kg·K to 13.53% at 10 kJ/kg·K. This could be explained by specific heat affecting the total thermal capacitance specifically, as the specific heat rises, the total thermal capacitance increases.

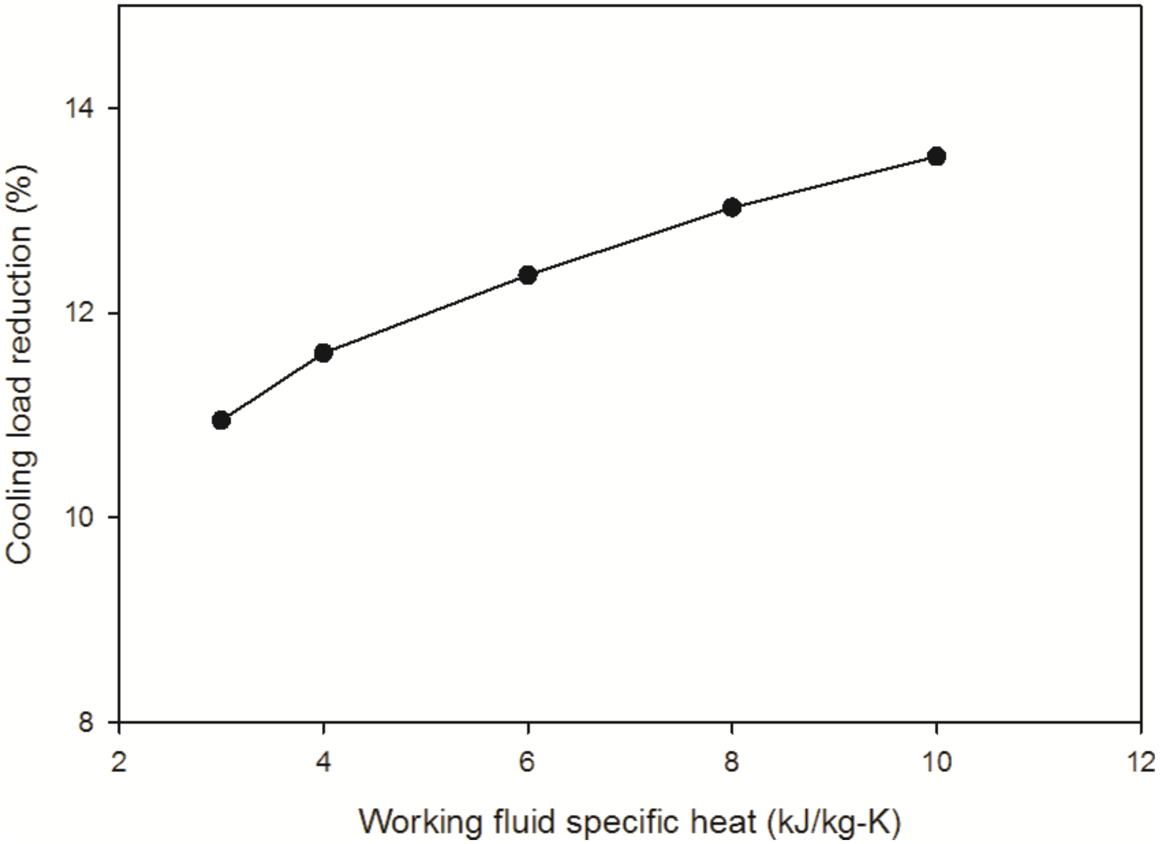


Figure 3.7 Effect of working fluid's specific heat on performance of ITC

3.3 Conclusion

This chapter examined the effect of several parameters on the benefits of using ITC as a passive energy management system to reduce the cooling load of buildings. A hypothetical reference building was simulated in Atlanta, GA for the month of May to get a base cooling load for comparison. An ITC system was then added to the reference building and simulated to verify that the cooling load was reduced. Several key parameters, such as pipe thermal conductivity, pipe wall thickness, pipe location in the ceiling, and specific heat of the working fluid were analyzed to assess the influence of each parameter on the performance of the ITC. Results indicate that the piping thickness and piping thermal conductivity do not have a strong influence on the benefits that could be obtained from the ITC application since the reduction of the cooling load stays around 11% while varying these two parameters. On the other hand, the analysis showed that the location of the piping system within the insulation layer is the parameter that has more influence on the ability of the ITC to reduce the cooling load. Results indicated that the piping system should be located closer to the interior to obtained most benefits from ITC. The cooling load is reduced from 9.10% (ITC located closer to the exterior) to 14.05% (ITC located closer to the interior). Similarly, the specific heat of the working fluid can significant affect the benefits obtained from ITC. For the evaluated case, the cooling load reduction increased from 10.83% at 3 kJ/kg·K to 13.53% at 10 kJ/kg·K. In general, based on the results obtained in this paper, the piping system should be located closer to the interior and use a working fluid that has a high specific heat.

CHAPTER IV

CONCLUSION

In this research the use of ITC as a new passive energy management system on a building's cooling load by circulating water through a piping system located either in the building's walls or ceiling was investigated. A building with and without ITC was simulated in TRNSYS for the month of May in Atlanta, GA. Then, several flow parameters, such as tank size, working fluid mass flow rate, working fluid initial temperature were analyzed. An analysis was conducted to measure the effect of window-to-wall ratio on the performance of ITC on the walls. Finally, design parameters such as pipe material, pipe wall thickness, location of piping in the ceiling, and working fluid's specific heat were analyzed for their effect on the performance of ITC on the ceiling.

In Chapter 2 the cooling load obtained from the reference building was compared to the building with ITC in either the building's walls or ceiling. After the initial comparison several flow parameters, such as the effect of tank size, the mass flow rate of the working fluid, and initial temperature of the working fluid were analyzed to evaluate the performance of the ITC. The performance of ITC on the walls showed a potential of reducing the cooling load by 7% for a building with no windows and by about 11% when the ITC is implemented in the ceiling. The performance of the proposed ITC improved by increasing the tank size. On the other hand, the performance of the ITC decreased with higher mass flow rates. The initial fluid temperature had little effect on the performance of the ITC in either the walls or the ceiling. In addition, the effect of the window-to-wall ratio was analyzed for the ITC case in the walls. It was found that as the window-to-wall ratio increases the amount of potential cooling energy savings decreases. In general, the implementation of ITC on the ceiling provided the best results and is considered the best scenario for application.

In Chapter 3, the effect of several design parameters were analyzed on the performance of ITC in the ceiling with the ceiling being chosen based upon results from Chapter 2. The design parameters analyzed in this study were pipe thermal conductivity, pipe wall thickness, pipe location in the ceiling, and specific heat of the working fluid. Results indicated that pipe thermal conductivity and pipe wall thickness do not have a strong influence on the benefits that could be obtained from ITC application, with the cooling load reduction remaining around 11% for both. However, the analysis showed that the location of the pipes within the insulation layer is the parameter that has more influence on the ability of the ITC to reduce the cooling load. The results indicated that the piping system should be closer to the interior to obtain the greatest benefit from the ITC. The cooling load reduction increases from 9.10% (ITC located closer to the exterior) to 14.05% (ITC located closer to the interior). Similarly, the specific heat of the working fluid affects the benefits obtained from ITC. For the evaluated case, the cooling load reduction increased from 10.83% at 3 kJ/kg·K to 13.53% at 10 kJ/kg·K. Based on the results it can be concluded that the piping system should be located closer to the interior and use a working fluid with a high specific heat.

Future research has to be performed to get a more detailed cost comparison to determine the economic feasibility of the proposed system as well as to examine alternative configurations and operation modes for the ITC system which may result in additional savings. Suggestions for future research include variable flow rates throughout the day, geothermal piping for cooling the working fluid, and night cooling through the use of solar panels.

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