Energy Analysis of Using Thermal Mass in a Hot Humid climate

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Abstract: - The passive design strategy of using thermal mass has been shown to reduce building loads in certain climates. This paper aims to illustrate the ways that high-mass walls can be used in hot-humid climates to reduce heating and cooling loads. By considering various codes and standards a baseline model was developed and simulated in *EnergyPlus* to assess the savings associated with altering wall constructions. Three design strategies have been analyzed: first, the use of high-mass exterior walls as compared to low-mass, second, the use of high-mass interior walls and third, the placement of high-mass walls on different building faces. The results show that interior thermal mass is the most energy efficient strategy, saving up to 0.14 \$/m^2. In addition, any orientation of thermal mass can save energy; however, the savings are not significant.

Key-Words: High-mass walls, low-mass walls, heating loads, cooling loads, total cost savings

1 Introduction

In the United States, commercial buildings account for under one-fifth of the total energy use and consume about 35% of the total US electricity [11]. With an increasing cost of energy, it is vital to design more energy efficient buildings. The application of thermal mass is a passive design strategy that enables building materials to absorb, store, and gradually release heat at a later time. In climates with a large daily temperature fluctuation, the use of thermal mass has contributed to the lowering of heating and cooling loads [7]. Since Austin has a hot-humid climate, it does not exhibit large fluctuations in outdoor temperatures. This can compromise the effectiveness of thermal mass. As a result, the goal of this research is to assess the impact of thermal mass in this climate zone.

There is substantial literature on the application of thermal mass and its impact on indoor thermal behavior. For example, Di Perna et al. conducted a research that analyzed the effect of thermal mass on indoor temperature in a moderate climate. This research is based on an experimentation and energy simulation of a case study [6]. However, there are limited studies conducted for hot-humid climates. The following two articles have analyzed the impact of thermal mass for indoor temperature control in a hot-humid climate. One was based on experimental research and investigated the impact of thermal mass and light colored walls on a small room [4]. The second paper was based on extensive calculations and investigated the impact of natural ventilation and thermal mass with varying the placement of insulation [13]. Most studies, including the three mentioned papers, have concluded that thermal mass saves energy. However, these studies analyzed the effect of thermal mass on the indoor temperature and did not extend the results to the cooling/heating loads and total costs. Moreover, the base models are either case studies or not developed based on the ASHRAE 90.1 standard, American Society of Heating, Refrigerating and Air-Conditioning Engineers. The results of case studies are not generalizable while most of the energy codes and programs require an accurate simulation with a base model developed by ASHRAE suggestions. As a result, the current study adopts ASHRAE

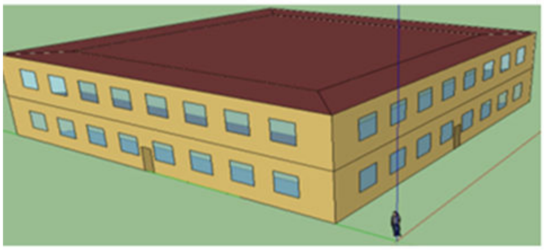

Fig.1 Small building office model

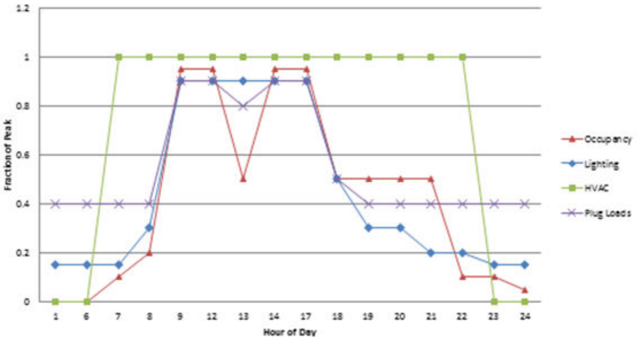

Fig. 2 Weekday schedule

requirements for the base model.

2 Methods

This section describes the methods that were used to analyze the energy savings with the application of a high-mass construction in a hot-humid climate. Initially, a baseline model was developed in terms of the following features: building form and orientation, operation, internal loads (people, lighting, equipment and infiltration) and an indoor temperature set point. Two different envelopes were developed to represent a low-mass construction and a high-mass construction. All other variables, such as the resistivity (R value) of the walls and roof were held constant to measure only the effect of the thermal mass in building loads.

The adopted software simulation in the current study is EnergyPlus version 6.0. According to the US Department of Energy, EnergyPlus is a whole building simulation program that can accurately model energy use in buildings [11]. The software is able to account for thermal mass. To define thermal mass, there is no maximum limit for specific heat and density while the thickness cannot exceed 3 meters [8] [5]. To get an accurate result all the materials and their properties are chosen from EnergyPlus database as specified by ASHRAE Standard 90.1[1].

Initially, the baseline model with all exterior walls as low-mass construction are simulated and compared to the baseline model with all exterior walls as high-mass construction. Second, the effect of different oriented high-mass exterior walls are analyzed as high-mass walls are placed at either north, south, east or west. Third, energy consumption data is collected for having all interior walls set to be constructed as high-mass walls and the exterior walls are considered as low-mass. For all these alternatives the location was Austin, TX. This city is representative of Zone 2A, hot and humid, as defined by ASHRAE Standard 90.1 [3].

3 Development of the Basic Model

The small office model is 1,858 m2 two-story building with dimensions of 30.5m by 30.5m. Shapes and orientations of small offices vary considerably throughout the country; therefore, a square shape is chosen to be orientation neutral (Figure1). This methodology was adopted from a study conducted by the Pacific Northwest National Laboratory for the US Department of Energy [10].

Operating hours are assumed to follow typical office occupancy patterns, with a peak occupancy load from 8am to 5pm weekdays. Schedules for lighting and equipment correspond with the occupancy schedules and adjusted with limited usage during unoccupied times [10]. Figure 2 shows all the schedules used in the simulations.

The air infiltration rate and number of people for the office originate from minimum requirements as specified in ASHRAE Standard 90.1[1]. The infiltration rate is assumed to be 1.9E-04 m3/s·m2. The occupancy is set at 160 people for the entire floor space, which is 11.6 m2/person. The internal lighting set to 11.84 W/m2 [2].

Table 1 HVAC inputs

Outdoor air flow rate per person	.00944 m^3/sec	**Fan total efficiency**	0.7	**Heating Coild Type**	Gas
Minimum outdoor flow rate	.001 m^3/sec	**Cooling coil COP**	3	**Economizer**	No
Cooling coil type	SingleSpeedDX	**Heating coil efficiency**	0.9	**Heat Recovery Type**	Enthalpy

Table 2 Material Properties

		Thickness (m)	**Conductivity (W/mK)**	**Density (kg/m^3)**
Exterior Floor Slab	Heavyweight concrete	0.2	1.95	2240
Interior Floor	Tile	0.01	0.056	380
	Air Space	-	-	-
	Concrete	0.01	1.13	2000
	Tile	0.01	0.056	380
Interior Wall	Gypsum Board	0.0127	0.16	800
	Air Space	-	-	-
	Gypsum Board	0.0127	0.16	800
Roof (R-35)	Metal Roof	0.00076	45.3	7817
	Air Space	-	-	-
	Insulation (Glass Fiber)	0.229	0.036	20
	Gypsum Board	0.0127	0.16	801
Door	Steel	0.003	50	7800
	Air Space	-	-	-
	Steel	0.003	50	7800
	Solar Heat Gain Coefficient	**U-factor (W/m^{2}K)**	**Visible Transmittance**	
Window	0.31	2.56	0.5	

For zoning purposes, each floor of the small office model is divided into 5 thermal zones equaling to a total of 10 zones. For the HVAC system in each zone a unitary packaged system was modeled. We chose this methodology to determine the effect of thermal mass on HVAC load in each zone. The setpoints for the system were defined to maintain a 21˚C for heating and 24˚C for cooling. During unoccupied hours, the thermostat is set to 18.3˚C for heating and 26.7˚C for cooling. Table 1 shows all the assumptions for the HVAC system.

In addition, Table 2 outlines the wall constructions and material properties. According to ASHRAE thermal mass effects are quantified based on a wall's heat capacity and density. In order to analyze only the thermal impacts, the high-mass and low-mass walls have the same resistivity (R value) but their constructions have different materials with different values for thickness, conductivity and density.

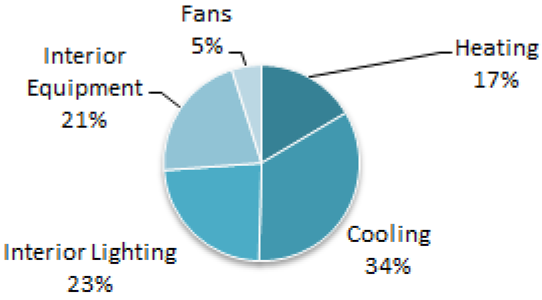

Fig. 3 Site Energy Analysis

Table 3 Low-Mass and High-Mass properties

		Thickness (m)	**Conductivity (W/mK)**	**Density (kg/m^3)**	**Specific Heat (J/kg-K)**	**Total R-Value (h·ft^2·°F/Btu)**
Low-Mass Exterior Wall	Composite 2 X 6 Wood Stud Layer 3	0.025	0.246	492.67	1006	R19
	Composite 2 X 6 Wood Stud Layer 2	0.133	0.047	93.84		
	Composite 2 X 6 Wood Stud Layer 1	0.019	0.137	640		
High-Mass Exterior Wall	Concrete	0.203	1.73	2243	836.76	R19
	Insulation Board (HF B5)	0.12	0.043	91	836.38	
	Gypsum Board	0.019	0.16	800	836.38	
Low-Mass Interior Wall	Gypsum Board	0.0127	0.16	800	836.38	R2
	Air Space	-	0.15 m^{2}k/W	-	-	
	Gypsum Board	0.0127	0.16	800	836.38	

As shown in Table 3 the chosen concrete for the high-mass wall is very dense with a high heat capacity. For our high-mass wall the insulation was placed in the interior side of the wall while the typical position of insulation is outside of the exterior walls. If thermal mass is in the interior side of the wall, this can be considered as internal mass. To avoid that, thermal mass is located in the exterior side of the wall. This choice was also made because of architectural reasons. It looks aesthetically more pleasing to have the materials with high-mass on the façade of the building.

4 Results

This section outlines the findings from the simulations. First, to verify the base model, we prepared the breakdown of energy use (Figure 3). According to Commercial Buildings Energy Consumption Survey (CBECS) Electricity Energy Intensity (EUI) for an average commercial building in a South region is 13.1 kWh/ft2 [12]. Electricity EUI of the base model in this research is 11 kWh/ft2. The reason that the base model's EUI is lower than CBECS is that CBECS data is for existing buildings which may not comply with ASHRAE standards while the base model in the current study is a new building based on ASHRAE Standard 90.1 [1]. For the base model the values obtained for each energy component are comparable to the energy component of the CBECS typical office building which are equal to 29% for lighting, 25% for space heating, 17% equipment, 9% cooling and 5% fans, 6% others and 9% water heating. The model cooling value is relatively higher due to the hot-humid climate.

5 Low Mass vs. High Mass

The heating and cooling loads were determined for the baseline model with all exterior walls as low-mass and they were compared to the building modeled with all exterior walls as high-mass. Figures 4 and 5 show the comparison of heating and cooling loads for each zone. Considering the COP,

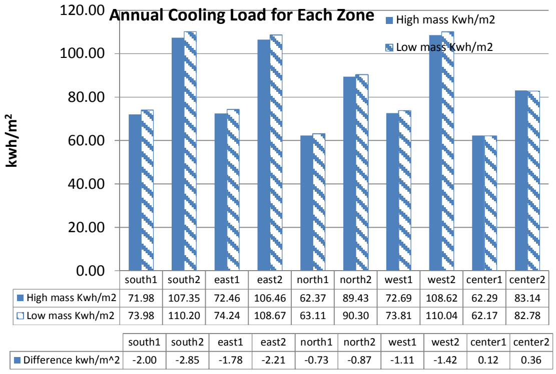

Fig.4 Cooling Load

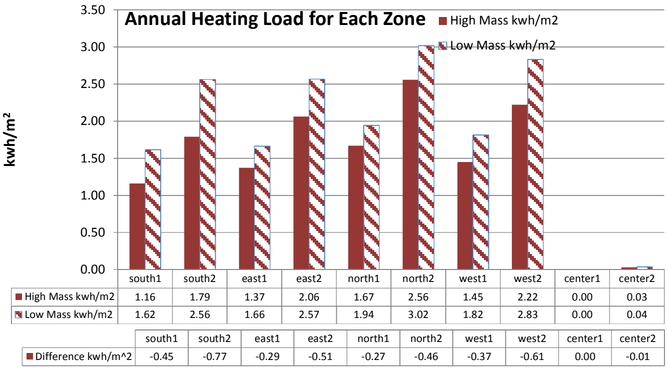

Fig. 5 Heating Load

the cooling load for the high-mass wall model consumes 1015.85kWh less than low-mass wall model.

Assuming electrical energy to cost $0.10/kWh, the savings associated with this modification is $101.58. For the total heating load, the high-mass building, considering the efficiency, consumes 370.31 kWh less. The cost of natural gas is 1$/therm with each therm equaling to 29.3 kWh [16]. This results in a savings of $12.64. In determining the cost of energy, the rate of peak demand was not considered due to the unsteady rate.

6 Varying Placement of High mass Wall

High-mass walls were placed in different orientations. All other external walls were kept to be low-mass walls except the first and second floor of the desired side. This procedure was repeated four times to account for all four orientations. The results are shown in the following figures (6 and 7). In addition, another model was simulated with internal high-mass walls in order to understand if massive walls in interior spaces can save energy.

Figures 6 through 8 sequence the strategies depending on the normalized cooling, heating, and fan loads from lowest to highest. For all the energy loads the efficiency of heating and fan, as well as the COP of the air conditioner are considered. Converting the required heating and cooling loads to a dollar amount, Figure 9 illustrates the total cost of the HVAC loads due to the heating, cooling and fan loads.

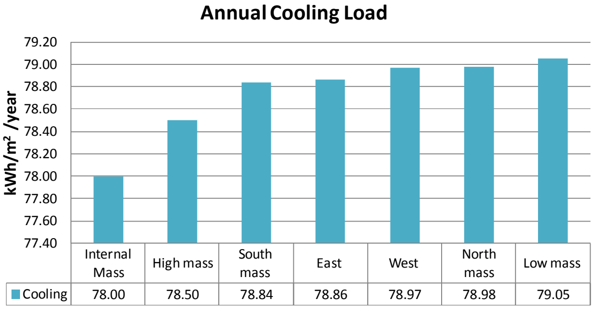

Fig. 6 Annual Cooling Load

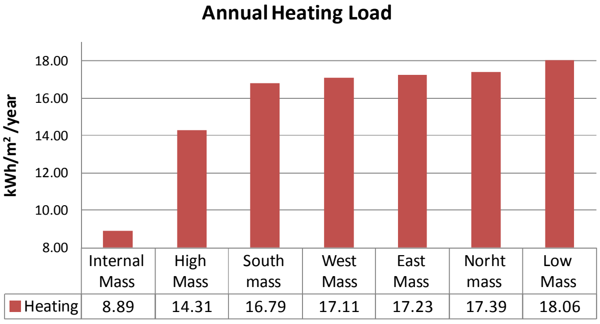

Fig. 7 Annual Heating Load

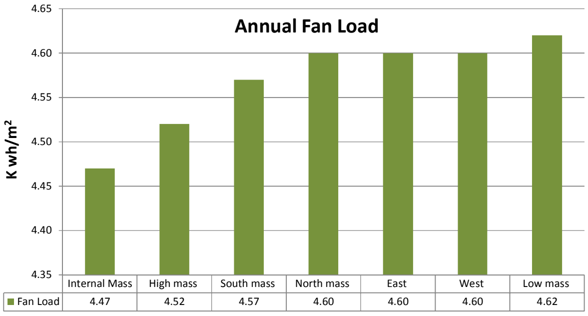

Fig. 8 Annual Fan Load

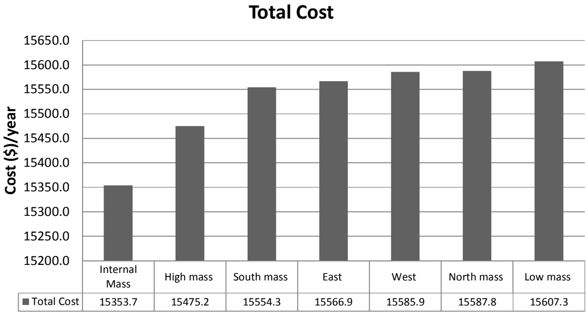

Fig. 9 Total Cost

7 Discussion

Illustrated in Figures 4 and 5 the ratio of the energy reduction for the high-mass model to the low-mass model is higher for heating loads than cooling loads. However, the total heating loads in this climate is insignificant. In addition, the inexpensive gas prices result in a very low savings for the heating load. Center zones show the lowest change for both heating and cooling loads compared to other zones. Since the thermal mass is located in the exterior walls, the thermal behavior of the center zones are not significantly affected. Moreover, all second floor zones consume more energy than their respective first floors. This is most likely due to second floor exposure to sun's radiation through the roof and the first floor slab exposure to the Earth. The south zone appears to have the most savings in both heating and cooling loads. In a hot-humid climate like Austin thermal mass strategy can reduce both heating and cooling loads. However, converting both the heating and cooling load savings into dollar amounts, the total savings of thermal mass model is $114. This is an insignificant savings for a small office building.

The results of second series of simulations, shown in figures 6, 7, 8 and 9 illustrate that the total HVAC cost of interior high-mass walls is the lowest compared to other alternatives. On one hand, there is not enough outside temperature fluctuation to flush the external thermal mass in a hot-humid climate. On the other hand, interior thermal mass does not get as hot or as cold as exterior thermal mass, which helps reduce the fluctuation of the inside temperature. The second best alternative was using high-mass walls for the whole envelope. We interpret that the improvement of thermal-mass effectiveness can save energy even though the outside temperature fluctuations are not much. Either extensively large volume of thermal mass or a material with very high density and high heat capacity can boost the effectiveness of thermal mass, such as phase changing materials. From the figures it is evident that the south facing thermal mass wall is not the most energy efficient strategy compared to the high-mass exterior wall and interior wall; however, it is still the most energy efficient thermal mass orientation compared to the other thermal mass orientations.

Finally, examining the cooling and heating loads due to the placement of thermal mass on different facing walls it is evident that having any amount of thermal mass within the building reduces the loads compared to a low-mass building. However, this energy efficiency is not significant. Comparing the best and worst scenarios (internal thermal-mass and low-mass) the total saving is about $254.

7 Conclusion

The goal of this study was to investigate if thermal mass is considered an energy efficient strategy in a hot-humid climate. In this study comparison of low-mass and high-mass walls shows that thermal mass can save energy in a hot-humid climate. The maximum saving is $254 for 1858m2 which equals to $0.14/m2. The cooling and heating savings of thermal mass application in a hot-humid climate is not very substantial but it is still considered more efficient than low-mass walls. This study helps practitioners to understand that thermal mass in a hot-humid climate may not be as energy efficient as other climates but it still can save energy. This paper also helps practitioners decide which orientation and scenario is the most efficient for the utilization of thermal mass in a hot-humid climate.

In this paper we only assessed the savings associated with the use of thermal mass for exterior and interior walls. All other variables were held constant to directly analyze the impact of the two constructions, which were chosen to have the same R-value. However, this study did not analyze the impact of the chosen construction for structural integrity or moisture intrusions. The study also did not consider the initial cost of using the concrete walls and the life cycle cost associated with the various wall constructions. In addition, for cost analysis the peak loads were not considered. However, to make savings more accurate, the shift in peak demand due to thermal mass can be analyzed in future studies.

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