PCM (Phase Change Material) Optimization Modeling for Passive Cooling in South Texas

Bronson Ferster[1,2], Hui Shen[1], Joseph D. Rendall[1]
[1]Texas A&M University-Kingsville, Kingsville, United States.
[2]Pennsylvania State University, University Park, United States.

ABSTRACT

In the twenty-first century, the generation and utilization of energy is receiving intensified scrutiny. Space heating and cooling dominate the consumption of residential energy. PCM (Phase Change Material) integrated building envelopes have demonstrated great potential in mitigating residential energy demands. PCM envelopes store surplus energy through latent heat. Many factors (i.e. thickness and geographic location) contribute to the performance of PCM integrated building; the range of performance variables results in an ambiguous standard of expectation for PCM performance. This study uses an optimization theory in order to set a performance expectation and determine a combination of variables that maximize PCM performance for a given region. South Texas is an extremely warm climate that may dramatically benefit from PCM induced passive cooling, a still largely understudied application. Confidence has been rising in the ability of EnergyPlus to accurately model PCM envelopes through simulation. Therefore, EnergyPlus is used to model the impact of PCMs in south Texas. The PCM optimization theory calls for setting a geographic location and an application (cooling or heating); then, optimize PCM performance through simulation by finding the ideal PCM melting temperature, the optimum location within the envelope, and the most essential surfaces of the envelope.

INTRODUCTION

1.1 Residential Energy Consumption and the Application of Phase Changing Materials

Due to the limited supply of conventional fossil fuels, rapid increases in global energy demands from developing nations, and dangerous environmental phenomenon such as climate change, the nature of how societies generate and utilize energy has developed an intensified scrutiny. In 2015, nearly 80% of the United States' energy consumption was derived from non-renewable fossil fuels (U.S. Energy Information Administration , 2015); these same sources are quickly depleting and largely contribute to climate change when combusted. This energy problem is compounded by pressures from around the world: developing nations continue to stress energy demands as they begin to use as much energy as first-world nations (U.S. Energy Information Administration, 2013). It is clear that the energy solution for the twenty-first century must be more comprehensive than simply transitioning to sustainably based electricity sources. Of course, society must address how energy is *converted*, but equal consideration should be given to how energy is *used*. In the United States, about 40% of our energy is consumed by residential and non-manufacturing commercial buildings (U.S. Energy Information Administration, 2016), and across the nation, 43% of the energy consumed by residential buildings was used for cooling and space heating (Office of Energy Efficiency and Renewable Energy, 2015). These statistics accumulate to a tremendous amount of our national energy being dedicated to heating and cooling the space in our houses and offices.

Phase Change Material (PCM) integrated building envelopes offer a promising opportunity to greatly reduce the energy needed for heating and cooling. Although the applications of PCMs have been extensively researched, the widespread use of the technology remains negligible. Furthermore, results for energy reduction vary substantially 10-90% (Zhu, Zhenjun, & Shengwei, 2009). The variety in PCM performances derive from the large range of factors that contribute to energy reduction: thickness of PCM, type of encapsulation, passive cooling or passive heating, organic or non-organic, latent heat change, melting temperature, geographic location, placement within envelope, etc (Zhu, Zhenjun, & Shengwei, 2009). Although some variables such as PCM melting temperature (Ascione, Bianco, Francesca De Masi, Filippo , & Vanoli, 2013) and location within envelope (Jin, Medina, & Zhang, 2013) are argued to produce a more considerable impact, an overwhelming issue remains for determining the effectiveness of PCM technology: many test variables are not held constant across individual research projects. These inconsistencies create a large spectrum of results and make the true potential of a PCM seem uncertain to a consumer. The performance ambiguity surrounding PCMs is extremely unfortunate considering the excellent exigence (absurd amounts of energy are demanded to heat and cool buildings) for the technology. This conclusion is even more troubling since these different research groups near unanimously agree that PCMs produce a series of positive benefits.

1.2 PCMs in Literature

The potential of Phase Changing Materials has been widely researched and reviewed. A comprehensive history of PCM research was published in 2009 concludes that nearly all research groups agree there are positive benefits

https://doi.org/10.26868/25222708.2017.255

to PCM integrated envelopes: reduction in HVAC use, increased comfort levels, and shifts in peak energy demands (Zhu, Zhenjun, & Shengwei, 2009). In a different review of PCM applications, Akeiber et al. compiled a series of notable studies regarding PCM integrated envelopes. Akeiber et al. addresses a lack of research on PCMs used for passive cooling, and the group notes that a strong majority of studies on PCMs are conducted through experiment as opposed to simulation (Akeiber, et al., 2016).

Computational modeling of PCMs has many benefits. The results are gained after several minutes as opposed to an entire season, and there are few costs associated with the simulation compared to constructing a physical model for experiment (and necessary measuring equipment). Unfortunately, the simulation of PCMs for energy modeling has historically been arduous and unreliable. Although, substantial progress has been made in recent years. Tabares-Velasco et al. accounts the journey of verification and validation for EnergyPlus. EnergyPlus is a popular residential energy modeling software that was created and is continually improved by the U.S. Department of Energy's National Renewable Energy Laboratory. PCM modelling was verified through empirical and analytical means for EnergyPlus in versions 8 and newer (Tabares-Velasco, Christensen, & Bianchi, 2012). The ability to accurately model PCMs is an exciting boost to the industry; researchers can now analyze, in a relative instant, a vast range of PCM factors, in various geographic locations, with confidence.

METHODOLOGY

2.1 Using Optimization Techniques to Maximize PCM Energy Savings – in South Texas

Verified PCM modeling in EnergyPlus allows for clarification in the potential and optimization of PCM applications. Simulations take only a matter of minutes to compute (of course, only after significant effort is used to adequately construct the virtual building), have virtually no material costs, are easily controlled, are easily repeatable, and can test a range of variables (i.e. geographic location, PCM thickness, PCM envelope location, etc.).

Many factors contribute to the performance of PCM envelopes; these factors produce an uncomfortably large range of potential results for consumers. Some of these variables (i.e. PCM thickness) will vary based on the individual consumer's budget and the specific abilities of the manufacturer; such variables will be nearly impossible to standardize. Fortunately, many influential factors of PCM performance (i.e. PCM melting temperature and PCM location in envelope) are easily controlled and tested by a simulation.

In order to establish the savings potential and optimization for the applications of PCM integrated building envelopes in south Texas, the following methodology was utilized: geographic location and PCM application (passive heating or cooling) must first be established, and then, PCM melting temperature and envelope location can be optimized through simulation.

South Texas is an extremely warm region where residential buildings dedicate a tremendous percentage of annual energy consumption for cooling – over three times the national average (U.S. Energy Information Administration, 2009). The south Texas region, given the intense heat and extensive use of space cooling, may experience the significant potential for incorporating PCM technology. Therefore, weather from Kingsville, Texas was selected to represent the region, and passive cooling was the chosen application for the PCM. EnergyPlus and property data from commercial vendors of PCMs were used to run a series of simulations. Finally, optimization techniques were utilized to maximize the performance of PCMs based on PCM melting temperature and placement within the envelope.

2.2 Setting Up the Simulation in EnergyPlus

EnergyPlus has the capability to create a phase change material and use it within a model. Property data for PCMs were obtained through request from commercial vendors (Figure 1). EnergyPlus requires several physical properties to accurately model the PCM: density, temperature dependent thermal conductivity, but most importantly, temperature dependent enthalpy.

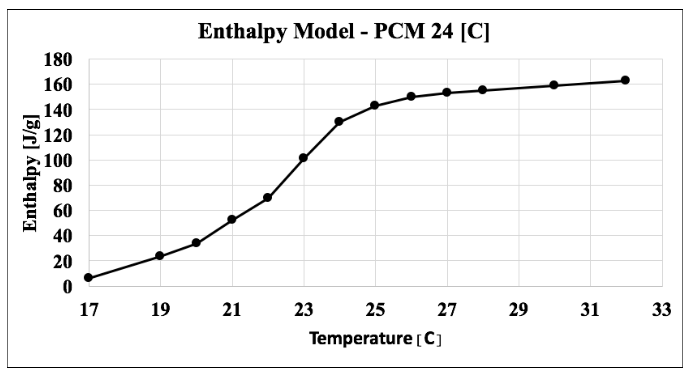

Figure 1. Enthalpy data entered into EnergyPlus to model a PCM; provided by commercial PCM vendor.

Each PCM constructed in EnergyPlus has a thickness of 1 [cm]. This measurement was chosen to be somewhere between the thickest and thinnest that commercial vendors supply. The thickness is held constant since the study was focused on optimizing PCM melting temperature and location in the envelope; also, PCM thickness may be limited by either personal budget or regional PCM manufacturing capabilities.

A 456 [m^2] residential building was modeled in EnergyPlus for the experiments (Figure 2). The PCM was incorporated into the envelope walls and ceiling surrounding the 186 [m^2] living zone; PCMs were not placed in the floor, the garage (seen as windowless extension in Figure 2), or the unconditioned attic.

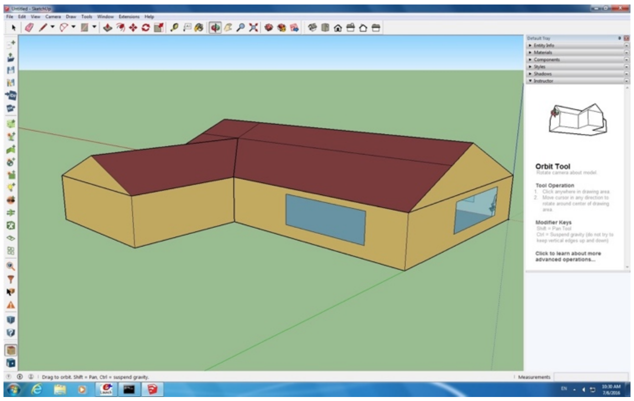

Figure 2. SketchUp depiction of model house for EnergyPlus simulations.

The house has three humans living inside: two working adults and one child. Internal gains for residential essentials such as a refrigerator, dishwasher, and washing machine are included in the model; internal gains are set to published ASHRAE standards. The thermostat in the model has a dual setpoint of 21[C] and 23[C]; setpoints were selected such that the building temperature remains within the ASHRAE Standard-55, 2013 range of thermal comfort for human occupants.

The simulations utilized weather from Kingsville, Texas, courtesy of the EnergyPlus website. Kingsville was selected to represent the general geographic behaviors of south Texas. The simulations model an entire year; Therefore, the performance and optimization of PCMs can be analyzed throughout transition months as well, instead of only the cooling season.

In EnergyPlus, models that incorporate phase change materials must use the conduction finite difference solution algorithm (condFD). CondFD is a heat balance algorithm that is uniquely capable of the computational rigors involved with correctly modelling PCMs. A timestep of two minutes is used; a timestep less than three minutes is recommended for condFD.

Various PCMs were modeled in EnergyPlus. Seven different PCM melting temperatures ranging from 15 [C] to 31 [C] were tested. A base model simulation was run and used as a control. Results from the PCM incorporated simulations were analyzed and compared against each other, as well as the control case.

2.3 Running experiments in EnergyPlus

The performance of the PCM models were gauged predominately on two factors: (1) the cooling load [W] and (2) heat flux through the envelope [W/m^2]. EnergyPlus measured these factors through the following output variables: Zone Predicted Sensible Load to Cooling Setpoint Heat Transfer Rate [W] and Surface Inside Face Conduction Heat Transfer Rate per Area [W/m^2]. Methods were employed to allow optimization techniques for PCM melting temperature and envelope location. A range melting temperatures from commercially available PCMs (15 [C] – 31 [C]) were simulated. The range was large enough to notice a peak or curve in cooling load reductions when the PCM models at different temperatures were each compared to the control model. For envelope location, the same PCM was tested at several different depths in the wall (Lee & Medina, 2016). The PCM was inserted in one of five intervals across the 0.25 [m] envelope (Figure 3). The stucco, CB11, and gypsum envelope in the EnergyPlus model (Figure 4) was sliced into sections when appropriate in order to accommodate the PCM implementation (Jin X. et al., 2016).

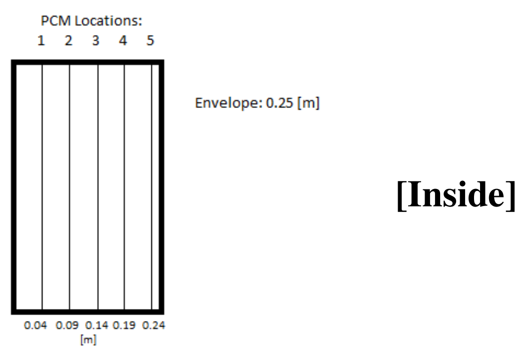

Figure 3. Locations of PCM placement within EnergyPlus model envelope.

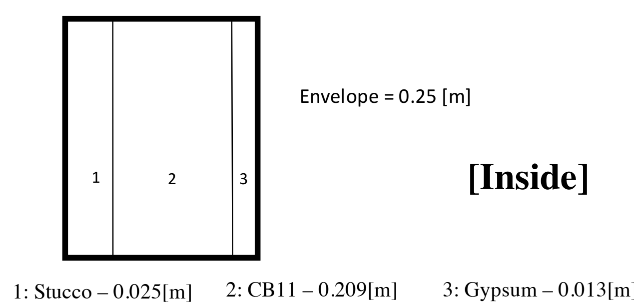

Figure 4. Envelope in base model.

The percent reduction in cooling loads at the five locations were then be compared in order to find the optimum location of the PCM layer.

Lastly, orientation of the implemented PCM was assessed with heat flux per area through each PCM incorporated surface. The output variable is normalized per area to compensate for the differences in surface size. The goal of this analysis was to determine which surfaces (i.e. west wall or ceiling) were most influential and essential to the overall PCM performance. This experiment analyzed heat fluxes through all surfaces over a four-day interval in late July (the midst of the cooling season); measurements were simulated on the timestep (every two minutes) in order to ensure high quality results.

RESULTS

3.1 PCM performance

Each PCM resulted in substantial reductions in cooling loads and variations in heat flux. Annual cooling loads were reduced by as much as 31% and, in the worst case, as little as about 26%. In each simulation, the west wall contained the largest heat flux per area (measured over a four-day period in late July) both with and without PCMs. Peak heat flux was reduced in all cases with PCM envelopes (Table 1).

Table 1. Summary table of PCM performance.

PCM Melting Temperature [C] - Location	Annual Cooling Load [kW]	Percent Reduction in Cooling Load	Peak Heat Flux [W/m^2] / Wall
Control	21,509	--	59.05 / West
PCM 25 - 5	14,874	30.8%	52.15 / West
PCM 15 - 1	15,740	26.8%	52.56 / West

3.2 Optimized results:

The following demonstrate the results of the optimization tests for the PCM application of passive cooling in south Texas. The model was optimized for three variables: PCM melting temperature, PCM location in envelope, and PCM wall orientation.

3.2.1 PCM melting temperature

Seven different PCMs with unique melting temperatures ranging from 15 [C] to 31 [C] were entered into a full-year simulation. Annual cooling loads were compared to the cooling load of the control model in order to establish a percent load reduction for each PCM. A smooth parabola is generated by the distribution of cooling reductions against PCM melting temperature. A decisive and obvious reduction peak occurs with PCM melting temperatures of about 24 [C] to 25 [C]. PCM melting temperature improved performance by 11% (about a 3.4% increase in cooling load reduction) (Figure 5).

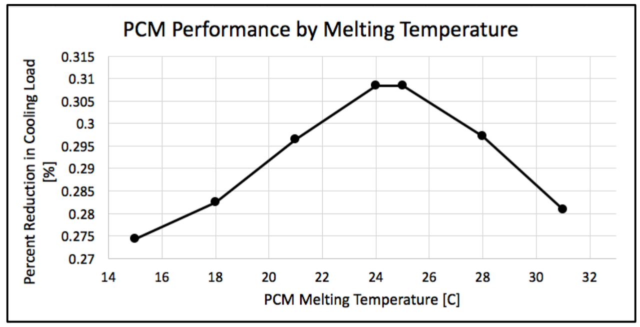

Figure 5. Cooling load reduction of seven PCMs with a range of melting temperatures. At location 5.

3.2.2 Location in envelope

The 0.25 [m] envelope was tested with a PCM layer at five distinct locations. The location of the PCM within the envelope caused noticeable changes in PCM performance. Cooling load reductions exponentially increase as the PCM is placed closer to the interior of the building. Envelope location had the potential to improve PCM performance by 12% (about a 3.6% increase in cooling load reduction) (Figure 5).

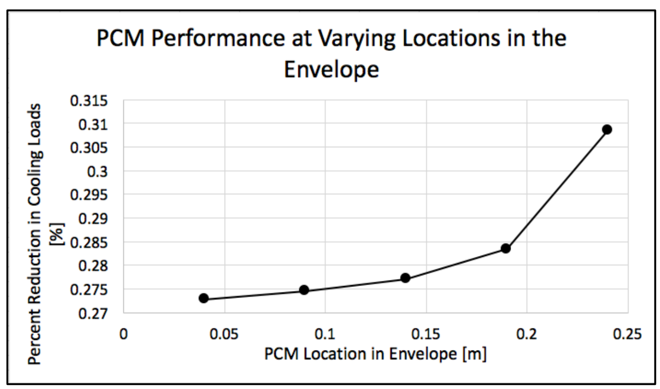

Figure 6. Cooling load reduction of PCM at five distinct locations in 0.25 [m] envelope.

3.2.3 PCM orientation

Both heat flux (per area) and reduction in peak flux varied based on wall orientation. The west wall consistently had the largest average and peak heat flux. The ceiling, despite having the lowest overall heat flux, produced the largest percent reduction with an incorporated PCM. Percent flux reductions varied and were not linear when plotted against peak flux (Table 2).

Table 2 Heat flux per area through PCM (melting temperature 25 [C]; location 5) incorporated surfaces and respective flux reductions. Heat flux was measured over the same four-day period in late July.

	North	South	East	West	Ceiling
Peak Heat Flux through PCM integrated Surface [W/m^2]	30.21	29.80	43.88	52.15	0.72
Difference from Control [W/m^2]	2.88	1.92	3.90	6.90	4.88
Percent Reduction through surface [%]	8.7	6.1	8.2	11.7	87.2

DISCUSSION

The EnergyPlus simulations demonstrate that there is substantial energy savings potential involved with the technology. Potentially, over 30% in cooling load reductions for a residential building in the south Texas region.

Defining a region (south Texas) and application (passive cooling) established a concise and consistent range for predicted PCM performance (26-31% cooling load reduction). These findings dramatically reduce the ambiguity of PCM performance for south Texas or any similarly hot and humid climate. Although actual results will vary based on PCM thickness and other factors such as shading, consumers should be able to have a better understanding of the potential they can expect from PCM envelopes in this region.

Optimization techniques were straight forward to implement and provided clear results: data analysis was able to identify both an ideal melting temperature for the PCM (25 [C]) and an optimum location within the envelope (location 5; close to the interior of the building). Heat flux per area through the envelope surfaces was able to identify the west wall with the largest change in heat transfer and the ceiling as the largest percent change in flux. While energy savings resulted from every tested case of PCM integrated envelopes, proper employment of optimization increased reduction of the cooling load (4% difference from lowest performing case to optimized case).

When comparing the load reductions of PCMs with different melting temperatures, a relatively smooth parabola was generated. The concave downward graph peaked at about 25 [C]. PCMs with melting temperatures on both extremes were underperforming. This may have a simple explanation. A PCM with too low of a melting point will be in the melted state for most of (if not all of) the day in the hot Texan climate. The storage ability of PCM envelopes derive entirely from the latent heat phenomenon during a phase change; if the PCM does not change phase, it is unable to store energy. With a PCM that has too high of a melting temperature, the storage of energy may be too late. Although the high melting temperature PCM may still change phase, it only begins storing energy after the temperature has risen far above the cooling set point in the house. Therefore, energy for space cooling must still be called upon. The PCMs that melted at the peak of the cooling load reduction curve (24 [C] and 25 [C]) were possibly the best combination of regularly changing phase but not changing phase before the indoor temperature rises too much.

The simulations consistently showed higher PCM performance when placed closest to the interior of the building (location 5). An interesting dilemma arises out of this conclusion: the feasibility retrofitting. It is practical enough to build a house with a PCM layer near the interior of the envelope, but the optimized PCM location may include more problems when retrofitting houses. Living space may temporarily need to be vacated, walls may need to be repainted, or internal room dimensions may change if the envelope is altered from the interior. In order for an ideal mass implementation of PCM technology, a viable means of retrofitting must be available; it would be disappointing to limit optimized PCM envelopes to only new constructions. However, even if a less optimum PCM location were utilized for passive cooling in south Texas, based on the simulation results (cooling load reduction of about 26%), it would still probably be a worthwhile investment.

The heat flux measurements from July point to a crucial idea: a PCM incorporated into the ceiling is very effective. The ceiling in the control model had the lowest peak heat flux (5.60 [W/m^2]) of any surface, but still managed the second largest overall reduction (4.88 [W/m^2]) and by far the largest percent reduction of peak heat flux through a surface in July (87.2%). Overall PCM performance may have been dramatically less if the ceiling was neglected from the model.

PCM integrated envelopes are an effective means for passive cooling in south Texas. However, much is still left unaddressed for the feasibility of PCM building envelopes for passive cooling in south Texas. Substantial savings (of both energy and money) could be generated over the lifespan of a house with the incorporation of PCMs; however, a thorough economic analysis investigating the complete costs of PCM installation and local electricity price has yet to be completed. An experimental validation of the results would be useful to confirm the optimized melting temperature, envelope location, and energy savings potential for south Texas. New design and implementation methods could be explored for the retrofitting of envelopes to include PCMs; such innovations could catalyze the mass use of the technology. Finally, further analysis should be conducted on the impact of individual envelope surfaces and PCM performance. The simulations demonstrated some surfaces produce less of an impact per unit area (i.e. south wall); perhaps some surfaces are not as economically sound as others.

CONCLUSION

PCM (phase change material) integrated building envelopes can dramatically reduce the massive amount of energy required to heat or cool a building, but the precise extent to which savings will occur is dependent on a wide variety of factors. This study optimized PCM energy savings for south Texas by finding an ideal PCM melting temperature and envelope location through "year-long" EnergyPlus simulations. The largest reductions in the cooling load occurred with a PCM melting temperature of 25 [C] and placed closest to the interior of the building (location 5). PCM in the ceiling was a crucial inclusion (87.2% reduction in peak heat flux through surface) to the overall energy performance. When fully optimized, the model produced a 31% reduction in the annual cooling load.

The EnergyPlus simulations were able to optimize the application of passive cooling in PCM envelopes for south Texas. The variety of tests were able to set a standard (about 30% reduction in cooling load) for PCM performance in the south Texas region; the benchmark reduces the ambiguity of the potential energy savings and sets an expectation for consumers.

ACKNOWLEDGMENTS

This project would not have been possible without Dr. Hua Li, the IR-SEED (Integrating Research in Sustainable Energy and Environment across Disciplines) REU program held at Texas A&M University-Kingsville, or funding from the National Science Foundation (Grant No. EEC-1359414). PCM properties and data were graciously provided by Andreas Lärz and RubiTherm, a commercial vendor of PCM technology. Lastly, a special thanks to the U.S. Department of Energy and the National Renewable Energy Lab for the development and the free use of the EnergyPlus software.

LITERATURE CITED

Akeiber, H., Nejat, P., Majid, M. Z., Wahid, M., Jomehzadeh, F., Famileh, I., et al. (2016). A review on phase change material (PCM) for sustainable passive cooling in building envelopes. *Renewable and Sustainable Energy Reviews , 60*, 1470-1497.

Ascione, F., Bianco, N., Francesca De Masi, R., Filippo , D., & Vanoli, G. P. (2013). Energy refurbishment of existing buildings through the use of phase change materials: Energy savings and indoor comfort in the cooling season. *Applied Energy , 113*, 990-1007.

ASHRAE. (2013). *Thermal Environmental Conditions for Human Occupancy.* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. ASHRAE.

Jin, X. M. (2016, June). Numerical analysis for the optimal location of a thin PCM layer in frame walls. *Applied Thermal Engineering* .

Jin, X., Medina, M., & Zhang, X. (2013). On the importance of the location of PCMs in building walls for enhanced thermal performance. *Applied Energy , 106*, 72-78.

Lee, K. O. (2016, January). Using phase change materials for residential air conditioning peak demand reduction and energy conservation in coastal and transitional climates in the State of California. *Energy and Buildings* .

Office of Energy Efficiency and Renewable Energy. (2015). *Residential Sector Energy Consumption.* Retrieved March 2017, from buildingsdatabook.eren.doe.gov: http://buildingsdatabook.eren.doe.gov/TableView.aspx?table=2.1.6

Tabares-Velasco, P. C., Christensen, C., & Bianchi, M. (2012). Verficiation and validation of EnergyPlus phase change material model for opaque wall assemblies. *Building and Environment , 54*, 186-196.

U.S. Energy Information Administration . (2015, July 2). *Fossil Fuels Have Made up at Least 80% of the U.S. Fuel Mix Since 1990* . Retrieved June 2016, from eia.gov: http://www.eia.gov

U.S. Energy Information Administration. (2013, December 3). *Future world energy demand driven by trends in developing countries.* Retrieved June 2016, from eia.gov: eia.gov

U.S. Energy Information Administration. (2009). *Household Energy Use in Texas.* Retrieved June 2016, from eia.gov: eia.gov

U.S. Energy Information Administration. (2016, April 6). *How much energy is consumed in residential and* *commercial buildings in the United States?* Retrieved June 2016, from eia.gov: eia.gov

Zhu, N., Zhenjun, M., & Shengwei, W. (2009). Dynamic characteristics and and energy performance of buildings using phase change materials: A review. *Energy and Conversion Management , 50*, 3169-3181.