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Assessment Of Walls with Phase Change Materials Through Synergistic and Performance Measures Using Experimental and Simulated Test Houses

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ABSTRACT

Current research on living and working spaces continues to strive to identify the most energy-efficient methods for heating and cooling, and many novel technologies have emerged from the research. One of the most promising, and the topic of this quantitative analysis, is the retrofitting of phase change materials (PCMs) into the walls of structures. Research has shown positive results, such as a reduced transfer of heat through walls, when PCMs are retrofitted into wall construction. The present research takes previously gathered data from test houses, built with typical North American framing, and simulates an additional fourteen test houses from the gathered data. The simulated houses consisted of a unique combination of walls retrofitted with and without PCM in them. The fourteen unique simulations allowed for seven metrics, such as max heat flux, time delays (start, peak, and end), total heat, heat flux average, and standard deviation, to be measured. Most of the measure indicated a positive correlation with the addition of PCM being retrofitted into a wall. From the results, the east, west and south walls emerged to be the most influential when it came to the seven measures, and it is recommended that at least one of these three walls be included when retrofitting buildings

INTRODUCTION

Combating climate change has become increasingly difficult as energy consumption rates continue to rise. Of the energy being consumed, nearly forty percent can be directly attributed to buildings, with about half of the energy consumed by buildings related to the heating and cooling of the structure [1,2]. Because of this, researchers have identified current building comfort practices as energy inefficient; additionally, researchers have identified elements within buildings, such as walls, that can be improved to elevate the energy efficiency of individual buildings. Elevated wall efficiency typically requires a wall medium that resists thermal inequalities between the indoor and outdoor temperatures. A higher thermal resistance helps to keep indoor temperature at the desired level for longer. Because of walls' unique ability to maintain indoor air temperatures, researchers have focused on improving walls' efficiency through the integration of phase change materials (PCMs) into the wall cavities. PCMs have been shown to significantly reduce the transfer of heat in and out of structures. A reduction of heat transfer in walls yields more consistent indoor temperatures, which reduces the energy load required by an HVAC system. Despite the positive results of walls with PCMs, further work is needed to show that retrofitting PCMs in walls has a profitable return on investment (i.e., reduction of energy cost in the long term). This analysis aims to quantify synergy between walls and their capabilities of keeping the heat transfer rate close to zero. Additionally, the study aims to determine an optimal combination of walls, using data collected from the synergy analysis, to reduce the cost of retrofitting while still maintaining the desired energy saving qualities.

BACKGROUND

Energy background

Currently, the United States is the world's second-largest consumer of energy, consuming over one-hundred quadrillion BTU (British Thermal Units) (about 17% of the world's energy) annually. By the year 2050, energy consumption in the United States is expected to increase by nearly 50% due to population growth, economic growth, and climatic factors [1], [2]. As a result, researchers have begun to look for solutions that reduce the consumption of energy. Buildings consume a large portion of the total energy produced and have the most potential for energy consumption reduction. In the United States, buildings consume around 40% of all produced energy with nearly half of that energy going to maintaining thermal comfort for humans [1], [2]. For this reason, advancements in construction techniques and technology are needed to reduce energy consumption. These advances are happening in heating, ventilation, and air conditioning (HVAC) system improvements, renewable and clean energy, and improvement in construction methods.

Current solutions to decrease energy consumption

There are currently at least five novel technologies that improve the energy efficiency of HVAC systems. They are independent temperature and humidity controls, stratified ventilation, thermal energy storage (TES), heat recovery ventilation, and indirect evaporation cooling. These five technologies have improved HVAC systems and have shown the potential for reducing energy consumption in buildings without sacrificing the comfort and benefits of controlled interior climate [3]. The most recent solution being researched is the incorporation of TES into the construction of buildings, which increases the efficiency of building insulation. TES can occur through a chemical or physical process, such as a material going through a phase change or an endothermic or exothermic chemical reaction. Whatever the reaction chosen, the TES acts as a storage medium for the incoming heat, thus acting not only as an improved insulation but as a heat reservoir. The stored heat is then released when external temperatures drop, which allows the stored heat to flow out of the walls into the living space. In the case of most studies, the physical process of a phase change is used for building incorporation because of the complexities and dangers of incorporating a chemical process into building materials [4]. To harness and exploit the phase change process, in which energy can be stored and released in a material when it changes from one phase to another, PCMs are utilized in walls by way of retrofitting them into the construction to store incoming thermal energy [5], [6].

PCMs, by increasing thermal mass and thermal inertia, make it more difficult to change the indoor temperature of a building, thus allowing for easier climate control with less energy being consumed [6], [7]. PCMs can experience a variety of phase changes depending on the type chosen. For example, PCMs can experience a liquid-to-vapor phase change, a solid-to-solid phase change, and lastly a solid-to-liquid phase change [4]. For most building applications, a solid-to-liquid PCM is used to absorb heat. Essentially, the PCM absorbs sensible heat until its melting point is reached, which is when the phase change begins. As the PCM changes from solid to liquid, it absorbs and stores heat as latent heat. Once the PCM is fully liquid, it goes back to absorbing sensible heat until it reaches its thermal capacity [4], [8]. While the PCM is undergoing its phase change, heat is being stored but the temperature is not rising (Figure 1). Once the PCM has completed its phase change, it stores heat sensible heat, and the temperature begins to increase again.

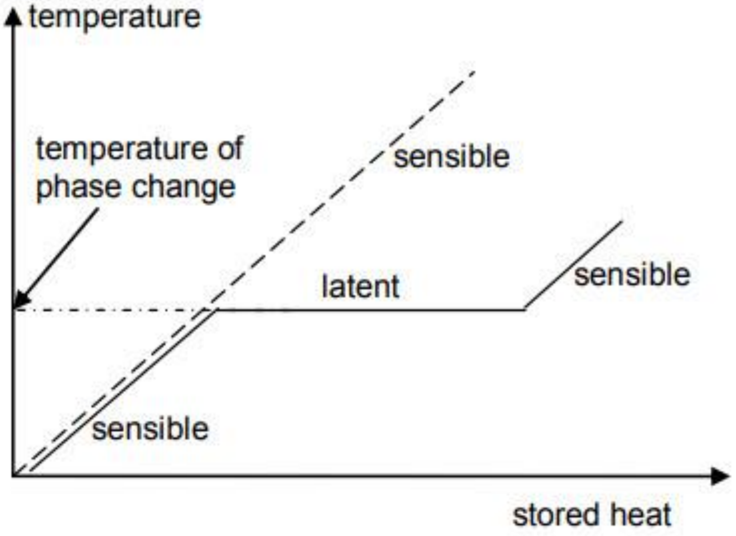

Figure 1: Example of PCM heating [5]

When incorporated into buildings, PCMs store the heat that would enter the building and reduce the need for cooling (i.e., lower energy consumption). Then, when the temperatures drop below the melting point or the freezing point (e.g., night hours), the PCMs revert to their solid state, which releases the heat back into the space reducing the need for heating.

PCM background

The type of PCM and incorporation method alters the PCMs' effectiveness when retrofitted into walls. PCMs can be organic (paraffins and fatty acids), inorganic (salt hydrates and alloys), or eutectic (mixtures of organic and inorganic PCMs) and can be incorporated in walls using micro-encapsulation, macro-encapsulation, and porous inclusion (wallboards soaked in PCMs) [4]–[7]. Selecting a PCM type is dependent on the conditions it will experience (e.g., weather patterns and incorporation methods). Milder climates would require a PCM with a higher melting point so that it will begin its phase change process during the hottest parts of the day. Similarly, in a cooler climate, a PCM with a lower melting point would be recommended for the same reasons. In fact, the PCM type can be selected to match the conditions it will experience without the need for intensive field research. However, researchers must still consider the thermal (melting point, specific heat, etc.), physical (volume change, vapor pressure, etc.), kinetic (supercooling, nucleation and crystallization rate), and chemical (chemical stability, non-toxic, etc.) properties when choosing PCMs to ensure the desired results [6].

Many of the properties mentioned previously can carry considerable drawbacks when considering incorporating PCMs into building construction. The physical properties, for instance, can significantly affect how the PCM will be incorporated and the longevity of the storage methods. Ensuring the incorporated PCM has a small volume change and a low vapor pressure is critical for the success of the selected incorporation method. Kinetic and thermal properties relate more to the effectiveness of the PCM in reducing the gained heat. Thermal properties are important for being effective in the climate in which it is used, and kinetic properties relate to the effectiveness of a PCM's phase change. The chemical properties raise the most concerns and could have the most potential drawbacks. PCMs must be chosen to ensure the health and safety of the building's occupants, which means the selected PCM should not be corrosive, toxic, flammable, or explosive;

furthermore, it needs to be compatible with the chosen construction materials, have long-term stability, and have reversible phase change cycles. Though all the properties are important to the success of the PCM, the chemical properties have the most potential for having adverse effects on the building and its occupants.

Incorporation methods also require more testing to determine the most effective strategy, since incorporation methods range greatly (Figure 2) and are not reliant on weather conditions. Rather, incorporation methods are often left to the designer and are dependent upon the needs and wants of the architect. Micro-encapsulation is generally used when the PCM is contained by a coating or shell and then added directly to the wallboard. This is done either during the wallboard's manufacturing or added to the insulation after manufacturing [6]. Macro-encapsulation can be anything from thin reflective foil sheets, to piping in the walls, to structurally insulated panels (SIPs) or masonry bricks [4], [7].

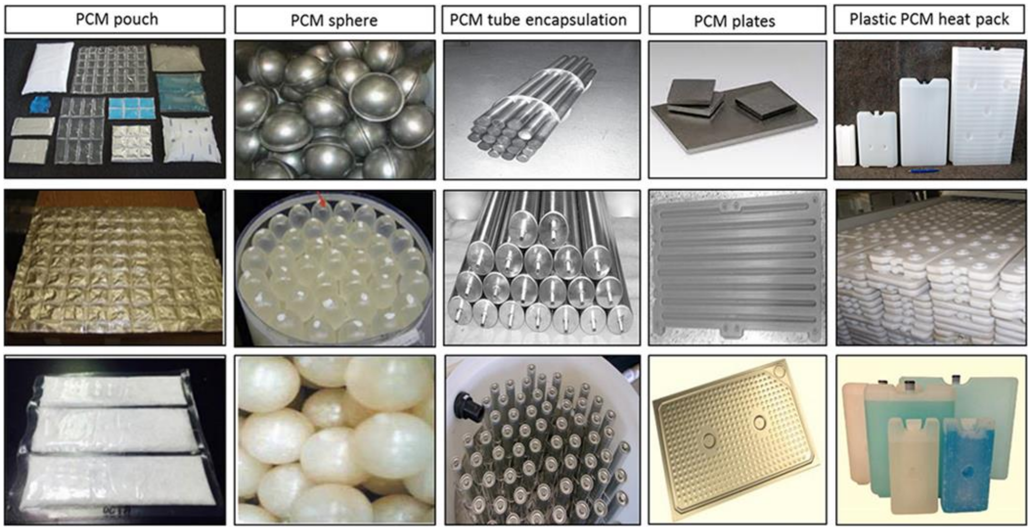

Figure 2: Example of PCM incorporation methods

PCM research

Previous research has tested various combinations of PCM types and incorporation methods, and the consensus has been positive. When testing the effectiveness of PCMs, researchers focus on metrics such as average heat flux, peak heat flux, time delays in terms of peak heat flux, energy efficiency, and a variety of temperature comparisons (e.g., indoor wall temperatures versus outdoor temperatures) [9]. The most common types of encapsulation methods in research are incorporated PCM in wallboards, pipes containing PCM, reflective foil sheets, metal casings, structurally insulated panels (SIPs), and masonry bricks.

PCM wallboard research indicates that PCM reduces indoor air temperature fluctuations and that PCM can shift the peak thermal loads to a later time when compared to control walls (i.e., walls without PCM) [10], [11]. Pipes containing PCMs showed capability to reduce both the total heat flux and the peak heat flux by 20-35%. In addition, pipes with PCM were also able to create a time delay in the peak heat fluxes [12], [13]. Like the piping method, SIPs and masonry brick enhanced with PCMs were able to achieve peak heat flux reductions up to 37% as well as peak temperature reductions [14]–[16]. Using reflective foil or metal casings for an incorporation method was found to reduce maximum temperatures by 17-67% depending on the season, smooth out temperature fluctuations, reduce heat fluxes by 29-51%, and achieve time delays ranging from two to six hours [17]–[19]. For all incorporation methods, PCM enhancements helped reduce peak heat fluxes, temperatures, and/or cause a time delay that shifts the max load later.

These results strongly indicate that buildings with PCM walls can experience more consistent thermal levels, yielding less strain on the heating and cooling systems. In addition, these results show that structures with PCM experience time shifts for the peak hours of energy demands and reduces the overall positive heat flux, allowing for the heavy energy loads to occur when energy is cheaper, thus saving consumers money while conserving energy. The culmination of each metric reduction in favor of PCMs translates into significant energy and money-saving potential. The initial investment of installing PCMs on average can be paid back within a 7-to-10-year period, but this period can vary depending on geographic location and the initial investment [20]. Furthermore, the load shifting many PCM walls experience can access energy rates that are 20-35% of the peak energy price [21], [22]. On top of this, one study found that during a 12-day study, ten of those days experienced energy conservation ranging from 16% to 100% for an office building outfitted with PCMs [23].

Despite the positive results of PCMs in walls, there are still challenges that must be solved before PCMs can be widely used. Lack of knowledge about PCMs cost to retrofit into existing buildings, corrosion, and flammability plague the incorporation of PCMs [24]. However, an evident challenge comes from the fact that most research has been conducted under extreme conditions (summer and winter days) and not over everyday conditions. One study estimates that PCMs are only effective for about 40% of the entire year because of the different seasons and weather conditions experienced throughout the year [14]. Tackling this issue requires a different type of research that focuses on best practices.

One way of conducting this research would be through the creation of a new metric that measures how each wall works in conjunction with the others towards the goal of limiting heat transfer. The current metrics for PCM wall effectiveness looks at how well individual walls are at reducing heat transfer, but these measures do not consider the synergy of the walls with each other. In other words, the current measures do not consider if all walls are working together to attain the main goal of keeping heat transfer close to zero. Studying the synergy of the walls could reveal if there is a more optimal combination of walls, some retrofitted with PCM and some not, that could lead to more energy efficient buildings.

METHODOLOGY

Data acquisition

The data used in this study was collected in a previous study at the University of Kansas in Lawrence, Kansas [25]. Briefly, two test houses (Figure 3) were constructed using typical North American construction practices (Figure 4). One house was constructed as the control house and did not contain any enhancement from PCMs. The second house, the PCM house, was constructed with PCM pouches embedded within the wall insulation. Paraffin PCM (n-Octadecane) (T_m (K) = 301.2; Cp (J/kg*K) = 2150 (Solid-phase), 2180 (Liquid phase); k (W/m*K) = 0.358 (Solid-phase), 0.152 (Liquid phase) [27]) was encapsulated in reflective foil PCM pouches and chosen for its ideal properties and cost effectiveness (Figure 5) [25]. The houses were both outfitted with a south-facing window, chilled water cooler, and asphalt shingles and were insulated with a fiberglass and cellulose mixture [25].

Figure 3: Test houses [26]

Figure 4: Typical North American residential construction [26]

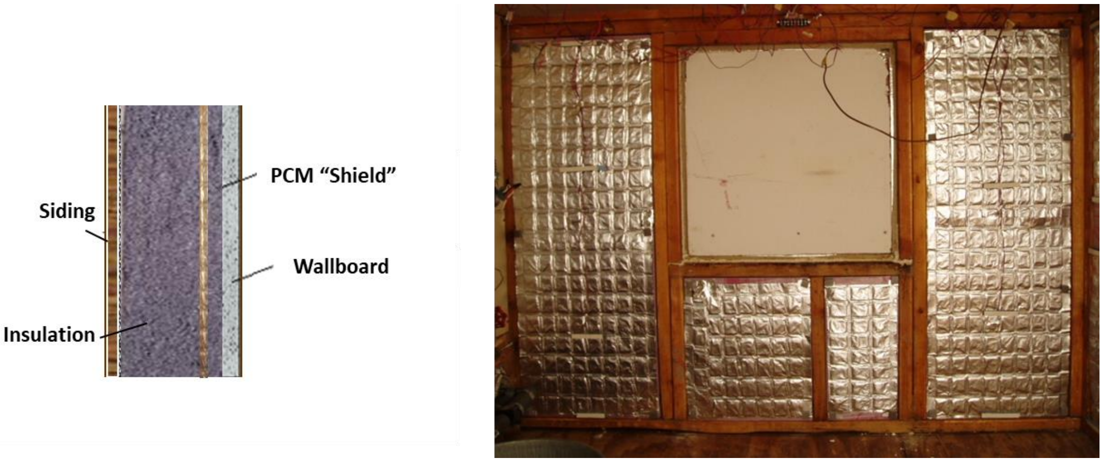

Figure 5: PCM pouches incorporation [26]

Data on heat transfer was collected from the four cardinal orientations of the homes (North, East, South, and West) in a 3x3 grid pattern (Figure 6) [25]. Data was collected every thirty minutes over two days in September. The experiment collected temperature, relative humidity, and heat flux over the course of the test period utilizing Type T thermocouples, relative humidity transducers, and thermal flux meters respectively [25]. The sensors were attached directly to the walls on both the inside and the outside of the wall in a three-by-three grid pattern. All the data is available for all cardinal directions but for this study only heat fluxes were used.

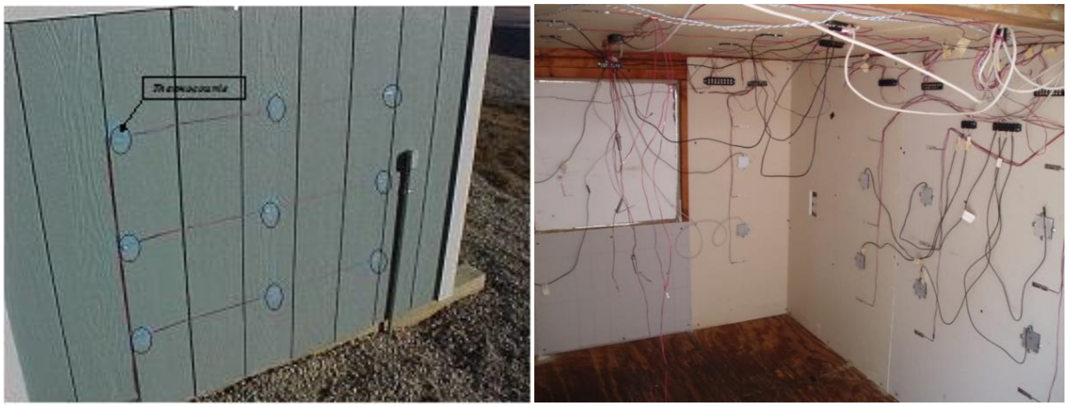

Figure 6: Outdoor (left) and indoor (right) sensor arrangement [26]

Data Analysis

The analysis was run using seven measures, including heat flux reduction, time delays, averages of the heat flux, and standard deviation of the heat flux, to fully understand the impacts of incorporating PCM into homes. Reducing heat flux means reducing the flow of energy, or heat in this case, in and out of the building to help reduce the wear and tear on HVAC systems. Time delays work by utilizing the heat storing capacities of PCMs to delay when the heat begins to infiltrate the living space. This delay, called a time delay, shrinks the positive heat flux curve (heat entering the living space), which also delays when the positive heat flux first occurs. The time delays result in reduced stress on HVAC equipment, reduced energy cost, and a reduced maximum heat flux. The last two metrics are the typical averages and standard deviations used in statistics, which measured how close to zero each simulation could get. A heat flux of zero is the ideal condition because it indicates that there is no loss or gain of heat for the house.

For all analyses, MATLAB R2021a (MathWorks, MA) was used. First, fourteen test houses were simulated using the experimental data previously collected. Previous data covered a control home and a home with PCM in all walls. The fourteen simulated houses were created using a sequence of four binary numbers, where a 0 equated to a control wall and a 1 equated to a PCM wall. Using this numbering system, the control home can be designated 0000, whereas the home with PCM in all walls can be designated as 1111. The order of the numbers in the four-digit combination corresponded to the cardinal directions of the walls: west, south, east, and north. For example, the simulated test home 5 corresponded to the binary combination 0101, which translates to a simulated house with control walls (no PCMs) for the west and east wall, and PCM walls for the south and north walls.

For each of the simulated (14) and tested (2) houses, the previous seven measures were used to gauge the effectiveness and synergy of PCM with different simulated wall configurations. Before extracting the measures, the heat fluxes for the four walls were added together to create one heat flux curve to simplify the analysis and directly compare the houses rather than individual walls. For each house and day, the following measures were extracted: maximum heat flux, total heat flux, time delays (start of positive heat flux, peak time, and end of positive heat flux), average heat flux, and the standard deviation. The first five measures are the most common measures used by researchers working on the effectiveness of PCMs, and the last two were added to determine how close the simulations were to the ideal heat flux scenario, which would be zero heat flux.

Using the two experimental and the fourteen simulated homes, the contribution of each wall towards reducing heat transfer and keeping it close to zero was determined. To measure a wall's contribution, the percent difference between the control house and the measured value was found by taking a wall combination and subtracting it from an identical wall configuration differing only by omission of the wall of interest. For example, if the wall of interest was the northern wall and the home combination was 0011 (WSEN), the percent difference for each of the extracted measures was (0011-0010)/0010 (i.e., comparing it to a home identical except for lacking PCM in the northern wall). Using this method in all combinations where the north wall had PCM, the wall's contribution was quantified. This process was repeated for the four walls and for each of the seven measures, allowing us to understand in detail how particular walls contributed to the simulated heat flow in or out of the home.

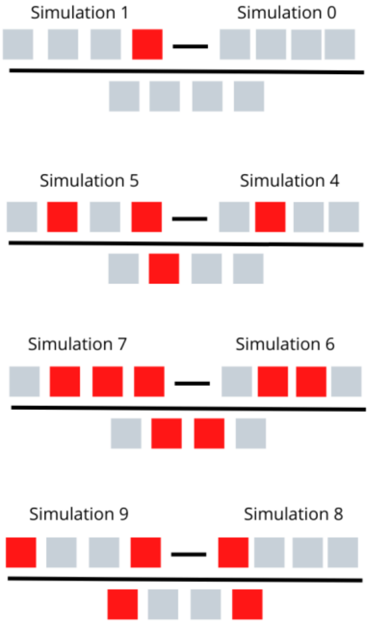

Figure 7: Example of wall contribution calculation

RESULTS

Heat flux heat map

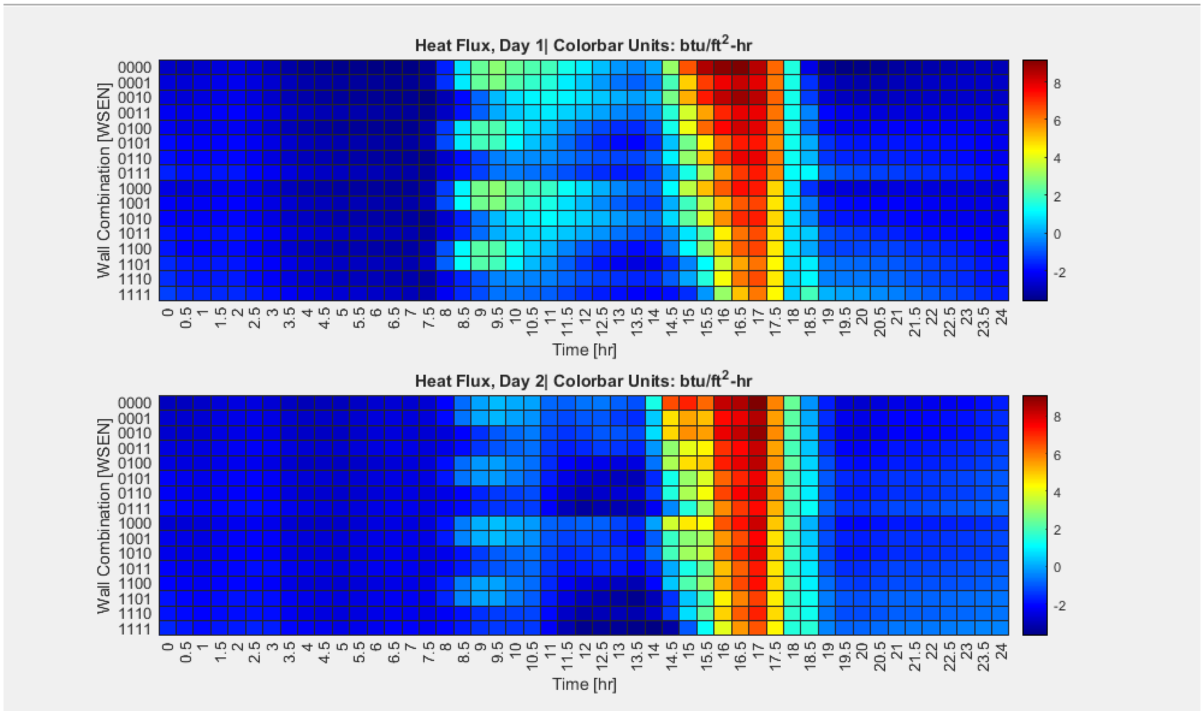

Figure 8: Heat flux heat map

The graphic above depicts the heat flux for each day using a heat map to show the heating periods throughout the day. Some simulations experienced two heating periods, heating both in the morning hours and during afternoon period (i.e., the typical heating period). The eight simulations above that experienced two heating periods all lacked a PCM wall in the eastern direction. Similarly, the eight simulations containing an eastern PCM wall only had one heating period (the afternoon period), and the addition of the eastern wall helped reduce the overall heating period. Furthermore, an eastern PCM wall also showed heating occurring later in the day compared to other simulations without an eastern PCM wall. Additional investigation reveals that the western wall had a similar effect when retrofitted with PCMs, but it influenced the back half of the heating curve (late afternoon) rather than the beginning (morning). Additionally, the southern wall when outfitted with PCMs was observed to lower the peak heat flux values more than other walls when added to simulations. Overall, the heat map revealed that by adding more PCM walls to a simulation, the peaks could be reduced and the home could experience more consistent temperatures. This result was expected, but additional insights arise in evaluating specific measurements.

Graphs of the seven measures

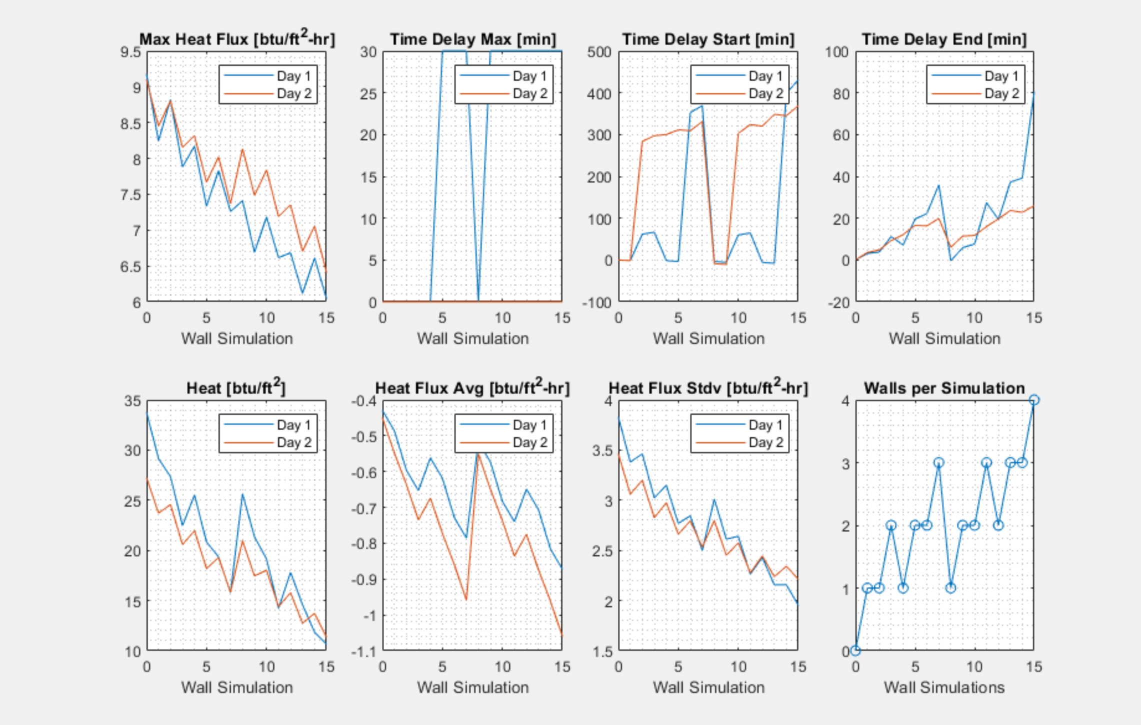

Figure 9: Graphical summary of results

The figure above depicts the seven measures in a graphical manner, starting with the peak heat flux and continuing to time delays, total heat, average heat flux, and heat flux standard deviation. Each graph is set up the same way, showing the results for both test days with the house simulation number on the x-axis and the unit measure on the y-axis. The x-axis starts with the control house (simulation 0) and finishes with the full PCM house (simulation 15). The final graph represents the number of walls in each simulation, which shows an inverse trend compared to the heat flux measurements. Further detail is given on the individual measures below.

Maximum heat flux

Maximum heat flux refers to the peak heat flux record for each simulation during each day. One of the main objectives of adding PCMs to wall production is to lower the peak heat flux homes experience during the day. Both days followed the same general trend downward as more PCMs were added with only small deviations occurring due to differences in temperature and weather conditions. The graph below represents each of the max heat fluxes for each simulation during each test day.

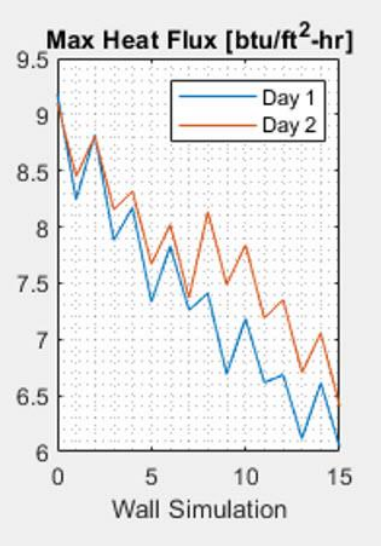

Figure 10: Maximum heat flux

As more PCMs were added to each simulation the maximum heat flux decreased; however, the graph does not show a steady decrease in maximum heat flux. This phenomenon can be explained by two ideas. Firstly, simulations rotated between one, two and three PCM walls until simulation 15 (refer to Figure 7 for number of PCM walls per simulation), which would affect the results, and secondly, the walls with PCMs also alternated between west, south, east, and north with each wall contributing differently to the main objective. Moreover, this trend is repeated in the other graphs depicting heat flux data. Because the x-axis does not represent a simple linear increase in PCM but rather these variations, the trend line of decreasing heat flux is not straight.

With this in mind, a few data points still showed intriguing results. The first few data points of interest were simulations 1 and 2. Though their results did not decrease significantly from the control house, an interesting phenomenon occurred within the simulations. Both simulations had only one PCM wall, but the results for each simulation were surprisingly different. Simulation 2 (0010) had a peak result that was like the control house's peak even though it contained a PCM wall. Meanwhile, simulation 1 (0001) had a peak that was less than both the control house and simulation 2. A similar occurrence happened on the opposite side of the spectrum, leading to a more positive result. Simulation 13 (1101) had a result that was comparable to the full PCM house, whereas simulation 14 (1110) had a higher result than both simulation 13 and the PCM house. The only difference in these two instances were which walls had PCMs incorporated into them which implies the potential existence of synergy between walls.

Time delays

Time delays deal with the shifting of heating load away from peak load times (typical in the early to midafternoon) so that homeowners can utilizes the cheaper energy prices offered in later parts of the day. Time delays are achieved by reducing the heating period and delaying when heat begins to enter the building. However, a time delay can also affect when the peak heat flux occurs or when the house stops gaining heat. Time delays in any case save money and reduce energy consumption. Regarding the peak heat flux time delays, only the first day showed any evidence of shifting the peak time away from typical peak times. Furthermore, only simulations with two or more PCMs achieved any delay for the peak heat flux.

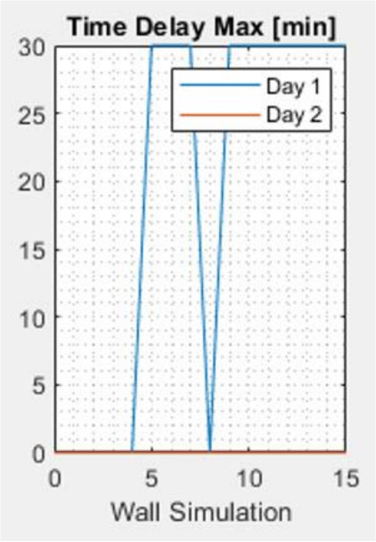

Figure 11: Peak time delays

Start time delays are the most common and easiest to achieve with the use of PCMs. Despite this, results showed that to achieve any sort of significant delay required the use of two or more PCM walls. Similarly, like most of the measures in this study, the addition of more PCM walls resulted in better results overall. Interestingly, the start time delays were one of the only measures to have a significant and noticeable difference between day one and day two.

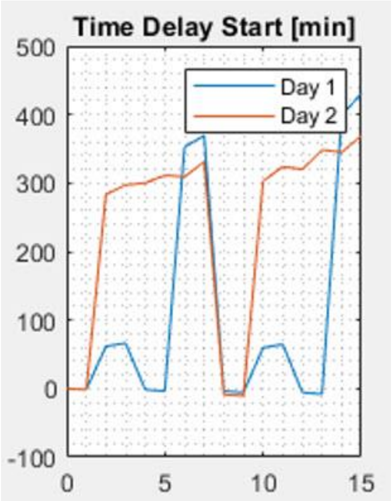

Figure 12: Start time delays

The first day saw simulations 6 (0110), 7 (0111), and 14 (1110) registering results similar to the full PCM house though not utilizing PCM walls in every wall. The three simulations mentioned contained more than two PCM walls and always had PCMs in the Southern and Eastern wall. For day two, more simulations registered positive results. Simulations 2 through 7 and 10 through 14 had very similar delays to one another and to the full PCM house. Similar to the first day, these simulations contained either an Eastern wall or a combination of a Western and Southern wall.

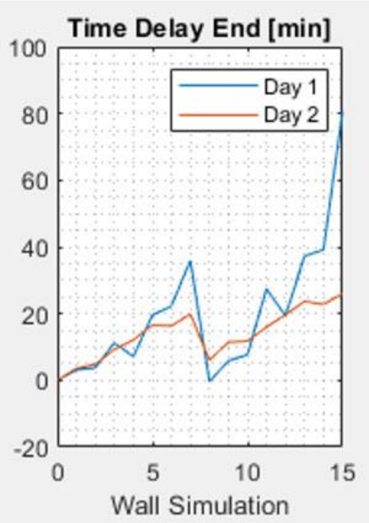

Figure 13: End time delays

The final time delay evaluated was the end time delay, or when the house was no longer gaining heat. Unlike the start time delay, which pushes the start of heating back, end time delay pushes the end of heating forward. In other words, the house will stop gaining heat sooner and begin the cooling process sooner. End delays had a steady rise across the simulations has more PCMs were added to each test house. Simulation 8 (1000), performed as well as the control house even though the simulation contained a PCM wall. Typically, the most effective test homes were those that utilized three or more PCMs retrofitted into the walls. In this study, simulations 7 (0111), 13 (1101), and 14 (1110) had results comparable in end time delays to the full PCM house during the first test day. The same simulations also had very good performances during the second day of testing; however, the results during day two were not as impressive as day one.

Total heat

Total heat was found by taking the integral across all positive heat fluxes for each day. The integral allowed for heat flux to be transformed into heat entering per square foot. This allowed determination of the total heat entering during a day’s heating period. Due to wall combinations, some house experienced a morning heating period and an afternoon heating period, but for research purposes, any positive heat flux was used for the integral’s results.

Figure 14: Total heat

In previous results, adding more PCMs helped reduce the measured value, in this case heat entering the building. From control house to full PCM house, results show an almost twenty-four [btu/ft^2] reduction in heat entering the building for an entire heating period. Simulations performing the best usually contained a western and southern wall or a western and eastern wall. Not significant outliers were found within under these measuring parameters.

Average heat flux

Averages were gathered by summing the entire test day and averaging the heat flux values for each simulation. In every case, the simulations spend most of the time experiencing negative heat fluxes, resulting in every simulation having a negative average. In this study's case, negative heat flux represents heat flowing out of the built and into the natural environment. Though heat is being lost the majority of the time, the heat gained during the heating period has a larger impact on indoor environment than the heat lost during the cooling period.

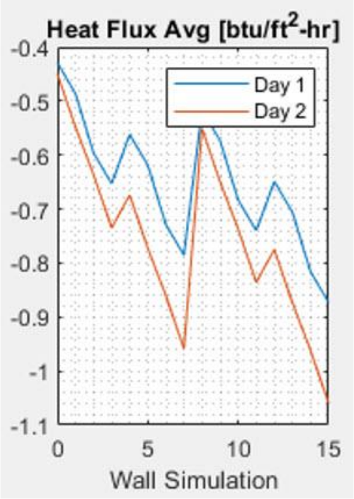

Figure 15: Average heat flux

The addition of more PCMs resulted in a lower average heat flux and thus was more likely to reverse the flow of heat. The simulations that produced the lowest averages were those with three

PCMs. With this in mind, simulations 7 (0111) and simulation 14 (1110) produced averages comparable to the full PCM house without having to utilize four PCM walls. Furthermore, if simulations did not employ three PCM walls, utilizing an eastern PCM wall or a combination containing the western and southern PCM wall would result in a lower heat flux average like houses with three or more PCM walls.

Standard deviation

Standard deviation, like average, compared the data for the entire day and gauged its consistency throughout the day. For this measure, a value close to zero meant more consistent indoor temperatures. It is important to note that a low standard deviation does not translate to a lower heat flux but rather that the heat flux stays at a more consistent value. Consistency is key in reducing the stress on HVACs and reducing energy consumption.

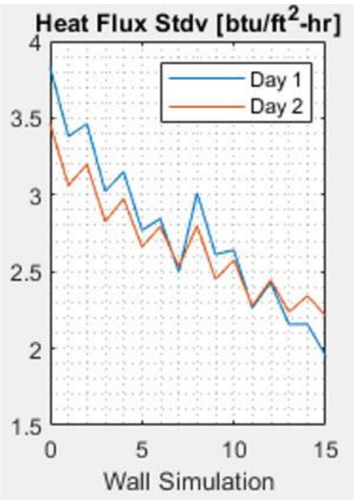

Figure 16: Standard deviation of heat flux

Again, the addition of more PCMs resulted in a more positive result for the measure. In general, having three PCM walls meant a result comparable to the full PCM house, but simulation 7 (0111) did not perform as well as its three PCM simulations counterparts. Upon further investigation, the combinations of walls revealed that simulation 7 lacked a western facing wall.

Quantification of wall contributions (non-time delay measures)

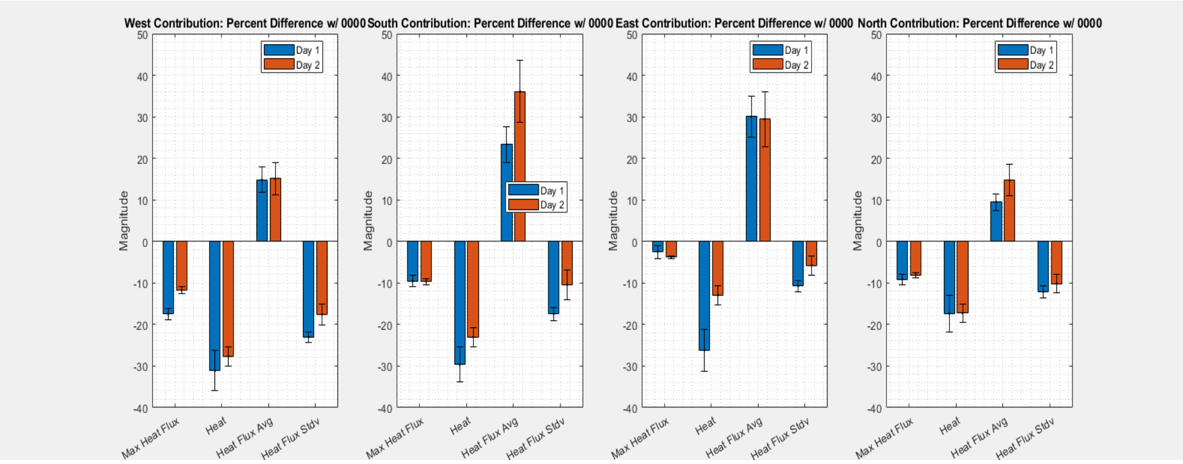

Figure 17: Wall contributions for non-time delay measures

Figure 17 depicts the wall contribution for each individual wall across the four measures without time. The walls are shown individually starting with the west wall on the left followed by the south, east and north walls. From the figure, the west wall (furthest left) contributed most to the reduction of the peak heat flux and the standard deviation values of the home. In both these measures, the southern wall contributed the second most to the aforementioned measures. The east facing wall, however, contributed the most to the heat flux averages, or in other words helped to reduce the average heat fluxes, and again the southern wall followed behind being the second largest contributor. For the last measure, total heat, the west, south, and east facing walls all had comparable results to one another. The northern wall made little contribution to the main goal of the measures usually contributing the least or second-to-least.

Wall contribution (time delays)

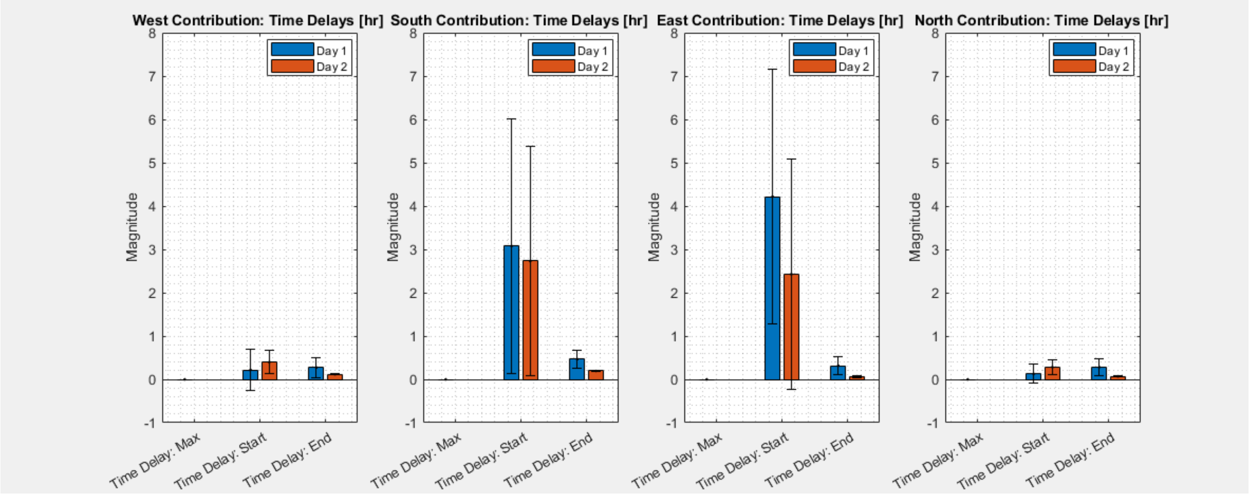

Figure 18: Wall contribution of time delays

Like the last figure, Figure 18 depicts the individual walls and their contributions to the time delays for the start, peak and end of the heat flux curve. Again, the figure starts with the west wall and finishes with the north wall. The contribution of having PCM in specific walls to energy efficiency was most noticeable in delays to the start of the heating periods of each day. These delays were led by the southern wall and eastern wall, respectively. Little to no contribution was seen by individual walls for peak time delays and end time delays. Walls were unable to effectively delay the timing of heating on their own and often required the combination of multiple PCM walls to achieve a significant and meaningful delay.

DISCUSSION

Synergistic trends

The research presented simulated fourteen unique test houses by alternating non-PCM and PCM wall combinations. One of the goals of this study was to determine if there existed a synergistic trend between walls, and though the results were inconclusive, some promising patterns emerged that imply the existence of synergy between specific walls. Performance for each measure was heavily influenced by the number of PCMs used and the location of the PCMs in the simulated house. Simulations had varied results across the board, with some performing well in one measure but poor in another measure. Through analysis of the results, patterns of synergy emerged among wall combinations and their performance in specific measures. Each measure saw different simulations performing better, which supports the idea that a synergy exists between certain walls for certain measures, summarized below.

Max heat flux

Some simulations, even though they contained a PCM wall, performed similarly to the control house or worse than its counterparts. Simulations with the eastern wall resulted in a higher peak fall compared to simulations with a similar wall combination. Logically, this does not make sense: with the sun rising in the east, it is assumed that the eastern wall would receive the most sunning; however, due to the reheating of the earth's surface in the morning, the heating process does not contribute as much to the building as it does when the earth's surface is sufficiently heated. Furthermore, simulations with the southward or westward facing wall did see significant reductions in the maximum heat flux value.

Time delays

Time delays provided the least significant results across the board. Overall, it was difficult to find a trend among the results, and often the data revealed no significant patterns. Delaying the peak, start, and end of the heat flux is imperative for achieving maximum savings. A delay in any of these can shift the curve to access a cheaper energy and shorten the time the house is experiencing heat gained. Achieving a significant delay for the timing of when the peak heat flux occurs is one of the most difficult yet most beneficial time delays. A delay in the peak can move the heaviest loading time from the most expensive period for energy cost, which allows for consumers to access cheaper energy. Though no individual wall contributed directly to a significant peak delay, using a combination of PCM walls, usually including three or more, would directly result in a peak time delay.

Like the peak time delay, having a start time delay could result in consumers accessing cheaper energy. Achieving the most significant time delay required reducing the heat flux gained in the early part of the days. Logically, including the eastern wall should be the best option, but the results showed significant delays in simulations that included the western and southern wall retrofitted with PCMs. These combinations can reduce the heat gained by the building during the morning periods, which reduces the heat entering the living space. The reduction of heat flux in the morning hours shortens the overall positive heat flux curve thus requiring less HVAC intervention to keep indoor temperatures stable.

Delaying the end of the heat flux curve worked identically to the start delay except reversed. For significant end time delays, the western wall would be utilized to capture the warm afternoon sun's heat. Additionally, like the peak time delays, utilizing three or more PCM walls typically resulted in more favorable time delays. Furthermore, like the start time delays, simulations containing the west south PCM wall combination resulted in more positive time delays. Using time delays can help to shrink the amount of time heat is entering the building and moves the peak to a part of the day when the grid is under less strain resulting in cheaper energy prices.

Total heat

Prioritizing walls that will receive the most sunning throughout the day is ideal for reducing the total heat entering the building, but the sun's intensity should also be considered when thinking about adding a PCM wall. For instance, the west wall will receive the more intense afternoon sun, but the eastern facing wall will receive sunning for longer periods of time. The results showed a synergistic trend between the west, east, and south facing walls and their ability to reduce the amount of heat entering the simulated home. For these reasons, ensuring that a combination of the aforementioned walls will result in more favorable heat results.

Average heat flux and standard deviation

Most of the measures strive at reducing the heat flux as much as possible, and though heat flux will never truly be stabilized at zero, due to infiltration, or the phenomena of air seeping through existing crevices in the structure. Standard deviation and average heat flux aim to achieve a heat flux of zero despite the issue of infiltration. The other measures look at only a portion of the data, typically the heating period during the day, but average heat flux and standard deviation consider the whole data set. For the measures to register positive results, the data needs to be as close to zero as possible. A near-zero average means heat is not entering or escaping the home, which translates to constancy in indoor air temperatures. Similarly, standard deviation measures strive to be as close to zero as possible.

Having a positive or negative average heat flux describes the direction of heat flow the simulation experienced the most over a twenty-four-hour period. A positive average heat flux indicates the heat is flowing into the house, whereas a negative heat flux indicates that heat is flowing out of the house. Initially, the simulations with little to no PCM involvement had the best averages (averages closest to zero but still negative) but considering how the averages were taken this can be easily explained. Simulations without PCMs experienced more extreme highs than simulations with PCMs, so the extreme peaks helped to pull the average up closer to zero resulting in skewed results. To combat these ambiguous results, focusing on a balance between infiltrating and escaping air will help keep heat flux averages close to zero.

Standard deviation works identically to average heat fluxes. Though the standard deviation results are positive, it is ideal for the results to be as close to zero as possible. Results registering close to zero indicate indoor air temperatures are remaining more consistent. Attaining zero for standard deviation translates into zero heat loss or gained.

Overall, the goal of finding a synergistic measure between walls was a partial success. Trends began to become clearer as the data was analyzed. When broken down by simulations, certain wall combinations begin to appear more frequently and hint at a synergistic trend with that combination. For more concrete evidence of a synergistic trend, more data needs to be analyzed over a longer period to show the trend continues beyond the two days used in this study.

Recommendations

The most important thing to consider is the purpose of adding PCM walls to a structure. Is reducing heat flux the main goal, achieving a time delay, having consistent indoor air temperatures, or a combination of these? The most obvious answer is to use the full PCM house to achieve the best case for all scenarios, but PCMs are expensive and there may be a more cost-efficient method for achieving the same results. Simulations with one wall performed similar to the control house, so recommending and utilizing a single PCM wall would be a waste of resources. Two-walled and three-walled simulations had resulted most similar to the full PCM house. The best two-walled simulation was simulation 6, which corresponded to (0110) Other two-walled simulations had lower results than the control house, but the results were not significant enough to warrant implementation. For three-walled simulations, simulations 13 and 14, which corresponded to (1101) and (1110), respectively, had the best combinations.

Wall contribution

The results, as discussed in the previous section, clearly showed the contributions of each wall for each of the measures. This portion of the study can be considered a success because walls can now be recommended with some degree of confidence based on their contribution to the goal. Contribution can also be used to identify synergistic trends. Where one wall may lack in a measure, another wall could be exceptional in it. By combining these two walls together a more powerful combinations can be attained. The following section pertains to recommendations based on a wall's contribution to a measure and its synergy with other walls.

Based on contributions and overall results, the south facing wall performed the best or second-best in all measures. Additionally, the western wall also proved very positive and should be highly considered when retrofitting buildings with PCMs. The eastern wall also had comparable results to the western and southern walls. The northern wall, however, contributed little to most measures and could be considered to be left out with little to no noticeable negative effects. Some results showed no or little contribution from a specific wall, yet for the measures overall the results varied widely. This phenomenon points to the need of walls being used in conjunction and a synergistic connection between walls. One of the most notable occurrences of this was during time delays, especially for peak time delays. Though there are recorded occurrences of time delays occurring, significant results were only attained when multiple walls were used together.

CONCLUSION

The aim of this study was to determine synergistic trends between individual walls and each wall’s contributions for individual measures. Because of the strong results from the wall contribution study, the existence of wall synergistic trends likely exists between walls. Some of the walls with the strongest synergy included the west, south and east wall. When in combination with one another, they performed extremely well and simulation 14, which contained all the three walls, had results comparable to the full PCM house. Wall contributions strengthened the previous results by showing the strengths of individual walls. From the wall contribution study, the western and southern facing walls contributed the most in the seven measures studied, and they were the walls that showed the most synergy. When these two walls were utilized within a simulation, that simulation performed the best. (Refer to simulations 12, 13, and 14). Therefore, utilizing wall contribution and synergistic measures can be used to advise the best combination of PCM wall to use. Based on the recommendations, investors can use less PCM to get the same results, which can save money and energy.

Further fesearch

The introduction new measuring techniques and simulations would allow further and more in-depth research on new and existing data. Furthermore, the concept of simulations can be applied to other data including wall temperatures and wall humidity. The simulated house also gives insight on unique wall combinations to consider testing in real life applications. Researchers should also consider running longer studies that encompass multiple seasons. Finally, a comprehensive cost analysis for wall inclusion could be beneficial for determining best practices for incorporating PCM walls into structures.

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