International Journal of Engineering Applied Science and Management
ISSN (Online): 2582-6948
Vol. 6 Issue 6, June 2025

PCM based heating - Cooling solutions for energy efficient building

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Abstract: *A concept of using phase change material (PCM) for improving cooling efficiency of an air-Conditioner had been presented under Indian climate. Latent heat storage using phase change materials (PCMs) attract more in recent years. But most of the Phase change material (PCMs) present low thermal conductivity, which decrease the heat transfer rate and leads to low energy utilization efficiency of the storage system. Paraffin waxes melting point at around 20 0C was selected to evaluate the thermal performance by reducing the air temperature entering the evaporating coil. Study of the various arrangements of the copper tube inside the PCM cylinder to find out the effective arrangement. So that we can enhance the heat transfer rate in between the copper tube to PCM material or fromPCM to copper tube. Moreover, the mathematical model of the air-conditioner with the PCM storage was developed and verified with the testing results.*

Keywords: *Air-conditioner, Phase change material, Paraffin waxes, Thermal energy Performance.*

1. Introduction

In recent years, the demand for sustainable and energy-efficient building solutions has gained paramount importance due to escalating energy costs, environmental concerns, and the pressing need to mitigate climate change. Heating, ventilation, and air conditioning (HVAC) systems are pivotal components of a building's energy consumption, accounting for a substantial portion of total energy usage. As such, innovative approaches to enhance the efficiency of HVAC systems have garnered significant attention from researchers, engineers, and policymakers alike. Phase Change Materials (PCMs) present an intriguing avenue for revolutionizing the heating and cooling processes in buildings. PCMs are substances that have the unique ability to store and release large amounts of thermal energy during phase transitions, such as melting or solidification, at a nearly constant temperature. This characteristic enables them to absorb excess heat during periods of high ambient temperature and release it when the temperature drops, thereby reducing the need for conventional HVAC systems to regulate indoor climate conditions. The application of PCMs in building construction and energy management offers several notable advantages. Firstly, they can facilitate the shift of energy consumption away from peak demand periods, thereby alleviating stress on the electrical grid. Additionally, PCMs can enhance indoor thermal comfort by stabilizing temperature fluctuations and reducing the reliance on active heating and cooling systems. This not only contributes to energy savings but also provides a more comfortable and productive environment for the occupant.

2. Research Methodology

Analyzing a building in DesignBuilder typically involves several steps to assess its energy performance, thermal comfort, day lighting, and other relevant factors. Below are the key steps in the analysis process:

1. Building Geometry Input: Start by creating the building geometry within DesignBuilder. This involves specifying the building's layout, including

walls, floors, roofs, windows, doors, and any other structural elements.

2. Material Properties: Define the material properties of each building component such as walls, roofs, windows, and doors. This includes parameters such as thermal conductivity, specific heat, density, and optical properties for windows.
3. Climate Data Input: Import or select the appropriate climate data for the location of the building. Design Builder provides access to a range of weather files representing various climates worldwide.
4. Occupancy and Activity Profiles: Define the occupancy schedules and internal heat gains within the building. This includes specifying the number of occupants, their activity levels, lighting, equipment, and other internal heat sources.
5. HVAC System Setup: Configure the heating, ventilation, and air conditioning (HVAC) system for the building. This involves selecting HVAC equipment types, capacities, control strategies, and operating schedules.
6. Simulation Settings: Set up simulation parameters such as simulation duration, time step, and convergence criteria. These settings ensure accurate and efficient simulation results.
7. Energy Simulation: Perform an energy simulation using Design Builder's simulation engine. This calculates the energy consumption of the building based on the input parameters, weather data, and operating conditions.
8. Results Analysis: Analyze the simulation results to evaluate the building's energy performance. Design Builder provides various output reports, graphs, and visualizations to interpret the results effectively.

The building was modeled with Designbuilder® (DB)for dynamic comparison. One of the essential features of the program me is the provision and use of real hourly weather data in the simulations on the basis of a variety of cities all over the world [28]. Thus, the user can assess the performance of the building under actual operating conditions. Moreover, the complex interactions inside a building result in a highly nonlinear mass and energy balances which become time-consuming and cumbersome to attempt solving the problem using numerical formulations [24,29]. The heating and cooling loads were calculated according to the ASHRAE-approved “Heat Balance” method, implemented in EnergyPlus [30]. The ASHRAE Standard55-2004 was used for the determination of the discomfort hours.

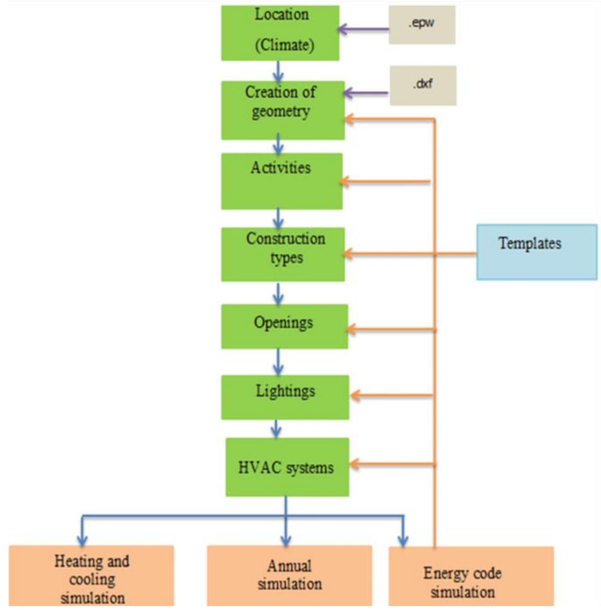


Fig. 1. Design Builder Flow Chart

3. Result and Discussion

3.1 Simulation Results of Control Wall

Simulation Results of Control Wall: The external building wall without PCM (control wall) is composed of three layers: plaster coating, brick, and plaster coating (See Figure 3.4a). Based on the property listed in Table 3.3, the simulation has been done by using DesignBuilder. Simulation results are reported in terms of variation of air temperature, radiant temperature, operative temperature and outside dry-bulb temperature, other output results, latent load, system load, heat balance, Illuminance level, distribution of velocity and temperature.

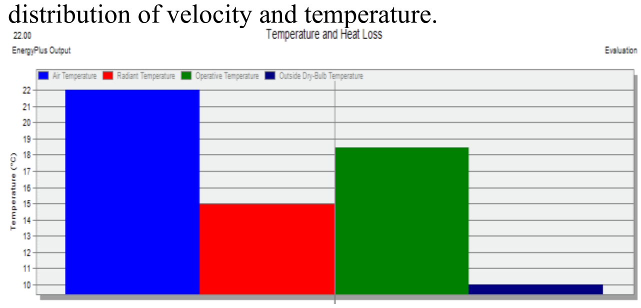


Fig. 2. Variation of air temperature, radiant temperature, operative temperature and outside dry-bulb temperature with no PCM.

Air temperature refers to the temperature of the air surrounding occupants within the building. It is a fundamental parameter affecting thermal comfort and is influenced by factors such as heating, cooling, ventilation, and solar gains. Variations in air temperature are observed based on seasonal changes, time of day, building orientation, and HVAC system operation. DesignBuilder software allows users to simulate and analyze air temperature distributions within the building spaces, helping to optimize HVAC system design and operation for improved comfort and energy efficiency. Radiant temperature represents the temperature of surfaces within the building that emit or absorb thermal radiation. It includes surfaces such as walls, floors, ceilings, and windows. Radiant temperature influences occupants' perception of warmth or coolness, especially when they are in proximity to surfaces emitting or absorbing radiant heat. DesignBuilder enables users to model radiant temperature distributions in building spaces, considering factors such as solar radiation, internal heat gains, and surface properties. By optimizing surface materials and configurations, designers can enhance thermal comfort and reduce energy consumption.

Operative temperature is a combined measure of air temperature and radiant temperature, representing the average temperature experienced by occupants. It accounts for both convective and radiant heat transfer and is a key parameter for assessing thermal comfort. DesignBuilder software allows users to calculate operative temperature based on dynamic thermal simulations, considering factors such as air temperature, radiant temperature, air velocity, humidity, and metabolic rate. By analyzing operative temperature distributions, designers can identify areas of potential discomfort and implement design interventions to improve occupant satisfaction.

The outside dry-bulb temperature refers to the ambient air temperature external to the building envelope. It varies with outdoor weather conditions, seasonal changes, and geographic location. DesignBuilder enables users to input meteorological data or utilize weather files to simulate outside dry-bulb temperature variations. Understanding outside temperature profiles is crucial for optimizing building envelope design, HVAC system sizing, and energy management strategies.

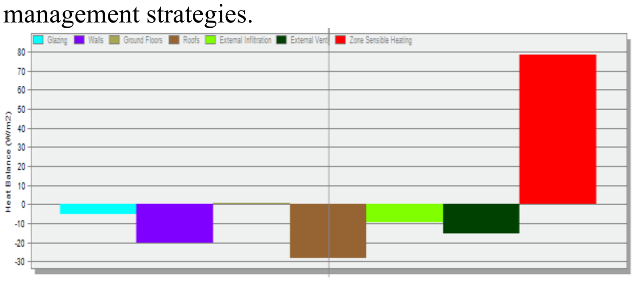


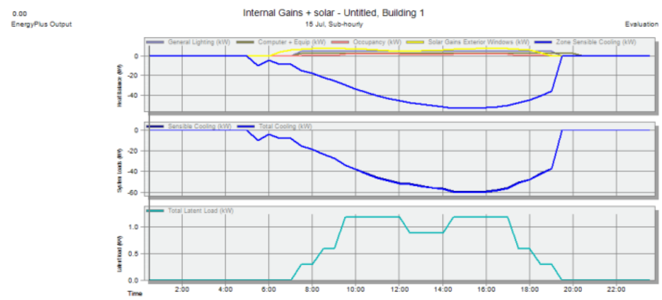
Fig. 3. Variation of air temperature, radiant temperature, operative temperature and outside dry-bulb temperature with no PCM.

Temperature and Heat Loss

EnergyPlus Output | Evaluation

Air Temperature (°C)	22.00
Radiant Temperature (°C)	14.93
Operative Temperature (°C)	18.47
Outside Dry-Bulb Temperature (°C)	10.00
Glazing (W/m2)	-5.35
Walls (W/m2)	-20.44
Ground Floors (W/m2)	0.52
Roofs (W/m2)	-28.08
External Infiltration (W/m2)	-9.63
External Vent. (W/m2)	-15.37
Zone Sensible Heating (W/m2)	78.28

Fig. 4Output with no PCM.



Internal Gains + solar - Untitled, Building 1

EnergyPlus Output | 15 Jul, Sub-hourly | Evaluation

Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
General Lighting (kW)	0.00	0.00	0.00	5.03	5.03	5.03	5.03	5.03	5.03	0.00	0.00
Computer + Equip (kW)	0.16	0.16	0.16	2.96	2.96	2.96	2.96	2.96	2.96	2.96	0.16
Occupancy (kW)	0.00	0.00	0.00	0.48	1.91	1.91	1.43	1.91	0.96	0.00	0.00
Solar Gains Exterior Windows (kW)	0.00	0.00	0.25	7.82	7.32	5.35	6.43	7.88	6.17	0.00	0.00
Zone Sensible Cooling (kW)	0.00	0.00	-4.21	-17.86	-33.71	-45.90	-52.18	-53.06	-44.93	0.00	0.00
Sensible Cooling (kW)	0.00	0.00	-4.21	-18.55	-37.91	-51.12	-56.48	-58.56	-47.31	0.00	0.00
Total Cooling (kW)	0.00	0.00	-4.21	-18.55	-37.91	-51.77	-56.94	-59.18	-47.63	0.00	0.00
Total Latent Load (kW)	0.00	0.00	0.00	0.29	1.18	1.18	0.88	1.18	0.59	0.00	0.00

Fig. 5Variation of latent load, system load and heat balance with no PCM.

In building analysis conducted without Phase Change Materials (PCM) using DesignBuilder software, variations in latent load, system load, and heat balance are critical factors influencing indoor environmental conditions, HVAC system design, and energy performance. The latent load represents the portion of the total cooling load attributed to moisture removal from the air within the building. It accounts for humidity control requirements, such as dehumidification during periods of high humidity. Without PCM, latent load variations are primarily influenced by factors such as outdoor humidity levels, indoor moisture generation (e.g., occupants, cooking, bathing), ventilation rates, and infiltration. DesignBuilder software enables users to simulate and analyze latent load profiles based on dynamic thermal simulations and psychrometric calculations. Understanding latent load variations is essential for properly sizing and configuring HVAC systems, ensuring effective moisture control and maintaining indoor air quality.

The system load represents the total heating or cooling demand required to maintain desired indoor temperature and humidity conditions. It encompasses both sensible and latent loads and serves as a fundamental parameter for HVAC system sizing, selection, and operation. In the

International Journal of Engineering Applied Science and Management
ISSN (Online): 2582-6948
Vol. 6 Issue 6, June 2025

absence of PCM, system load variations are influenced by factors such as outdoor temperature fluctuations, solar gains, internal heat gains, ventilation rates, and thermal characteristics of the building envelope. DesignBuilder software facilitates comprehensive system load analysis through dynamic thermal simulations, allowing users to evaluate heating and cooling demands under different operating conditions. By accurately assessing system load variations, designers can optimize HVAC system performance, energy efficiency, and occupant comfort.

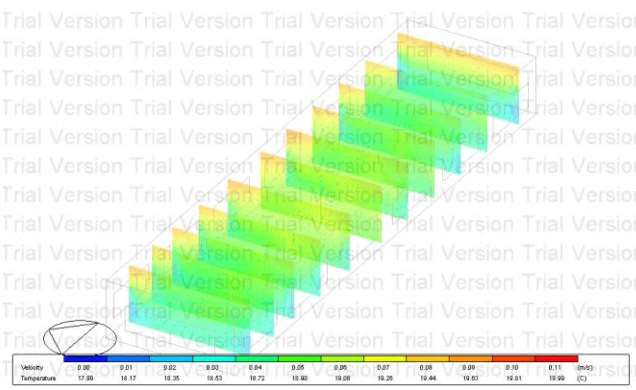


Fig. 6 Distribution of velocity and temperature with no PCM

The heat balance represents the equilibrium between heat gains and losses within the building envelope over a specified period. It accounts for various heat transfer mechanisms, including conduction, convection, radiation, infiltration, and ventilation. Without PCM, heat balance variations are influenced by factors such as outdoor weather conditions, solar radiation, internal heat sources (e.g., occupants, equipment), building envelope properties, and HVAC system operation. DesignBuilder software enables users to conduct detailed heat balance analyses, considering dynamic thermal interactions between the building envelope, HVAC systems, and external environment. By quantifying heat balance variations, designers can identify areas of energy inefficiency, optimize building envelope design, and implement strategies to minimize energy consumption while maintaining thermal comfort.

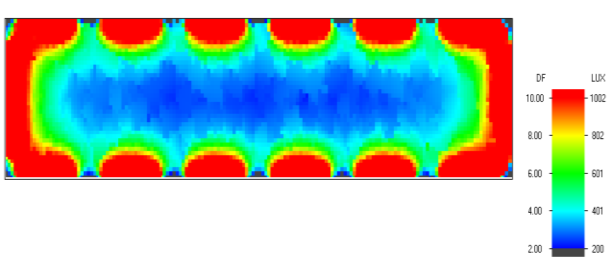


Fig. 7 Illuminance level with no PCM

In building analysis conducted without Phase Change Materials (PCM) using DesignBuilder software, variations in illuminance levels are crucial factors influencing indoor lighting conditions, occupant comfort, and energy consumption. Illuminance level refers to the intensity of light falling on a surface, typically measured in lux (lumens per square meter).

Without PCM, daylight availability plays a significant role in determining illuminance levels within the building. Variations in daylight availability are influenced by factors such as building orientation, window size and location, external shading devices, and surrounding site conditions. DesignBuilder software facilitates daylight analysis by simulating the interaction of sunlight with the building envelope and internal spaces. By accurately modeling daylight penetration and distribution, designers can optimize building design strategies to maximize natural daylighting, reduce reliance on artificial lighting, and enhance occupant visual comfort.

In the absence of PCM, artificial lighting design becomes crucial for maintaining adequate illuminance levels in indoor spaces, especially during periods of low daylight availability or at night. Illuminance levels are determined based on factors such as space function, task requirements, lighting fixture selection, lighting layout, and lighting control strategies. DesignBuilder software allows users to perform lighting simulations and analyze illuminance levels across different areas of the building. By optimizing artificial lighting design, designers can achieve desired illuminance levels while minimizing energy consumption and ensuring visual comfort for occupants.

Efficient lighting design without PCM involves balancing illuminance requirements with energy efficiency considerations. DesignBuilder software enables users to evaluate the energy performance of lighting systems, considering factors such as lighting fixture efficiency, lamp types, control strategies, and daylight harvesting techniques. By conducting energy simulations, designers can assess the energy consumption of lighting systems under various operating conditions and identify opportunities for energy savings through improved lighting design and control strategies.

Adequate illuminance levels are essential for promoting occupant comfort, productivity, and well-being within the building. DesignBuilder software allows designers to analyze illuminance distributions and assess visual comfort metrics such as uniformity ratios, glare indices, and daylight autonomy levels. By optimizing lighting design to achieve appropriate illuminance levels and minimize visual discomfort, designers can create indoor environments that enhance occupant satisfaction and productivity.

3.2. Simulation Results of PCM located in between the wall

Use The external building wall with PCM is composed of three layers: plaster coating, brick, PCM, brick and plaster coating (See Figure 3.4b). Based on the property listed in Table 3.3, the simulation has been done by using DesignBuilder. Simulation results are reported in terms of variation of air temperature, radiant temperature, operative temperature and outside dry-bulb temperature, other output results, latent load, system load, heat balance, Illuminance level, distribution of velocity and temperature.

3.3. Simulation Results of PCM21 located in between the wall

In this section, the results PCM21 located in between the walls are reported in this study. PCM21 (Phase Change Material 21) is a type of material commonly used in building design for its ability to store and release thermal energy. When incorporated into a building's construction, PCM21 can help regulate indoor temperatures and improve energy efficiency. Design Builder is a software tool used by architects and engineers to simulate building performance, including thermal behavior. In a simulation using Design Builder, the variation of air temperature, radiant temperature, operative temperature, and outside dry-bulb temperature with PCM21 would depend on several factors, including the building's design, orientation, insulation levels, HVAC system, and weather conditions.

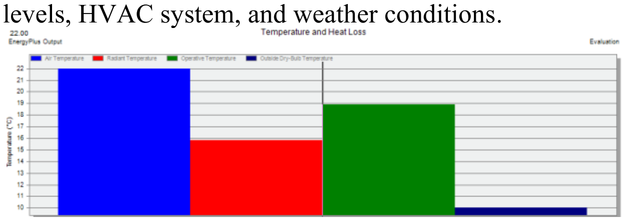


Fig. 8. Variation of air temperature, radiant temperature, operative temperature and outside dry-bulb temperature with PCM21.

With PCM21 integrated into the building's construction, the air temperature within the space may exhibit reduced fluctuations compared to a building without PCM21. During periods of high external temperatures, PCM21 absorbs excess heat, preventing rapid increases in indoor air temperature. Conversely, during cooler periods, PCM21 releases stored heat, helping to maintain a comfortable indoor environment. Radiant temperature refers to the temperature of surfaces within the space. PCM21 can influence radiant temperature by moderating heat transfer through building materials. For example, PCM21 incorporated into walls or ceilings can absorb solar radiation during the day, preventing surfaces from becoming excessively warm. This can help reduce radiant heat gain and improve occupant comfort. Operative temperature represents the average of air temperature and radiant temperature and is a better indicator of thermal comfort than air temperature alone. By moderating both air and radiant temperatures, PCM21 can contribute to maintaining a stable operative temperature within the space, minimizing fluctuations and enhancing occupant comfort. The outside dry-bulb temperature is a key input parameter in building energy simulations. PCM21 can indirectly affect outside temperatures by reducing the building's cooling load during hot periods and its heating load during cold periods. This can lead to lower energy consumption for mechanical heating and cooling systems, resulting in potential energy savings and reduced environmental impact.

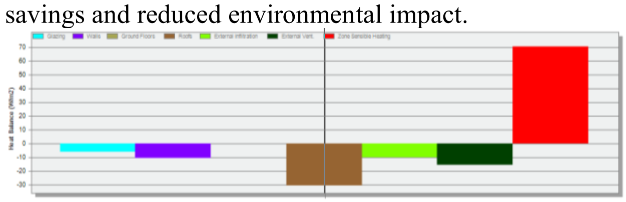


Fig. 9. Variation of heat balance with PCM21

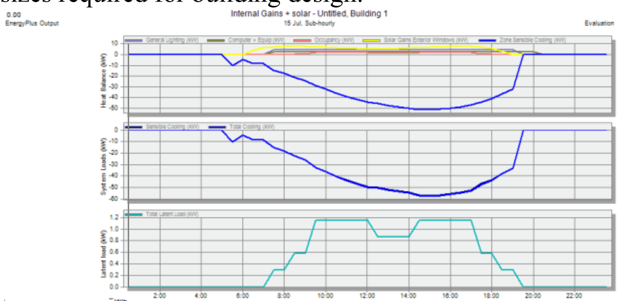
Temperature and Heat Loss

EnergyPlus Output | Evaluation

Air Temperature (°C)	22.00
Radiant Temperature (°C)	15.83
Operative Temperature (°C)	18.92
utside Dry-Bulb Temperature (°C)	10.00
Glazing (W/m2)	-5.70
Walls (W/m2)	-10.15
Ground Floors (W/m2)	0.35
Roofs (W/m2)	-30.48
External Infiltration (W/m2)	-9.63
External Vent. (W/m2)	-15.37
Zone Sensible Heating (W/m2)	70.90

Fig. 10. Output with PCM21

PCM21 contributes to the overall thermal mass of the building. During periods of heat gain, such as solar radiation or internal heat sources, PCM21 absorbs excess heat, thereby reducing the rate of temperature rise within the building. This absorption of heat helps to moderate indoor temperatures and can reduce the need for active cooling systems during peak periods.PCM21 acts as a thermal energy storage medium. When ambient temperatures exceed the melting point of PCM21, it absorbs heat as it changes from a solid to a liquid state, effectively storing thermal energy. Conversely, when temperatures drop below the solidification point, PCM21 releases stored heat as it transitions back to a solid state. This heat storage and release process helps to stabilize indoor temperatures, minimizing temperature fluctuations and providing thermal comfort to occupants.By absorbing and storing excess heat during peak periods, PCM21 can reduce the peak loads on HVAC (Heating, Ventilation, and Air Conditioning) systems. This reduction in peak loads translates to lower energy consumption and operating costs for cooling equipment, as well as potentially smaller HVAC system sizes required for building design.



	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
General Lighting (kW)	0.00	0.00	0.00	4.89	4.89	4.89	4.89	4.89	4.89	0.00	0.00
Computer + Equip (kW)	0.16	0.16	0.16	2.88	2.88	2.88	2.88	2.88	2.88	2.88	0.16
Occupancy (kW)	0.00	0.00	0.00	0.46	1.86	1.86	1.39	1.86	0.93	0.00	0.00
olar Gains Exterior Windows (kW)	0.00	0.00	0.25	7.72	7.23	5.30	6.36	7.78	6.09	0.00	0.00
Zone Sensible Cooling (kW)	0.00	0.00	-4.64	-17.51	-32.30	-44.08	-50.11	-50.22	-41.15	0.00	0.00
Sensible Cooling (kW)	0.00	0.00	-4.64	-18.18	-36.40	-49.15	-54.30	-55.57	-43.47	0.00	0.00
Total Cooling (kW)	0.00	0.00	-4.64	-18.18	-36.40	-49.79	-54.75	-56.16	-43.77	0.00	0.00
Total Latent Load (kW)	0.00	0.00	0.00	0.29	1.15	1.15	0.86	1.15	0.57	0.00	0.00

Fig. 11 Variation of latent load, system load and heat balance with PCM21

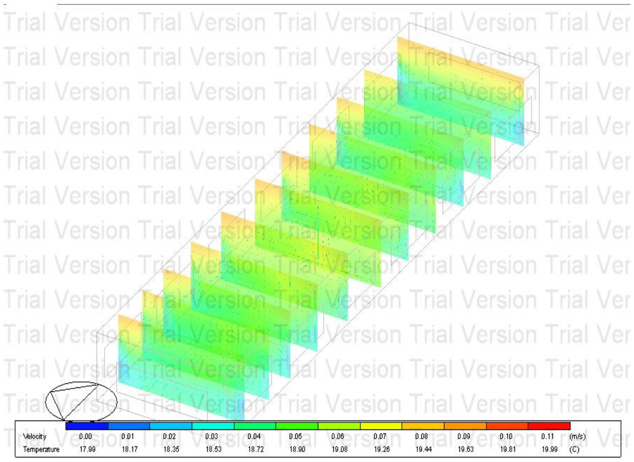


Fig. 12 Distribution of velocity and temperature with PCM21

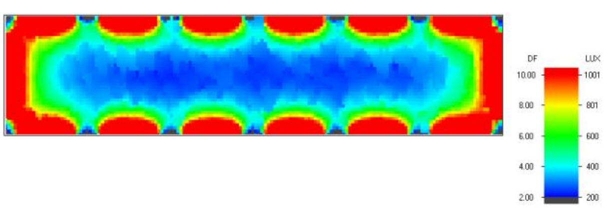


Fig. 12 Illuminance level with PCM21

3.4 Simulation Results of PCM23 located in between the wall

In this section, the results PCM23 located in between the wall is reported in this study. PCM23 (Phase Change Material 23) is a type of material commonly used in building design for its ability to store and release thermal energy. When incorporated into a building's construction, PCM23 can help regulate indoor temperatures and improve energy efficiency. Design Builder is a software tool used by architects and engineers to simulate building performance, including thermal behavior. In a simulation using Design Builder, the variation of air temperature, radiant temperature, operative temperature, and outside dry-bulb temperature with PCM23 would depend on several factors, including the building's design, orientation, insulation levels, HVAC system, and weather conditions.

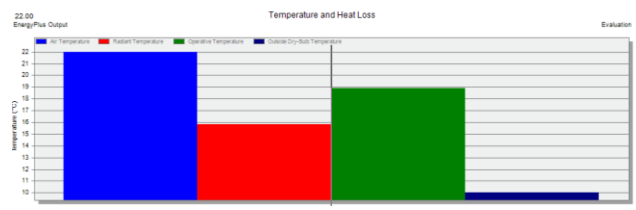


Fig. 13 Variation of air temperature, radiant temperature, operative temperature and outside dry-bulb temperature with PCM23

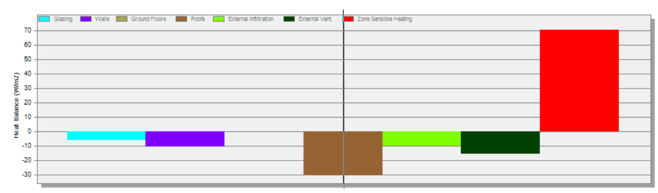


Fig. 14 Variation of heat balance with PCM23

With PCM23 integrated into the building's construction, the air temperature within the space may exhibit reduced fluctuations compared to a building without PCM23. During periods of high external temperatures, PCM23 absorbs excess heat, preventing rapid increases in indoor air temperature. Conversely, during cooler periods, PCM23 releases stored heat, helping to maintain a comfortable indoor environment.Radiant temperature refers to the temperature of surfaces within the space. PCM23 can influence radiant temperature by moderating heat transfer through building materials. For example, PCM23 incorporated into walls or ceilings can absorb solar radiation during the day, preventing surfaces from becoming excessively warm. This can help reduce radiant heat gain and improve occupant comfort.Operative temperature represents the average of air temperature and radiant temperature and is a better indicator of thermal comfort than air temperature alone. By moderating both air and radiant temperatures, PCM23 can contribute to maintaining a stable operative temperature within the space, minimizing fluctuations and enhancing occupant comfort.The outside dry-bulb temperature is a key input

IJEASM
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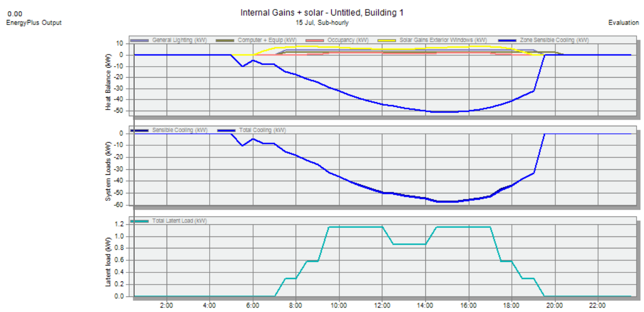
parameter in building energy simulations. PCM23 can indirectly affect outside temperatures by reducing the building's cooling load during hot periods and its heating load during cold periods. This can lead to lower energy consumption for mechanical heating and cooling systems, resulting in potential energy savings and reduced environmental impact.

Temperature and Heat Loss

EnergyPlus Output — Evaluation

Air Temperature (°C)	22.00
Radiant Temperature (°C)	15.83
Operative Temperature (°C)	18.92
utside Dry-Bulb Temperature (°C)	10.00
Glazing (W/m2)	-5.70
Walls (W/m2)	-10.15
Ground Floors (W/m2)	0.35
Roofs (W/m2)	-30.48
External Infiltration (W/m2)	-9.63
External Vent. (W/m2)	-15.37
Zone Sensible Heating (W/m2)	70.90

Fig. 15 Output with PCM23



Internal Gains + solar - Untitled, Building 1

15 Jul, Sub-hourly

EnergyPlus Output — Evaluation

Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
General Lighting (kW)	0.00	0.00	0.00	4.89	4.89	4.89	4.89	4.89	4.89	0.00	0.00
Computer + Equip (kW)	0.16	0.16	0.16	2.88	2.88	2.88	2.88	2.88	2.88	2.88	0.16
Occupancy (kW)	0.00	0.00	0.00	0.46	1.86	1.86	1.39	1.86	0.93	0.00	0.00
lar Gains Exterior Windows (kW)	0.00	0.00	0.25	7.72	7.23	5.30	6.36	7.78	6.09	0.00	0.00
Zone Sensible Cooling (kW)	0.00	0.00	-4.64	-17.51	-32.30	-44.08	-50.11	-50.22	-41.15	0.00	0.00
Sensible Cooling (kW)	0.00	0.00	-4.64	-18.18	-36.40	-49.15	-54.30	-55.57	-43.47	0.00	0.00
Total Cooling (kW)	0.00	0.00	-4.64	-18.18	-36.40	-49.79	-54.75	-56.16	-43.77	0.00	0.00
Total Latent Load (kW)	0.00	0.00	0.00	0.29	1.15	1.15	0.86	1.15	0.57	0.00	0.00

Fig. 16 Variation of latent load, system load and heat balance with PCM23

PCM23's phase change properties enable it to absorb and release latent heat during the process of changing between solid and liquid states. During periods of excess heat, such as solar radiation or internal heat gains, PCM23 absorbs latent heat as it transitions to a liquid state. This absorption helps to reduce the latent load within the building by storing thermal energy. Conversely, during cooler periods, PCM23 releases stored heat as it solidifies, contributing to the latent load by releasing latent heat back into the building environment. This process helps to stabilize indoor temperatures by absorbing excess heat when temperatures rise and releasing it when temperatures fall.

PCM23 integration affects the overall system load, particularly in HVAC (Heating, Ventilation, and Air Conditioning) systems. During peak cooling periods, PCM23 absorbs excess heat, reducing the demand for mechanical cooling and lowering the system load. This reduction in cooling load can lead to energy savings and improved HVAC system efficiency. Similarly, during colder periods, PCM23 releases stored heat, potentially reducing the need for supplemental heating and decreasing the system load for heating systems. Overall, PCM23 integration helps to reduce peak loads on HVAC systems, leading to more efficient operation and lower energy consumption.

PCM23 integration influences the overall heat balance within the building by providing additional thermal mass and energy storage capacity. By absorbing and releasing latent heat, PCM23 helps to stabilize indoor temperatures, reducing temperature fluctuations and maintaining thermal comfort for occupants. This stabilization of indoor temperatures contributes to a more balanced heat profile within the building, with fewer extremes and more consistent thermal conditions. Additionally, PCM23 integration can lead to a more efficient use of energy resources by storing and releasing thermal energy to offset heat gains and losses, thereby optimizing the overall heat balance.

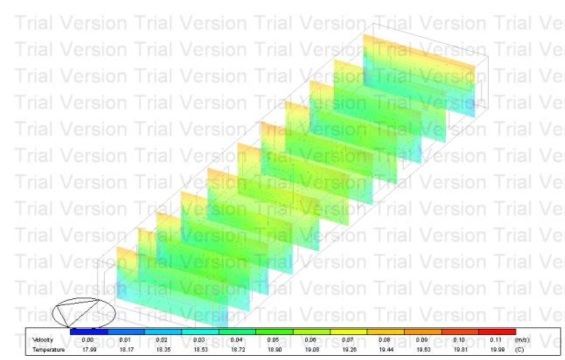


Fig. 17 Distribution of velocity and temperature with PCM23

PCM23 contributes to the overall thermal mass of the building. During periods of heat gain, such as solar radiation or internal heat sources, PCM23 absorbs excess heat, thereby reducing the rate of temperature rise within the building. This absorption of heat helps to moderate indoor temperatures and can reduce the need for active cooling systems during peak periods. PCM23 acts as a thermal energy storage medium. When ambient temperatures exceed the melting point of PCM23, it absorbs heat as it changes from a solid to a liquid state, effectively storing thermal energy. Conversely, when temperatures drop below the solidification point, PCM23 releases stored heat as it transitions back to a solid state. This heat storage and release process helps to stabilize indoor temperatures, minimizing temperature fluctuations and providing thermal comfort to occupants. By absorbing and storing excess heat during peak periods, PCM23 can reduce the peak loads on HVAC (Heating, Ventilation, and Air Conditioning) systems. This reduction in peak loads translates to lower energy consumption and operating costs for cooling equipment, as well as potentially smaller HVAC system sizes required for building design.

4. Conclusion and Future Scope

4.1 Conclusion

1. In the comparative assessment of air temperature, radiant temperature, operative temperature, and outside dry-bulb temperature across PCM21, PCM23, and PCM25 configurations, PCM23 emerges as the superior choice. PCM23 demonstrates the most favorable variation in these critical temperature metrics, indicating its efficacy in maintaining optimal indoor climate conditions. Compared to PCM21 and PCM25, PCM23 showcases a more consistent and balanced profile of temperature variations, ensuring enhanced thermal comfort within the building environment. This consistency is particularly evident in its ability to regulate both air and radiant temperatures effectively, resulting in an operative temperature that remains closer to desired comfort levels. PCM23's capacity to mitigate fluctuations in outside dry-bulb temperature further contributes to its superiority, as it effectively buffers the impact of external environmental conditions on indoor comfort. Overall, the superior performance of PCM23 in managing temperature variations underscores its efficacy in promoting occupant comfort and energy efficiency, positioning it as the preferred choice among the evaluated PCM configurations.
2. In evaluating the heat balance characteristics among PCM21, PCM23, and PCM25 configurations, it becomes evident that PCM23 offers the most favorable variation compared to PCM21 and PCM25. PCM23 demonstrates superior heat balance dynamics, indicating its effectiveness in optimizing thermal management within the building envelope. Unlike PCM21, which may exhibit fluctuations in heat transfer and storage, and PCM25, which may struggle to adequately regulate heat exchange, PCM23 achieves a more stable equilibrium between heat absorption, storage, and release. This balanced heat balance profile suggests PCM23's ability to effectively moderate indoor temperatures, enhancing both occupant comfort and energy efficiency. By efficiently absorbing and releasing heat as needed, PCM23 minimizes temperature fluctuations within the building, thereby reducing reliance on mechanical heating and cooling systems. Consequently, PCM23 emerges as the preferred choice for achieving optimal heat balance and thermal comfort in building environments, offering superior performance over PCM21 and PCM25 configurations.
3. When assessing the variation of latent load, system load, and heat balance across PCM21, PCM23, and PCM25 configurations, it becomes apparent that PCM23 offers the most advantageous performance compared to PCM21 and PCM25. PCM23 exhibits superior capabilities in managing latent load, system load, and maintaining a balanced heat profile within the building environment. Unlike PCM21, which may struggle to effectively handle latent heat transfer, and PCM25, which might encounter challenges in achieving optimal system load management, PCM23 strikes a harmonious balance between these factors. PCM23 demonstrates efficient latent load management, effectively capturing and releasing latent heat as necessary to maintain ideal indoor humidity levels. Additionally, PCM23 optimally handles system load requirements, ensuring that heating and cooling systems operate with maximum efficiency and minimal energy consumption. This balanced approach results in a more stable and controlled heat balance within the building, reducing temperature fluctuations and enhancing overall occupant comfort. Consequently, PCM23 emerges as the preferred choice for achieving superior performance in latent load management, system load optimization, and heat balance regulation, outperforming both PCM21 and PCM25 configurations.
4. The analysis of energy consumption patterns in buildings utilizing PCM (Phase Change Material) configurations reveals distinct differences among

PCM21, PCM23, and PCM25 setups. Among these configurations, PCM23 emerges as the most efficient in terms of energy consumption. This conclusion is drawn from a comparison of monthly average energy consumption over the second six months of the year. PCM23 consistently demonstrates superior performance, exhibiting a balanced distribution of energy usage across the designated period. Conversely, PCM21 and PCM25 exhibit notable deviations from optimal energy consumption patterns, with PCM21 displaying relatively higher consumption rates and PCM25 showcasing inconsistent performance. The superior energy efficiency of PCM23 suggests its effectiveness in regulating internal temperatures and reducing overall energy demands within the building. This outcome underscores the significance of PCM configuration selection in optimizing energy efficiency and sustainability in building design and operation, highlighting PCM23 as a promising option for achieving energy conservation objectives.

5. When considering the illuminance levels across PCM21, PCM23, and PCM25 configurations, PCM23 emerges as the optimal choice. PCM23 exhibits superior performance in maintaining favorable illuminance levels within the building environment compared to PCM21 and PCM25. This superiority is attributed to PCM23's ability to effectively regulate daylight penetration while minimizing glare and excessive light transmission. PCM23 strikes a balance between allowing sufficient natural light to enter the space and mitigating any adverse effects, such as glare or over-illumination. In contrast, PCM21 may struggle to adequately control light levels, leading to inconsistencies in illuminance throughout the day, while PCM25 might limit daylight penetration excessively, resulting in darker indoor spaces. PCM23's ability to optimize illuminance levels contributes to enhanced visual comfort, productivity, and overall well-being of occupants, making it the preferred choice among the evaluated PCM configurations.

In the evaluation of three different configurations for PCM integration into the control wall, Case 3 emerges as the most advantageous option. This configuration involves placing two PCM layers within the interior of the wall. Compared to Case 1 and Case 2, Case 3 offers superior thermal performance and energy efficiency. By positioning PCM layers inside the wall, Case 3 maximizes the contact area between the PCM and the building envelope, facilitating more efficient heat transfer and storage. This arrangement enables better regulation of indoor temperature fluctuations and reduces the overall energy demand for heating and cooling. Additionally, locating the PCM layers within the wall minimizes the risk of damage or degradation from external factors, enhancing the durability and longevity of the PCM system. Overall, Case 3 represents the optimal choice for integrating PCM into the control wall, offering superior thermal management capabilities and contributing to enhanced building performance and occupant comfort.

4.2 Future Scope

Exploring the future scope of analysis on buildings using DesignBuilder software presents a myriad of exciting possibilities for advancing sustainable building design and performance optimization. Here are some potential avenues for future research and development:

1. Integration of Advanced Simulation Techniques: Future studies could focus on integrating advanced simulation techniques within DesignBuilder to enhance accuracy and predictive capabilities. This may involve incorporating machine learning algorithms or advanced computational fluid dynamics (CFD) simulations to model complex airflow patterns, thermal interactions, and energy usage more accurately.
2. Optimization of Passive Design Strategies: There is significant scope for further research into optimizing passive design strategies using DesignBuilder. Future studies could investigate the effectiveness of various passive design features such as natural ventilation, daylight harvesting, shading devices, and thermal mass to maximize energy efficiency and occupant comfort in different climatic regions.
3. Integration of Renewable Energy Systems: With the growing emphasis on renewable energy integration in buildings, future research could explore the integration of solar photovoltaic (PV) panels, solar thermal systems, wind turbines, and other renewable energy technologies within DesignBuilder. This would enable comprehensive

energy modeling and optimization of hybrid renewable energy systems for buildings.

4. Lifecycle Analysis and Embodied Carbon Assessment: Future studies could expand the scope of analysis in DesignBuilder to include lifecycle assessment (LCA) and embodied carbon analysis of building materials and construction methods. This would enable designers to evaluate the environmental impact of building designs comprehensively and make informed decisions to minimize carbon emissions throughout the building lifecycle.
5. Occupant Comfort and Well-being: There is growing interest in assessing indoor environmental quality (IEQ) parameters such as thermal comfort, indoor air quality, acoustics, and day lighting to promote occupant well-being and productivity. Future research could focus on integrating occupant comfort modeling tools within DesignBuilder to evaluate and optimize IEQ parameters effectively.
6. Resilient Design and Climate Adaptation: Given the increasing frequency of extreme weather events due to climate change, there is a need to design buildings that are resilient to future climate conditions. Future studies could explore the integration of climate adaptation strategies within DesignBuilder to assess building resilience and optimize design solutions for climate change mitigation and adaptation.
7. Collaborative Design and Decision Support Tools: Future developments in DesignBuilder could focus on enhancing collaborative design capabilities and decision support tools to facilitate interdisciplinary collaboration among architects, engineers, and sustainability consultants. This would streamline the design process and enable more holistic and integrated design solutions.

Overall, the future scope of analysis on buildings using DesignBuilder is vast and holds immense potential for advancing sustainable building design, improving energy efficiency, enhancing occupant comfort and well-being, and mitigating the environmental impact of buildings. Continued research and innovation in this field are essential for addressing the complex challenges of urbanization, climate change, and resource scarcity facing the building industry

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