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REVIEW ARTICLE

EFFECTS OF VEGETATION AND PCM IN REDUCING URBAN HEAT ISLAND

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ABSTRACT

Globally, fast-tracked urbanization has led to diversified environmental challenges since the time of the industrial revolution. Among the challenges faced, Urban Heat Island (UHI) is caused by the replacement of natural materials with man-made ones such as concrete, asphalt, and increased anthropogenic heat production, among other factors. This study is on understanding the reasons behind UHI, its effects, and finding out proper strategies for mitigation in the context of Bangladesh. Among many ways, proper interior and exterior vegetation, sufficient wind flow, and appropriate building materials are chosen to be the proper methods to reduce UHI effects in Bangladesh. CFD analysis has been carried out to understand the effect of vegetation, wind flow, and different material to mitigate UHI. An estimation of the effect of temperature reduction in energy efficiency is also done. It is observed that a significant amount of energy can be saved by reducing the cooling load if these suggestions are followed. The study shows that the temperature is decreased up to 3°C with the increasing vegetation on exterior walls and rooftop. By using Wood Plastic Composite (WPC) on the rooftop as a phase change material, temperature is decreased around 4°C. By using all conditions (rooftop, sidewall, interior vegetation & PCM on rooftop) together temperature could be mitigated around 5°C.

KEYWORDS

Urban Heat Island, Fast-Tracked, Rooftop

1. INTRODUCTION

Recently, unrestrained use and modification of natural materials and ecosystems and the resulting consequences have led to a renovated focus on sustainability. Harm due to the UHI effect and global warming has attracted scholarly attention. The heat island effect on the urban environment also leads to increased energy needs that further contribute to the heating of our urban environment and the associated environmental and public health consequences. Day by day temperature is increasing in urban areas drastically rather than rural areas due to tremendous population growth, pollution, unplanned and haphazard urbanization, and industrialization. It affects the thermal comfort of millions of people worldwide. The greeneries associated with water bodies are at a horrible state, leveling with the replacement of concrete surfaces. Urban heat island also results in expanding energy and waste of energy. This phenomenon affects the natural environment and ecology to a great extent. It creates devastating consequences such as global warming, water pollution, air pollution, noise pollution, industrial waste, and many more. Urban heat islands affect not only the environment but also eventually our health as it causes perilous health issues.

Summer temperatures are expected to continue rising worldwide due to the presence of global warming and climate change, leading to negative effects on human environments and health. Urban areas, especially, are facing more serious conditions because of the urban heat island (UHI) effect (Zhang et al., 2019). In a city, man-made structures, such as buildings and roads covered with asphalt hinder ventilation and trap solar radiation. In addition to diverse urban activities producing heat and air pollution, increasing recently, unrestrained use and modification of natural materials and ecosystems and the resulting consequences have led to a renewed focus on sustainability. Harm due to the UHI effect and global warming has attracted scholarly attention. The heat island effect on the urban environment also leads to increased energy needs that further contribute to the heating of our urban environment and the associated environmental and public health consequences.

Voogt defined three types of UHI (Voogt, 2004). They are the Canopy layer heat island, Boundary layer heat island, Surface heat island. Bangladesh is the eighth-most populated country in the world with almost 2.2% of the world's population. The population is estimated by the 2019 revision of the World Population Prospects to have stood at 161,376,708 in 2018 (Wikipedia). It is high time to think about this alarming topic. Both domestic and global population growth is adding to conflicts over food, energy, water, open space and wilderness, school- college rooms, parks, resorts, transportation infrastructure and numerous other serious problems. In developing countries like ours, the sudden growth of unplanned cities, mills, industries and large family size is a major cause of poverty and poor health. One of the biggest threats of continued population growth is deforestation and serious health issues. Thus the population of our country has increased drastically.

Though urbanization and industrialization have made our life easy, it has blessed us with many devastating consequences such as global warming, air pollution, water pollution, noise pollution, industrial waste, thermal comfort, and many more dangerous health issues. As urbanization and industrialization are increasing day by day, it causes a drastic change in the global environment. It also has a very hazardous impact on our climate. New megacities are being born day by day and existing megacities are becoming more populated. With the increasing population, urban areas offer the most economical resources and energy demand in comparison

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with rural areas. New economical, managerial, and social challenges associated with growing cities, a deformed energy budget pulls them toward a warmer climatic condition, known as urban heat island (UHI).

In this study, a laboratory of the Department of Mechanical Engineering (Heat Engine Lab) of Rajshahi University of Engineering and Technology, Rajshahi, Bangladesh is taken into consideration as the model of an energy source. CFD analysis has been carried out to understand the effect of vegetation, wind flow, and different material to mitigate UHI. An estimation of the effect of temperature reduction in energy saving is also done. It is observed that a significant amount of energy can be saved by reducing the cooling load if these suggestions are followed.

2. Materials and Methodology

2.1 Numerical Tools

SolidWorks is a computer-aided engineering computer program which was published by Dassault Systems. SolidWorks employs the performance of planning, visual ideation, modeling, feasibility assessment, prototyping and project management. With this software one can easily design and build mechanical, electrical and software elements. For designing the proposed model SolidWorks 2019 was used. COMSOL Multi-physics is a powerful software package that can perform eigen-frequency and modal analysis. COMSOL employs the verified finite element method. The finite element analysis is run along with adaptive meshing and error control via different numerical solvers. With this software one can easily design by defining the sub-domains and boundary conditions with correct parameters and analyze the result. For simulating the proposed structure COMSOL version 5.5 was used. For the implementation of research, all the required dimensions and conditions was required taken from valid source. The ambient temperature, properties of build in materials, wind speed, solar irradiance, ambient pressure which was used in simulation are all updated from solver configuration in COMSOL. The conditions considering during build up the simulations is shown in below:

Table 1: Conditions considering during simulation	
Conditions	**Contents**
Space	Three dimensional
Mesh	Physics Controlled mesh
Mesh Element size	Normal
Study	Time dependent
External Radiation source	Sun
Fluid state	Equilibrium Air
Reynolds-turbulent flow	k-ε Turbulence
Wind direction	North to west

2.2 Computational Domain and Boundary Conditions

Latitude of Rajshahi citty is 24.3745° North and 88.6042° East. It is one of the most dignified city of Bangladesh. Actually, Rajshahi is a metropolitan city and a major urban, commercial and educational center of Bangladesh. It is also the administrative seat of eponymous division and district. Located on the north bank of the Padma River, near the Bangladesh-India border, the city has a population of over 763,952 residents. The predominant wind direction is north-west and the maximum average temperature is 39°C got in April (Wikipedia). The computational model is shown in below. In this model, dimensions have considered length 33m, width 12.2m, height 13.54m. The complete CFD calculated domain dimension is 50m×20m×20m. Physics controlled normal mesh was used. The coarse mesh had a perfect range of cells. Boundary conditions within the computational domain were set based on the weather data and latitude of Rajshahi city. Time dependent isothermal boundary conditions were used. Heat transfer in solids and surface to surface radiation were considered. Different materials were chosen for a particular simulation as required to maintain different conditions.

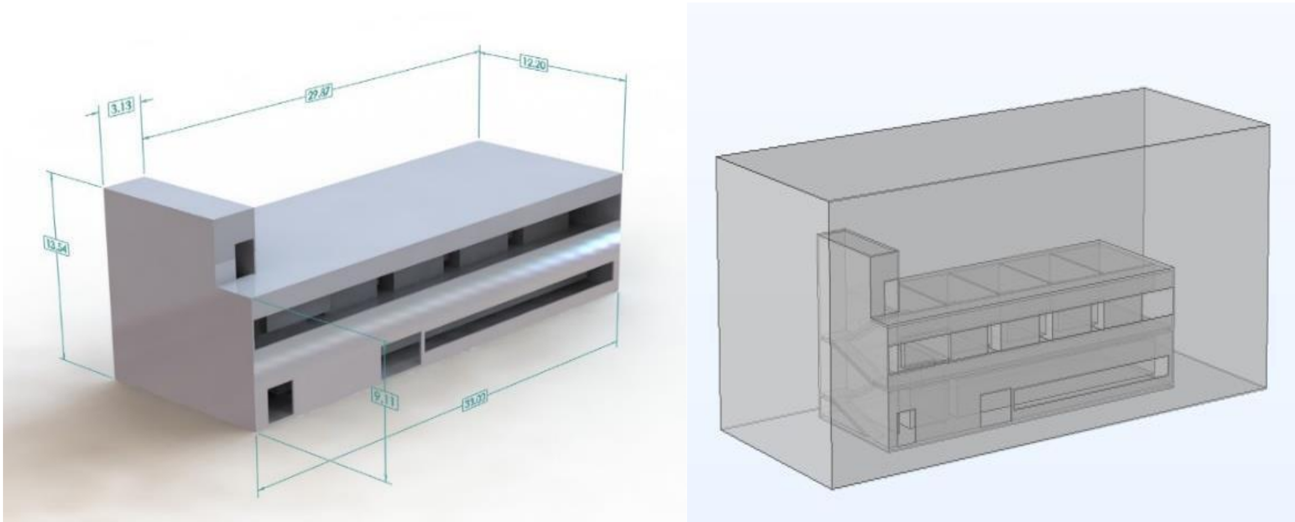

Figure 1: Computational model

2.3 Numerical Model

This study employed a three-dimensional CFD simulation based on the finite volume time dependent method. We had set the whole research in three conditions and for getting the analysis result different conditions and parameters were taken. First condition was considered in three sections. The sections were creating optimized rooftop vegetation, interior vegetation and the combination of interior and rooftop vegetation. For analyzing, solar irradiance was taken 600 W/m² and heat flux was considered in upper portion. Second condition was considered wind effect. Average wind speed was taken 14.4 km/h (4m/s) and simulated to mitigate temperature by changing orientation. Third condition was considered using PCM material on rooftop. We had selected Wood Plastic Composition (WPC) as PCM on rooftop.

2.4 Building the model for different conditions

Direct modeling for all the conditions will result in normal mesh, thereby leading to an unfavorable impact in calculating efficiency. For different conditions, different model was built. The different conditions are given below:

2.4.1 Without Any Condition

At first without any conditions model were built and simulation was done for three different months – April, May, June. Using two materials – brick and air, this simulation was done. All the properties which was considered during simulation is shown in table 2.

Table 2: Properties of different materials used during simulation Properties of brick Properties of air (Wikipedia)		
Property	**Value**	**Unit**
Density	2000	kg/m³
Heat capacity at constant pressure	900	J/(kg.k)
Thermal conductivity	0.5	W/(m.k)
Property	**Value**	**Unit**
Density	1.225	kg/m³
Heat capacity at constant pressure	1012	J/(kg.k)
Thermal conductivity	0.024	W/(m.k)

Global coordinate system was used at which volume reference temperature was taken 293.15K and absolute pressure was taken 1atm.

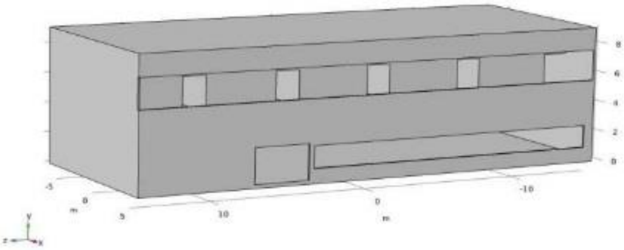

Figure 2: Simplified model and mesh with no condition

2.4.2 With proper vegetation

Vegetation is one of the important elements for mitigating UHI effect. Vegetation reduces UHI effect through shading and evapotranspiration. We had used four different models in which vegetation was created on different aspects. During building up the models, we had considered the optimized value for their dimensions. Using three materials – brick, air and cellulose, this simulation was done. The property of cellulose which was considered during simulation is shown in table below.

Table 3: Properties of cellulose (Wikipedia)

Property	Value	Unit
Density	37	kg/m^3
Heat capacity at constant pressure	2000	J/(kg.k)
Thermal conductivity	0.040	W/(m.k)

The models are described in below:

2.4.2.1 Model 1: With room interior vegetation

In this model, the dimension of Interior vegetation was considered as 0.5*0.5*0.5. Total room in 1st floor: 5

No of vegetation in each room: 7. Total area of vegetation: 8.75m^2.

Various types of plants can be used as an interior vegetation like jade plant, peace lily, English ivy, snake plant.

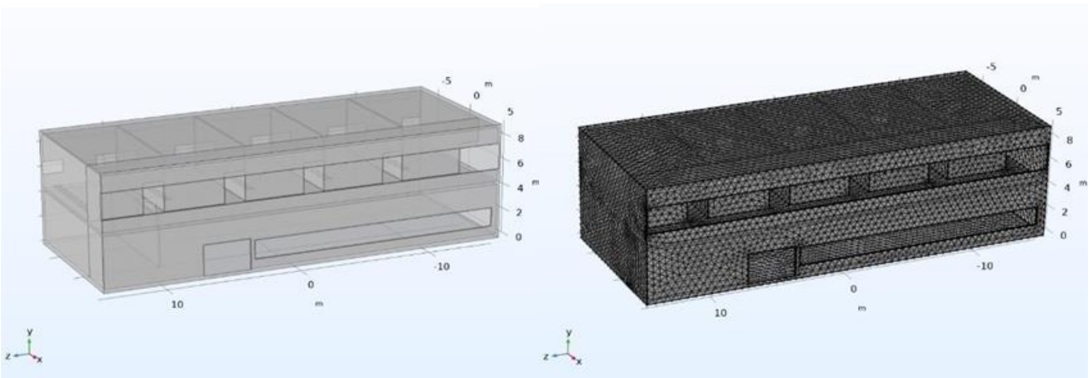

Figure 3: Simplified model and mesh with room interior vegetation

2.4.2.2 Model 2: With rooftop vegetation

The total vegetation area on rooftop for simulations was decided at 396 m^2. Then, it was modeled as a cubic configuration with a 0.5m height, 2m length and 1m width on the rooftop maintaining 2m distance with each cubic, shown in below. The total number of cubic vegetation was considered 30 so the total volume of cubic configuration was installed 30m^3.

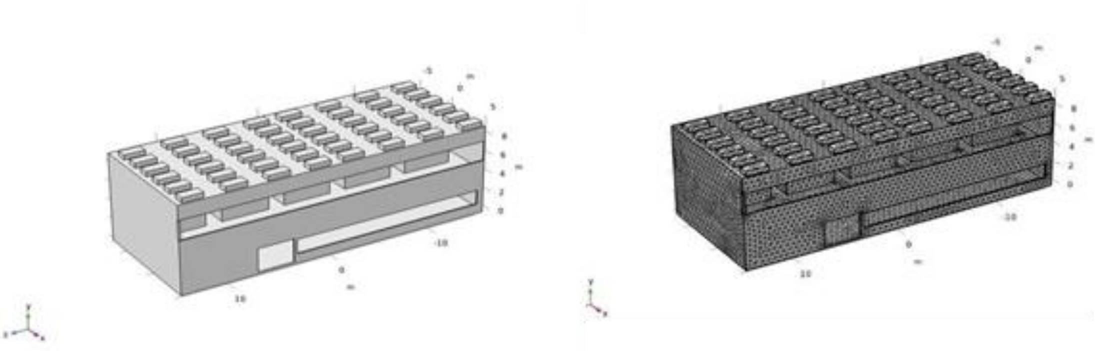

Figure 4: Simplify model and mesh with rooftop vegetation

2.4.2.3 Model 3: With both rooftop, interior & sidewall vegetation

For both rooftop considerations, the total vegetation area on rooftop for simulations was decided at 396 m^2. Then, it was modeled as a cubic configuration with a 0.5m height, 2m length and 1m width on the rooftop maintaining 2m distance with each cubic, shown in below. The total number of cubic vegetation was considered 30 so the total volume of cubic configuration was installed 30m^3. For interior consideration, it was modeled as a cubic configuration with a 0.5m height, 3m length and 0.8m width on the ground floor and 0.5m height, 4.02m length and 1.08m width on the first floor. The total number of cubic vegetation was considered 4 on first floor and 4 on ground floor considering distance between each cube 2m.

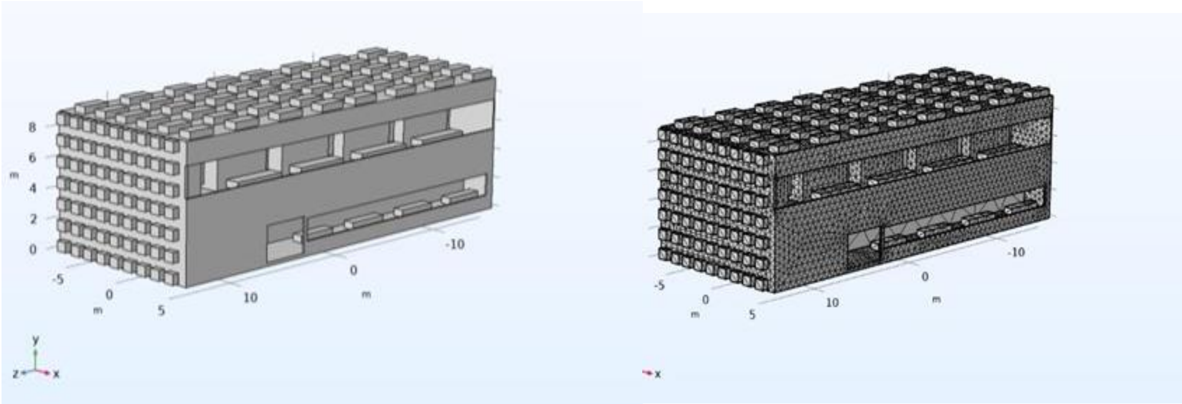

Figure 5: Simplified model and mesh with both rooftop, interior & sidewall vegetation

2.4.3 With PCM

To analyze the UHI mitigation effect through PCM the month of April, 2020 was decided. April month was considered because it has the highest effect on UHI. Later on changing volume reference temperature next two months was simulated. To mitigate the effect, wood plastic composite (WPC) material is used in roof and brick was used as building material. WPC is a synthetic material which is combined with 60% of natural tree powder and fiber, 30% of high-density polyethylene (HDPE), and 10% of chemical additives (UV protector, antioxidant, stabilizer, coloring agent, mold-inhibiting agent etc.). [7] WPC material change its phase at 25 (Yang et al., 2017). Using three materials – brick, air and PCM, this simulation was done. The property of WPC which was considered during simulation is shown in table below.

Table 4: Properties of WPC (Wikepedia)

Properties	Value	Unit
Density	953	Kg/m3
Thermal Conductivity	0.335	W/(m-k)
Heat capacity at constant pressure	2439	J/(kg-k)

For mitigating UHI with the use of PCM, a thin layer of PCM was used on rooftop. It was modeled as a cubic configuration with a height of 0.1m. Then, the total area of PCM material on rooftop was decided at 360m^2.

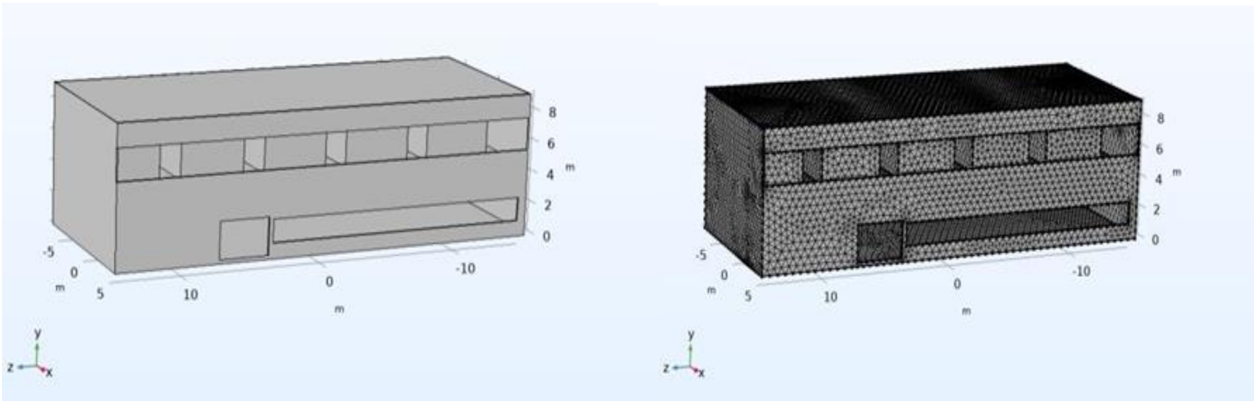

Figure 6: Simplify model and mesh with PCM

2.4.4 With vegetation and PCM

The model was designed again using both vegetation and PCM. For these cubic model considerations, previous dimensions were used. The picture of simplify model and mesh is given below.

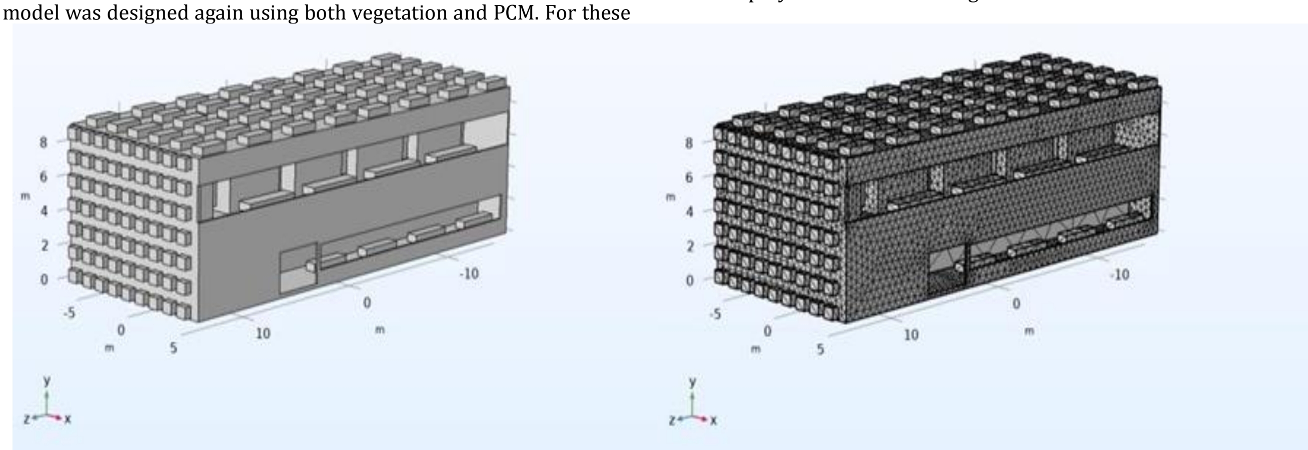

Figure 7: Simplified model and mesh with vegetation and PCM

3. Results and Discussion

3.1 Simulation without any condition

The distribution of maximum and minimum temperature for April, May, June 2020 is 310K and 296K, 308K and 296K, 305K and 296K respectively. The maximum temperature can be seen on partial portions of rooftop and the sidewall where the sunlight directly strikes. The lowest temperature can be seen in the ground portion.

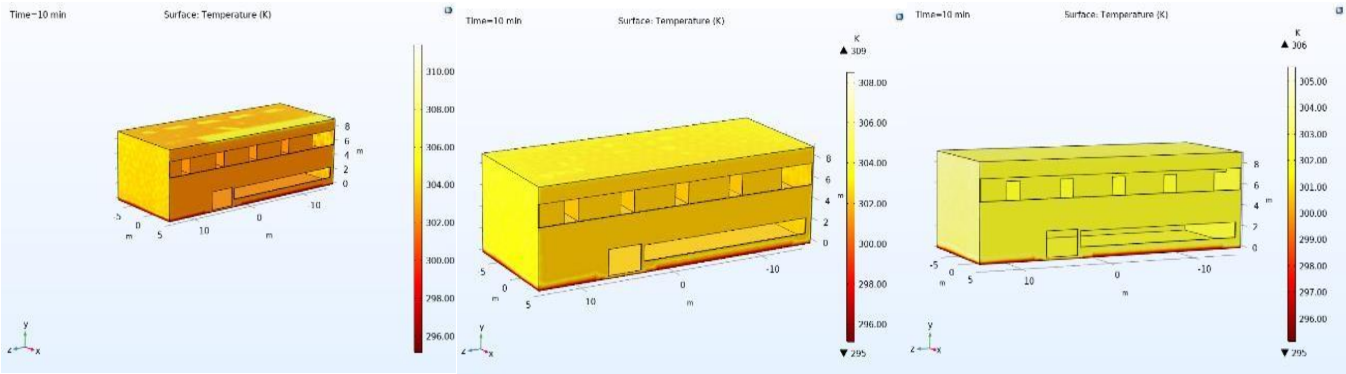

Figure 8: Temperature distribution for April, May, June

3.2 Simulation with different conditions

Direct simulation for all the conditions will result in normal mesh, thereby leading to an unfavorable impact in calculating efficiency. The simulations for different conditions on different model are given below:

3.2.1.1 Model 1: With room interior vegetation

3.2.1 Using proper vegetation

We had done three different simulations in which vegetation was created on different aspects. The temperature distribution analysis of three different simulations are given below:

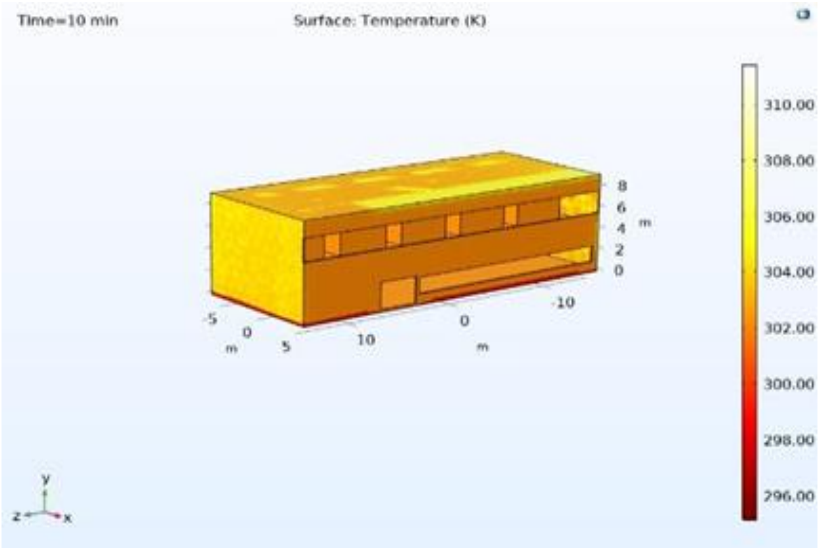

Figure 9: Temperature distribution for the month, April

From this simulation it can be seen that there is no significant change in temperature distribution. So interior vegetation is not helpful for reducing UHI effect. But it improves environment quality, boost moods and reduce air pollution.

3.2.1.2 Model 2: With rooftop vegetation

The distribution of maximum and minimum temperature for April, May, June 2020 is 308.80K and 296K, 306.95K and 296K, 304.565K and 296K respectively. The maximum temperature can be seen on partial portions of rooftop and the sidewall where the sunlight directly strikes. The lowest temperature can be seen in the ground portion.

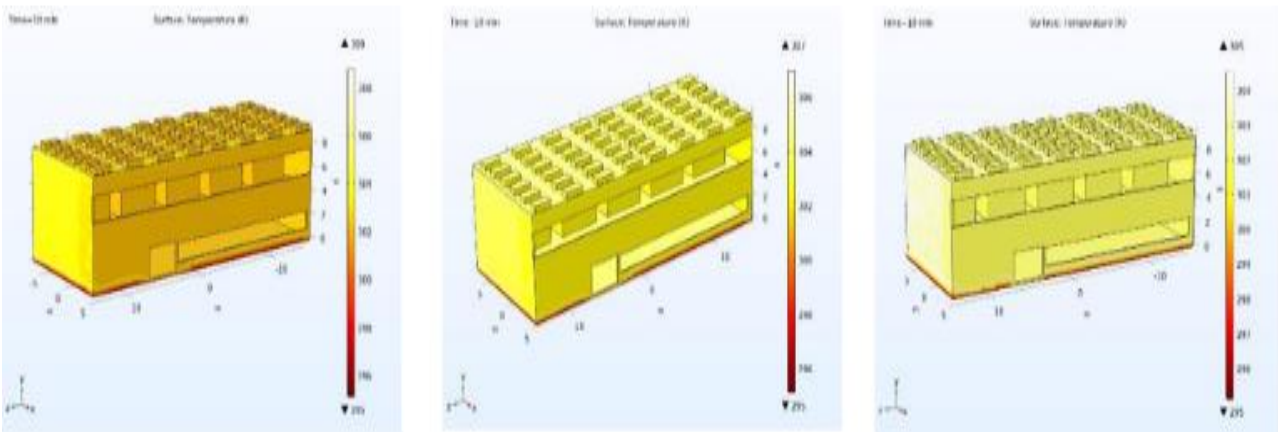

Figure 10: Temperature distribution for April, May, Jun

3.2.1.3 Model 3: With interior vegetation

The distribution of maximum and minimum temperature for April, May, June 2020 is 308.66K and 296K, 306.54K and 296K, 304.43K and 296K respectively. The maximum temperature can be seen on partial portions of rooftop and the sidewall where the sunlight directly strikes. The lowest temperature can be seen in the ground portion.

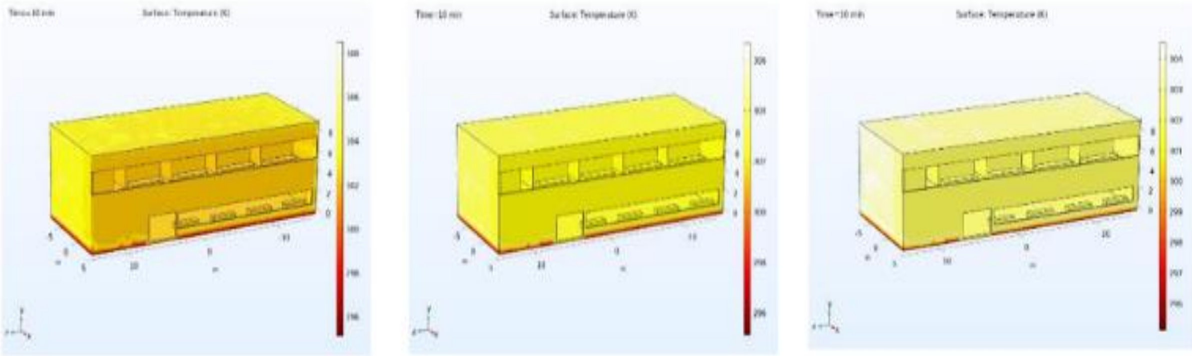

Figure 11: Temperature distribution for April, May, June

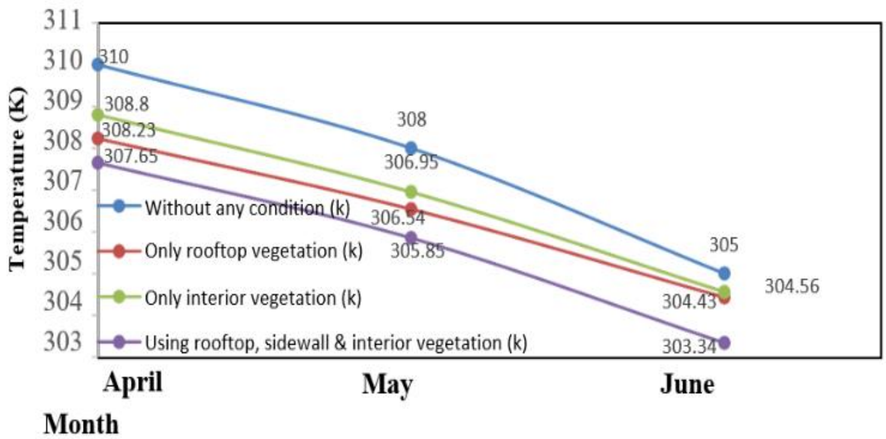

Figure 12: Comparison of temperature variation with vegetation vs Month

Figure 12 shows the mitigation of temperature with increasing vegetation. When there is no vegetation, it shows a higher temperature. But if there is proper distribution of vegetation on rooftop or interior or both rooftop and interior, it shows portentous reduction in temperature. For creating only rooftop or interior vegetation, it reduces around 1°C. But for creating optimized vegetation on rooftop and interior, it reduces almost 3°C.

3.2.2 With PCM

The distribution of maximum and minimum temperature for April, May, June 2020 is 307K and 296K, 305.52K and 296K, 301.85K and 296K respectively. The maximum temperature can be seen on partial portions of rooftop and the sidewall where the sunlight directly strikes. The lowest temperature can be seen in the ground portion.

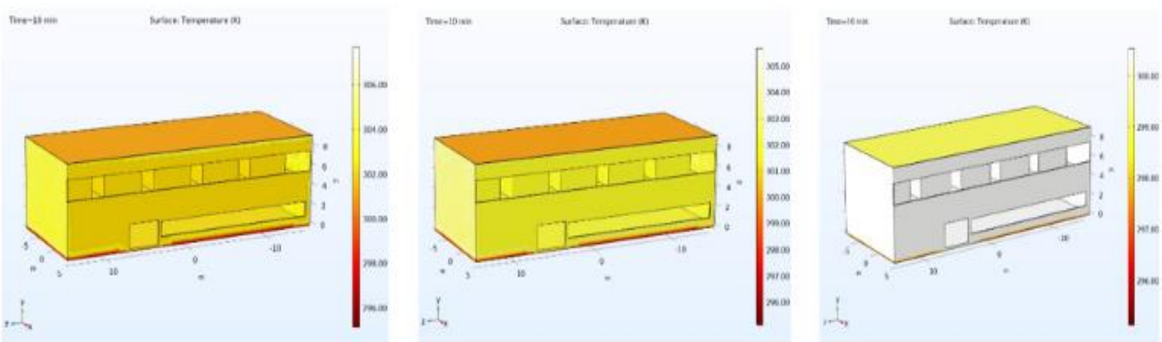

Figure 13: Temperature distribution for April, May, June

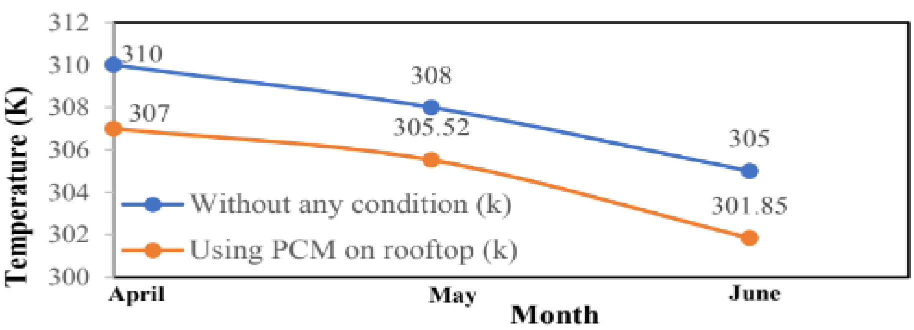

Figure 14: Comparison of temperature variation using PCM vs Month

Figure 14 shows the temperature reduction when PCM is used on rooftop. When there is no layer of PCM, it shows more temperature. It reduces almost 3°C temperature with the use of PCM.

3.2.3 With vegetation and PCM

The distribution of temperature after combining interior and rooftop vegetation with PCM material on rooftop is shown below. It can be seen maximum and minimum temperature is 305.46K and 296K respectively. The maximum temperature can be seen on rooftop and the sidewall where the sunlight directly strikes. The lowest temperature can be seen in the ground portion.

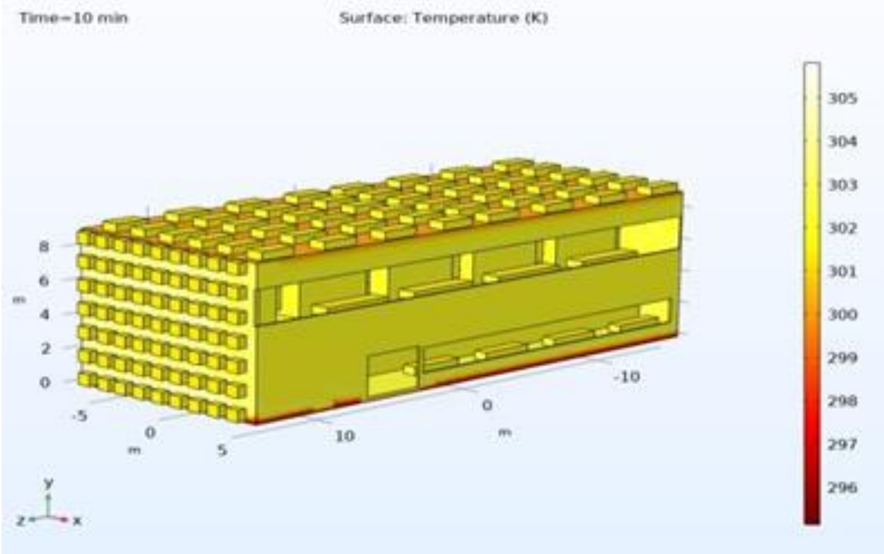

Figure 15: Temperature distribution using vegetation and PCM

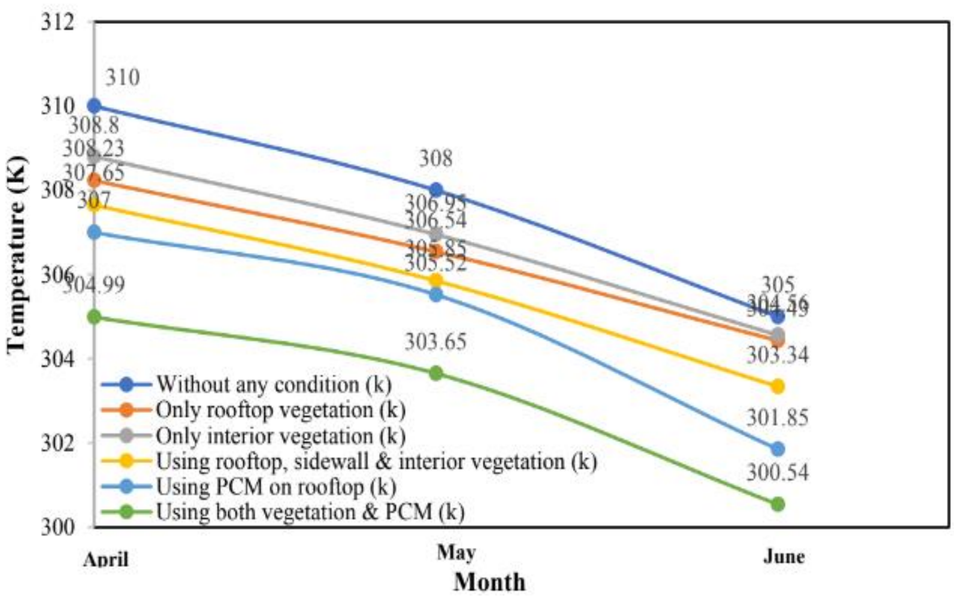

Figure 16: Comparison of temperature variation with different conditions vs Month

From Figure 15, it can be easily seen that there occurs a portentous change while considering both vegetation and PCM on the model at the same time. It reduces almost 5°C from normal condition.

4. Cost Analysis

4.1 Assumption and calculation

Assuming the ac to be a 3 star rated, its Energy Efficiency Ratio (EER)=2.7 Cooling capacity of 1 ton is equal to 3.517kW of power (Maheshwary and Al-Murad, 2001)

For 1.5 ton AC power consumption of ac = cooling capacity/EER

=1.5*3.517/2.7=1.954 kW

AC consists of two units, Indoor unit which is called the evaporator and the Outdoor Unit which called the Compressor. So, it is preferable for calculation that total power is consumed only by the compressor (Zhu, 2013). Compressor unit starts only when the indoor temperature is more than desired temperature and stops once the desired temperature is achieved. Compressor run time to drop temperature down 2 °C is 30 minutes (Moders, 2016)

Case 1: When there is no vegetation Ambient temperature, t_{amb}= 37°C Desired temperature, $t_{desired}$= 25 °C

So for dropping the temperature from 37 °C to 25 °C (T= 12 °C) run time of the compressor is= 30* 12/2 =180 min =3 hr

Energy consumption =1.954*3=5.862 kWh

Case 2: When there is vegetation on the rooftop, interior, sidewall and PCM over the roof it reduces the temperature around 5°C

Ambient temperature, t_{amb}= 32 °C Desired temperature, $t_{desired}$= 25 °C

So for dropping the temperature from 32 °C to 25°C (T= 7 °C) run time of the compressor is= 30* 7/2 =105 min

=1.75 hr

Energy consumption =1.954*1.75 =3.4195 kWh

So total energy consumption is reduced by vegetation = 5.862-3.4195= 2.4425kWh

Assuming electricity cost 7 TK per unit or KWh, an overall estimation of cost reduction is given below (Bpdb.gov):

Table 3: Cost reduction with different conditions

Months	Energy consumption without any condition	Energy consumption with vegetation & PCM on rooftop	Reduction in energy consumption (KWh)	Cost reduction per day (BDT)	Cost reduction average per month (BDT)
March	3.19	0.96	2.22	15.59	467.78
April	5.01	2.56	2.44	17.13	513.95
May	4.89	2.89	2.00	14.05	421.62
June	4.41	2.23	2.17	15.25	457.52
July	4.32	2.42	1.90	13.30	399.05
August	3.97	1.69	2.28	15.96	479.07
September	3.91	1.70	2.21	15.45	463.68
October	3.63	1.38	2.25	15.76	472.91
November	2.68	0.87	1.80	12.65	379.56
Annual reduction			19.27		4055.16

If a room size is above 201-300 sq ft, then 1.25 or 1.5 Ton AC is enough for cooling the room (Blog.Addotoday.com). The area of one room of our computaional model is 2660 square feet. So, for this model total 15 number of 1.5 ton ac is required .

Therefore, total cost reduction for 15 AC in 1 year =4055.16*15=60827.4 Tk Total reduction of energy consumption per year = 289.05 KWh

A graph for the consumption of energy in different month is given below:

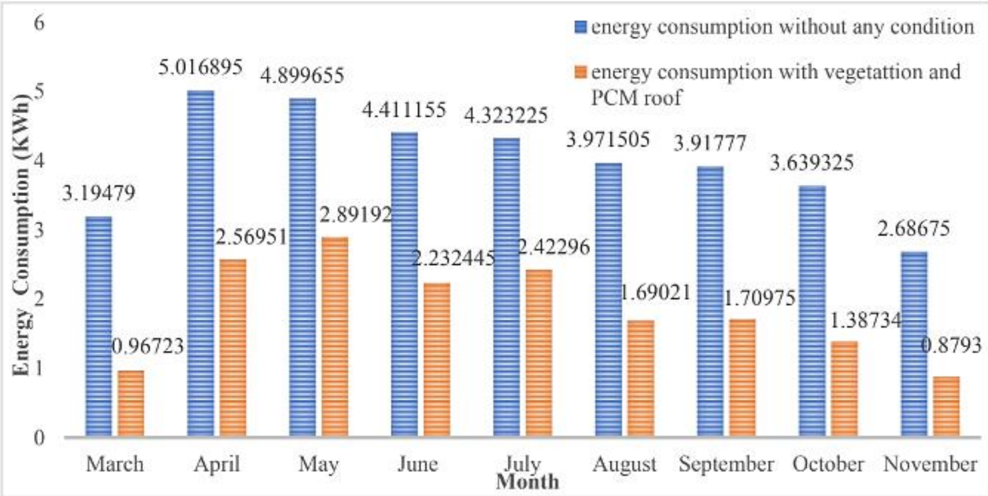

Figure 17: Graph for energy consumption vs. month

5. Conclusions

This study showed that for interior vegetation temperature didn't reduce. But it makes the environment healthy and reduces stress. It was observed that with increasing vegetation, the temperature decreased up to 3°C but after a certain period temperature didn't decrease more than 3°C although vegetation increased. By using WPC on the rooftop as a phase change material temperature decreased around 4°C. By using all conditions (rooftop, sidewall, interior vegetation & PCM on rooftop) together temperature could be mitigated around 5°C. From the cost analysis, it was found that for the mitigation of around 5°C, energy consumption can be decreased annually by around 289.05 KWh and the total cost could be decreased by around 60827.4 TK.

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