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Urban Heat Island: Causes, Effects & Mitigating Strategies

Gunjan Jain[1] & Shuvojit Sarkar[2]
[1]Associate Professor, MBS School of Planning & Architecture, New Delhi
[2] Assistant Professor, School of Planning & Architecture, New Delhi

***Abstract**: The increase of urban areas and dominance of the landscape of cities by dense built forms, roads, impermeable surfaces results in the phenomenon of urban heat island wherein the built areas experience higher temperature than the surrounding suburbs.*

The article highlights the various natural and anthropogenic causes of urban heat island effect ranging from geographic location and weather to urban sprawl, urban morphology, building materials and heat emitted by various urban activities. The article further discusses how the urban heat island effect is resulting in increased energy consumption and in turn increased emission of air pollutants, degradation of water quality of water bodies and thermal discomfort along with ill effects on human health.

The article explores the various mitigation strategies mainly trees and vegetation, green roofs and cool roofs, passive ventilation and reduction of anthropogenic heat due to building appliances. It stresses on an integrated and multidisciplinary approach to urban development involving participation of the various sectors namely public health, urban planning, architecture and transportation along with the community concerned.

1. Introduction

The 21st century is the century of "Cities" with more than half of the world human population concentrated in the urban areas. As per United Nations report 54 per cent of the world's population is urban in 2014 and around 66 per cent of the world's population will be urban by 2050 (UN World Urbanisation Prospects, 2014). In India, as per Census 2011, 31.2% of the total population is residing in urban areas, wherein the decadal urban growth rate is 31% compared to decadal rural growth at 12% only (Census 2011 & 2001).

The increasing urbanisation has led to drastic changes in the landcover with more of open land, soft permeable surfaces and vegetation being replaced by dense built forms, roads, impermeable hard surfaces and infrastructure. This change in landscape results in the phenomenon of urban heat island wherein the built areas experience higher temperature than the surrounding suburbs.

2. Urban Heat Island

The term "urban heat island" refers to the observed temperature difference between urban environments and the surrounding rural areas (Voogt, 2002).There are mainly two types of urban heat island phenomenon which are generally observed:

2.1 Surface Urban Heat Islands

During the day, the exposed urban surfaces like roofs and pavements get heated to temperatures ranging from 27 ^{o}C to 50^{o}C and become hotter than air and shaded or moist surfaces remain close to air temperatures (Berdahl P. &S. Bretz., 1997). The magnitude of surface heat islands changes with seasons due to changes in suns intensity, weather and ground cover and is strongest in summers (Oke, T.R.,1982).The surface heat island is most intense during the day and when the sky is clear and winds are calm. The difference in daytime surface temperatures between urban and rural areas is 10 to 15°C and the difference in night time surface temperatures is relatively smaller at 5 to 10°C (Voogt, J.A. & T.R. Oke. 2003, Roth, M., T. R. Oke & W. J. Emery, 1989)

2.2 Atmospheric Urban Heat Islands

It is characterised by warmer air in urban areas compared to cooler air in nearby rural areas. It can be further differentiated between the following two types:

- Canopy layer urban heat islands- exist in the layer from the ground to below the tops of trees and roofs where most of the human activities take place
- Boundary layer urban heat islands- exist in the layer above the rooftop and treetop level and extend up to the point where urban landscapes no longer influence the atmosphere which roughly extends up to1.5 km from the surface (Oke, T.R., 1982).

Atmospheric urban heat islands effect is more pronounced after sunset due to the slow release of heat from urban surfaces and is generally weak during morning and through the day. The annual mean air temperature of a city with one million or more people can be 1 to 3°C warmer than its surroundings (Oke, T.R., 1997) and on a clear, calm night, this temperature difference can be as much as

12°C (Oke. T.R. 1987). Even smaller cities and towns produce heat islands, though the effect is often less pronounced as city size decreases (Oke, T.R.,1982).

3. Causes of Urban Heat Island

3.1 Urban Sprawl and Loss of Green Cover

Urbanisation at an unprecedented rate is leading to dense built up areas, more impervious surfaces such as roofs, asphalt roads, paved sidewalks and reduced green and soft areas which results in less water infiltration. The soil infiltration rate in cities is only 15% and the quantity of rainwater runoff is 55%, whereas in the natural environment, approximately 50% of rainwater infiltrates the soil and 10% runs off toward watercourses (USEPA, 2007; Cyr et al., 1998). By restricting the availability of water in urban areas, natural cooling processes, such as evaporation of the moisture in soil and evapo-transpiration of vegetation, are limited and cannot offset urban warming (Brattebo and Booth, 2003).
In an urban heat island study conducted in 2011 by Mohan, Kandya and Bottripolu in the Delhi region of India, a difference in minimum night time temperature of areas over the years was observed due to rapid urbanisation. It was also found in the study that prior to 1985 Safdargunj area in Delhi had a higher night time temperature but after 1986, Palam area in Delhi experienced a higher night time temperature with respect to Safdargunj as most of the urbanisation in Palam area happened after 1986 with coming up of Asia's largest residential colony Dwarka and new international terminal at IGI airport.

3.2 Albedo & Thermal Emissivity of Building Materials

The building and surface materials in an urban area influence the microclimate and thermal comfort conditions as they absorb considerable heat during the day, which they release back into the atmosphere at night, thus contributing to the urban heat island effect (Asaeda et al., 1994). The "radiative properties" of materials such as solar reflectance, thermal emissivity and "thermal properties" of materials such as heat capacity, determine how the sun's energy is reflected, emitted, and absorbed.
Solar reflectance, or albedo, is the percentage of solar energy reflected by a surface and largely depends on the colour of the material. Darker surfaces tend to have lower solar reflectance values than lighter surface. A white surface with an albedo of 0.61 is only 5°C warmer than ambient air whereas conventional gravel with an albedo of 0.09 is 30°C warmer than air (Taha et al., 2004). The low-albedo materials can reach temperatures of 80°C in summer (Liébard and DeHerde, 2005). Urban areas typically have dark coloured surfaces such as asphalt roads which have a lower albedo and thus absorb more heat raising the surface temperatures and contribute to the formation of surface and atmospheric urban heat islands.
Thermal emissivity is a measure of a surface's ability to release heat i.e. infrared radiation. Surfaces with high thermal emittance values stay cooler as they release heat more rapidly. Apart from metals most of the construction materials have high thermal emittance values. Heat capacity of a material is its ability to store heat. Many building materials such as steel and stone have higher heat capacities than soil and sand. Thus built up urban areas store the sun's energy as heat within their infrastructure and contribute to urban heat island effect (Christen, A. & R. Vogt., 2004).

3.3 Urban Morphology

Urban morphology refers to the three-dimensional form, orientation and spacing of buildings in a city and plays an important role in the formation of urban heat islands (USEPA, 2008). Dense high rise buildings and narrow streets can restrict air movement and ventilation as they create urban canyons where the heat generated by solar radiation and human activities accumulates and remains trapped (Coutts et al., 2008). In fact, the reduction of the sky view factor limits net radiative losses of buildings and streets (Pigeon et al., 2008).
During the day in an urban canyon tall buildings create shade, reducing surface and air temperatures. On the other hand when sunlight reaches surfaces in the canyon, the sun's energy is reflected and absorbed by building walls, which diminishes the overall albedo of the built fabric and increases the temperatures. At night canyons generally hamper cooling, as buildings and structures can obstruct the heat that is being released from urban forms and surfaces (Sailor, D.J. &H. Fan., 2002).

3.4 Anthropogenic Heat

The production of anthropogenic heat such as heat emitted by vehicles, air conditioners and industrial activities is another factor that contributes to the development of heat islands, particularly in dense urban areas where activities are concentrated (USEPA, 2008). Anthropogenic heat varies by urban activity and infrastructure, with more energy-intensive buildings and transportation producing more heat (Voogt, J., 2002).

3.5 Geographic Location and Weather

The geographic location of an urban area determines the climate and topography and influences the formation of urban heat island. The urban areas which are near a large water body can be benefited by generation of winds that can convect heat away from cities and can reduce the temperatures. Similarly mountain ranges in a hilly region can either block wind from reaching a city, or create wind patterns that pass through a city. Urban heat island effect intensifies during periods of calm winds and clear skies as it maximises the amount of solar energy reaching urban surfaces and minimises the amount of heat that can be convected away.

4. Effects of Urban Heat Island

4.1 Increased Energy and Water Consumption

Across the globe, the increasing temperatures in the cities due to urban heat island effect is leading to increased energy consumption for cooling to provide thermal comfort in homes, offices, public buildings and vehicles. The peak urban electric demand increases 1.5 to 2 percent for every 0.6°C increase in summertime temperature. Steadily increasing temperatures of urban areas over the last many decades implies that 5 to 10 percent of electricity demand is used to compensate for the heat island effect (Akbari, H., 2005).

The impact of urban heat island has worsened due to increasing use of air conditioners due to hot air exhaust from air conditioners which further degrade the air quality and increase the temperature. According to World Bank study, 2008, the demand of air-conditioners in India will rise from 4.7 million in 2011 to 48 million by 2031 and it will create an additional power demand of 49928 GW/yr in 2031 which is equivalent to power generating capacity of 500MW power plants in a year.

There is also an increase in demand for water for cooling e.g. swimming pools and fountains or for watering plants (Balling et al., 2008).

4.2 Increased Emissions of Air Pollutants and Greenhouse Gases

The urban heat island effect leads to increased demand for energy and puts additional burden on power plants which mostly produce electricity from combustion of fossil fuels and release pollutants like Sulphur dioxide (SO_2), oxides of Nitrogen (NOx), Particulate Matter (PM), Carbon monoxide (CO), Mercury (Hg). Carbon dioxide (CO_2), a green house gas, is also a major residue from the power plants and contributes to global warming and climate change. The urban heat island effect also contributes to smog formation which is mainly fine particulate matter and tropospheric ozone. The elevated air temperatures increase the rate of ground-level ozone formation, which is produced when oxides of nitrogen react with volatile organic compounds in the presence of sunlight (Akbari et al., 2001).

The indoor air quality is also affected as increased heat promotes growth of mites, mould and bacteria and also leads to the release of toxic substances, such as formaldehydes, found in the glues used in furniture manufacturing. (Salomon and Aubert, 2004).

4.3 Compromised Human Health and Comfort

The urban heat island effect leads to reduced difference between the daytime and night time temperatures and increased air pollution levels which affect human health as it causes thermal discomfort, respiratory problems, heat cramps, exhaustion, heat stroke and heat-related mortality. Urban heat islands can also worsen the impact of heat waves. The lack of night time relief in air temperatures is strongly correlated with increased mortality during heat waves. According to many studies the domineering night time temperatures may be more significant than high maximum daytime temperatures (Kalkstein, L.S., 1991).

Sensitive population is more vulnerable to the effects of urban heat island, such as people with chronic diseases, aged people, young children, outdoor workers, persons of low socioeconomic status and people who engage in strenuous outdoor activities (Besancenot, 2004; WHO, 2007; CSST, 2004). According to the World Health Organization, anthropogenic warming claims more than 150,000 lives on an annual basis.

4.4 Degradation of Water Quality of Water Bodies

There is degradation of water quality of streams, rivers and lakes due to thermal pollution which is caused by storm water runoff from heated urban surfaces such as pavements, rooftops etc. According to studies runoff from urban areas is about 11-17°C hotter than runoff from a nearby rural area in summers when pavement temperatures at midday are 11-19°C above air temperature. When the rain comes before the pavement had a chance to heat up, runoff temperatures from the rural and urban areas differs by less than 2°C (Roa-Espinosa, A. et.al, 2003). Increased water temperature in surface water bodies affects the aquatic life and the functioning of the entire aquatic ecosystem (EPA, 2003).

5. Mitigation Strategies for Urban Heat Island Effect

There could be several methods or combination of different technologies which can help in reducing the impact of extreme heat within an urban environment. The following section discusses few mitigation strategies to reduce the urban heat island effect.

5.1 Vegetation

Trees improve the air quality through oxygen production, carbon capture and reducing the smog which builds up more in the rising temperature. Plantation of trees also reduce CO_2 indirectly from the atmosphere as they help in reducing the demand for cooling, thus minimising the burden on power plants for electricity production.

Trees directly trap ozone precursors by dry-deposition, a process in which ozone is directly absorbed by tree leaves and indirectly reduce the emission of these precursors from power plants by reducing combustion of fossil fuels and hence reducing NOx emissions from power plants (Taha 1997).

Trees and vegetation lower surface and air temperatures by providing shade, minimising ground temperature differences and through evapo-transpiration. Evapo-transpiration, alone or in combination with shading, can help reduce peak summer temperatures by 1–5°C. Trees and vegetation are most useful as a mitigation strategy when planted in strategic locations around buildings in west or south west direction and when they shade asphalt paved parking lots and streets.

5.2 Green Walls and Roofs

Green walls are vertical ecosystems that create a microclimate that substantially lowers the temperature of the building envelope and improves its energy efficiency (Kingsbury and Dunnett, 2008). These walls help reduce large temperature differences by increasing the building's thermal mass (Jour de la Terre Québec, 2008).

A green roof is a vegetative layer grown on a rooftop. Green roofs reduce the amount of heat transferred from the roof to the inside of building as a result of evapotranspiration and the shade created by the plants. They also cool the outside ambient air (McPherson, 1994)

On a sunny, 26°C day, a dark roof can reach a temperature of up to 80°C, a white roof, 45°C, and a green roof, 29°C (Fischetti, 2008; Liu and Bass, 2005). Green roof temperatures further depend on the roof's composition, moisture content of the growing medium, geographic location, solar exposure, and other site-specific factors (Akbari H., 2005).

In Germany, Green space is used as a premium in urban growth to limit the urban sprawl and developers are often required to provide green roofs as a compensation of lost open space (DDA Manual, 2007). Green roofs filter particulate matter from the air, retain and cleanse storm water and provide new opportunities for biodiversity preservation and habitat creation (Peck & Kuhn, 2003).

5.3 Albedo of Materials

The higher the reflectivity (albedo) and emissivity of a material, the less likely it is to store heat and radiate it back into the atmosphere or into the building through the walls and roof (Paroli and Gallagher, 2008; Synnefa, 2007). In most of the urban areas, roofs and pavements constitute almost 60% of the land surface area (Akbari et al. 2008).These surfaces especially the dark coloured roofs, streets and pavements absorb the solar energy and transmit them inside the buildings and contribute to urban heat island effect. Albedo of the pavement and roofs should be increased in order to minimize the buildup of heat and keep the surfaces at low temperature. High-performance roof coating products, such as elastomeric and polyurea membranes, light-coloured tiles and gravel have higher albedos than conventional materials and more suitable for flat roofs (Akbari et al., 2006). The albedo of pavement can be increased by adding reflective pigments to asphalt and concrete .A layer of concrete 2.5 cm to10 cm thick on top of a asphalt road keeps the surface temperature cooler as concrete has a higher albedo. This method is very effective and can accommodate all types of vehicles (Winkelman, 2005; Synnefa et al., 2007 ;). However, all reflective materials lose a little of their reflective effectiveness over time due to dirt deposited on the coating (USEPA, 2008b) and hence needs to recoated or washed on a regular basis.

5.4 Climate Responsive Architecture and Passive Cooling

Climatic considerations in the design of the building envelope, orientation of the building exposing the surfaces, design of shading devices and incorporation of passive cooling techniques ensures protection from heat and thermal comfort for the building occupants. Pressure system of passive ventilation rely on positive pressure on the windward side of the building causing a lower pressure on the leeward side, in turn creating air movement through the building vents and windows from the windward to the leeward side. Passive stack ventilation work on the buoyancy principle, wherein natural airflow, wind and the temperature differences in the indoor and outdoor air help to draw in fresh air and circulate it through the building. Hot air being lighter than cool air tends to rise and it helps in drawing cooler air into the buildings. Passive cooling techniques are the most cost effective and time tested mechanisms for maintaining thermal comfort in the buildings without relying on active heating and cooling systems.

5.5 Reducing Anthropogenic Heat

Heat production in the buildings by use of various appliances and vehicles in the urban areas contribute in developing the urban heat island. Various household appliances, light bulbs, computers, office equipments etc. converts much of the energy they consumed into heat and contributes to overheating of the building which is coupled by direct solar radiation and poor thermal insulation. Anthropogenic

heat can be responsible for 2°C to 3°C increase in temperature of urban centers (Taha, 1997).
The heat emitted by vehicles can remain trapped in poorly ventilated urban canyons, thereby reducing the thermal comfort of urban dwellers. Vehicle emissions also contribute to urban smog and global warming (Watkins et. al. 2007). Good transportation planning is essential in order to minimise heat gains in urban environments (Coutts et al., 2008). Use of public transportation system and less use of individual motorised vehicles along with switching to cleaner fuels like CNG can help in reducing not only reducing the pollution levels but also urban temperatures.

6. Conclusion

Although urban climatologists have been studying urban heat islands for decades, community interest and concern regarding them has been of quite recent. This increased attention to heat-related environment and health issues has helped to advance the development of heat island reduction strategies. Plantation of trees and vegetation, green roofs and cool roofs, passive ventilation and reduction of anthropogenic heat due to building appliances provide thermal comfort to building occupants. Implementing these measures will not only help to reduce the energy demand during peak summer but will also provide health and environmental benefits such as reduced mortality due to heat stroke, less CO_2 emission, increased thermal comfort, reduced air pollution and hence less pulmonary diseases. Future policy efforts may focus on encouraging strategies to modify urban geometry and reducing anthropogenic heat to plummet urban heat islands.
An urban heat island mitigation strategy must be based on an integrated and multidisciplinary approach to urban development and requires the participation of various actors, particularly from the community concerned, as well as various sectors, for example public health, urban planning, municipal statutes, architecture, transportation and natural resources. Creating awareness, sharing information and knowledge among cities across the globe, concerning their achievements and the evaluation of their experiences is essential for optimal mitigation of urban heat island effect.

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