Urban Physics for tomorrow's Urban Design

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ABSTRACT

The quality of urban life and urban experience is being compromised regularly in urban areas; one primary aspect being continuous urban climate degradation because of concentrated anthropogenic intervention in natural climate. As a result of rapid urban sprawl, drastic modification of the natural setup are common all around; like transformation of surface cover, alteration of watersheds and natural drainage, devastative destruction of natural flora and fauna, which in turn deteriorates the overall urban experience. On the other hand, urbanization is the necessity to sustain the economic growth and overall prosperity of the population in the present global scenario. Maintaining the quality of urban experience is one of the toughest challenges to the planners, urban designers and architects.

The researchers are investigating on the impacts of modified urban climate in terms of degraded air quality, thermal discomfort, unbalanced hydrological cycle, and various socio economic impacts as a result of the same. Urban physics is increasingly gaining importance in the research world as a tool to mitigate the urban climate and improve the overall living experience in urban areas. Urban physics is basically an inter-disciplinary approach combining physics, environmental chemistry, aerodynamics, climatology, mathematics and statistics, and most importantly urban morphology. But the real-life application of the knowledge acquired is limited. The pattern of urbanization and the main trend of building our cities remained primarily unchanged.

This paper will focus on different types of researches carried out so far in this Urban Physics domain, and their findings. This state of the art review will also provide a scope for the present authors to identify application potential of different researches in real life scenario. This can bring out scope for further research extensions on the basis of gaps found in research findings.

INTRODUCTION

The planning and designing of urban areas has taken a radical paradigm shift in the last few decades in the developed nations regarding the environmental sustainability. The change transcends from the early energy efficient buildings to the present net positive energy, intelligent buildings, which is really a big step towards the mitigation of the problem of climate change issues and global warming. The awareness of the people, encouragement from the government and social motivators played a great role to bring the wind of change.

The 20th century tendency of "design whatever the client wants, mostly on the basis of cost or aesthetics" (Butler, 2008) is an anomaly and hardly ever leaves much impact in our 'ecological age' (Head, 2008). Presently most of the buildings and urban settlements are designed in a much sustainable way remembering their context and subsequent environmental impact. But, climate-responsive design is becoming more and more difficult due to rapidly changing urban climate and the buildings are depending more and more on artificial cooling, mechanical ventilation and artificial lighting even at daytime. This problem becomes more traumatic in the urban areas of developing nations because of their high density and higher insolation which is further deteriorated due to tremendous population pressure, lack of financial support, political ill-will and ignorance of common mass to retrofit the urban growth pattern for a more positive outcome. The deteriorating urban climate casts doubt on the efficiency of traditional Indian design philosophy of open buildings with fuzzy demarcation between the inside and the out.

This rapid urbanization demands sprawl of the city boundaries and densification of the urban tissues as well. The latter frequently results in the erection of tall structures along narrow streets and complete eradication of green spaces. As a result of the altered climatic balance, the air temperature, humidity, air pollutants and concentration of Suspended Particulate Matters (SPM) in air rises, worsening the quality of life in urban areas by the decreased thermal comfort, acute air pollution, frequent urban floods and increased energy consumption.

In order to apprehend all the problems of urban areas, it is essential to look into the physical properties of the various elements of urban climate. Urban physics is the engineering discipline that establishes the interrelationship of the transfer of heat, wind flow, moisture, pollutants, light and sound in urban areas to have a better understanding on urban climate. The aim of the study of urban physics is to provide an outdoor and indoor built environment that is healthy and comfortable taking into account of existing and future economical, ecological and climatic constraints.

Presently most of the researches in urban physics focus on environmental degradation in urban areas taking into account the Urban Heat Island, evapotranspiration, wind driven rain, pollutant dispersion, wind turbulence etc. Techniques like advance measurement of climatic parameters in boundary layer, sophisticated modelling tools based on Computational Fluid Dynamics (CFD) and wind tunnel simulations are combined together to obtain knowledge about heat, moisture and air flow starting from individual building scale to neighbourhood and entire city scale. The study of urban physics is helping the researchers a lot to understand the urban climate and finding out solution for better urban experience.

OVERVIEW OF URBAN PROBLEMS

Urban areas are plagued with various issues like outdoor thermal discomfort, extreme air Pollution, Urban flood, Low water table, loss of natural vegetation etc. these are basically a result of the interaction between some more fundamental inherent and external factors. If these fundamental issues are understood first, it will be easier to formulate some streamlined mitigation strategies in order to make cities a better place for living. Issues related to the design of urban areas like the materials used to cover the surfaces, placement of plazas and courts, alignment of trees and vegetation etc. play a vital role in urban thermal dynamics. Based on the principles of urban physics high performance computers analyze huge data sets collected by the instruments and help to understand various responsible factors and the interrelationship between them. The most important issues and their impact on urban climate are described below stating their causal relationship with other factors.

Transformation of Urban Surface:

The urbanization of the natural landscape through the replacement of vegetation with roads, bridges, houses, and commercial buildings has dramatically altered the temperature profile of cities. In fact, even within a city, different zones have different temperature profiles, dependent on their surroundings, type of surfaces, and characteristics of ground cover. Urban areas are characterized by dry, impervious surfaces, such as conventional roads, roofs, sidewalks, and parking areas. As cities grow, more greenery is vanished, and more surfaces are either paved or covered with buildings. The transformation in ground cover consequences in less shade and evapo-transpiration to keep urban areas cool. Lesser evapo-transpiration from paved and built up areas contributes to the rise of ground and air temperatures. These transformations affect the natural hydrological cycle within the urban area, leading to extreme surface runoff, reduced baseflows and infiltration, greater amounts of non-point source pollution when compared to areas of a more rural nature, and especially forested areas.

The surface transformation brings in consequential changes in urban hydrologic cycle that contributes to greater localized flooding potential, water bodies that harbour more nutrients and other chemicals, resulting in a greater growth of algae and reduced diversity of fish and wildlife, and a general overall decline in the aesthetics of urban water resources.

Formation of Urban Heat Islands:

In most cities, urban air temperatures are generally greater than their corresponding rural counterparts. This occurrence, the urban heat island (UHI), has been known since the turn of this century and has been well documented (T.J. Chandler, 1960), (T.R. Oke, 1987), (T.R. Oke, 1988). The fluxes of heat, moisture, and momentum are significantly altered by the urban landscape and the contrast between the urban and 'undisturbed' climates is further enhanced by the input of anthropogenic heat, moisture, and pollutants into the atmosphere. It has been observed that the heat island intensities can go up to 10^{0}C in Indian cities (Pune) (Santamouris, 2001). The probable causes of the formation of UHI as suggested by oke (1982) are as follows:

i. Trapped short and long radiation between the buildings.
ii. Reduced Sky View Factor (SVF) resulting in decreased long wave radiative heat loss
iii. Increased heat storage in urban construction materials
iv. Abundant anthropogenic sources of heat and moisture from fuel combustion
v. Reduced evapo-transpiration
vi. Reduced wind speed resulting in reduced convective heat removal

Though UHIs are not always unfavorable for cold climatic regions (Erell et al., 2011), it substantially increases the cooling load in warm climate and causes serious effects on inhabitants regarding the comfort and health issues. The increased urban temperature not only creates acute heat stress, but it also leads to psychological and behavioural changes along with the reduction of human physical and mental performance which leads to lesser productivity (Evans, 1982).

Increased Energy Demand:-Increased energy demand costs the consumers and municipalities more energy related expenses to maintain the desired comfort levels. The heating and cooling load of a building depends on the climate to which the building is exposed. Buildings located in the same area can have entirely dissimilar energy consumption pattern due to altered local microclimates. High ambient temperature increases the cooling load and energy consumption as well. It has been stated that for US cities the peak electricity loads increase by 1.5−2 % for a temperature increase of 1 ◦F (Akbari et al. 1992). A number of studies has been carried out using urban physics to look into the effects of urban heat island on various cities like Athens (Santamouris et al.2001), London (Kolokotroni et al. 2010) (Kolokotroni et al. 2006), Kassel (Schneider & Maas, 2010), Tokyo (Hirano &Ohashi, 2009) etc. All studies indicate a substantial impact of the increased urban temperature on the energy consumption of buildings.

Wind movement:

Wind movement in urban areas is much restricted due to the high building density. It results in low air exchange and lower the potential of air circulation in and around the buildings (Hirano &Ohashi, 2009) (Ghiaus et al. 2010).

Convective heat transfer and evapo-transpiration is also affected by lower wind speed. This reduced heat exchange results in excess heat storage in the urban built environment and raises the temperature of urban microclimate which again increases the cooling demand of indoor spaces. As a result of the entrapped solar radiation, the building skin temperature is always higher than the ambient air temperature (Allegrini et al. 2011).

Air Pollution: -

Generation of more electricity by power plants leads to higher emissions of sulfur dioxide, nitrous oxide, carbon monoxide, and suspended particulate matters, along with carbon dioxide. Development of urban heat islands often escalates the formation of photochemical smog, as ozone precursors like nitrous oxides (NOx) and volatile organic compounds (VOCs) reacts photochemically to form ground level ozone.

As the intrinsic characteristics of the natural landcover is transformed in the urbanization process, the energy exchange which takes place within the boundary layer are highly affected. Transformation of the natural ground cover influences the local (microscale), mesoscale, and the macroscale climate and disrupts the natural route of energy flow through the land, atmospheric and water cycles.

Planning Issues:

A number of planning related issues are responsible for continuous degradation of urban climate. In most of the cities, urban growth happens in a haphazard way without proper planning. Though the urban development guidelines tell some sort of indirect guidelines, the planners and urban designers often neglect the issues. In most of the cases they only visualize the space but fail to apprehend impact of the proposed development after their construction on urban climate. The climatic data that are taken into account, mostly collected by the weather stations which are placed at a much higher height. The actual ground level climatic parameter and the impact of local anthropogenic factors like mutual shading and reflected heat from surroundings, very often remain unnoticed.

Absence of mandatory energy efficiency codes and the resulting energy wastage from buildings also play a vital role in deterioration of urban climate. Building energy efficiency policies and programs are mostly in an active design stage with limited implementation to date. Decision-making authority at the national level is spread between several agencies and program design and implementation responsibilities are spread across a large number of state and municipal agencies, resulting in a diversity of implementation regimes and little coordination. This micro level reduction in energy use can cumulatively make a great impact on improvement of urban climate.

The role of urban physics in better appreciation of the problems of urban climate is indisputable. A lot of researchers are working in this field presently in order to solve the problems generated by rapid urbanization in various parts in the world. For an in depth appraisal of urban climate in urban neighbourhoods and street canyons, the combined effect of solar radiation, wind flow and evapotranspiration is studied. Modelling and simulation of various cases are performed using computational fluid dynamics (CFD), Radiation simulation and whole building simulation tools. Wind tunnel simulations are often carried out to validate the CFD simulation. By varying the various parameters of the model (like building density, green plot ratio etc.) the impact on microclimatic variables like outdoor temperature, wind speed etc. are observed and optimum solution can be proposed.

APPLICATION OF URBAN PHYSICS

Urban physics not only helps a lot to identify the problems of urban areas but also has the capability to suggest the optimum solutions of the problems.

A substantial amount research has been done to reduce the detrimental impact of urban climate change which suggests various measures like the use of evaporative cooling from ground level (Kruger and Pearlmutter, 2008) and rooftop water bodies (Runsheng et al.,2003; Tiwari et al.,1982) or make use of evapo-transpiration from wetted ground. Alternatively the design of the buildings with lesser exposed flat surfaces to control the direct solar access and aerodynamic design of the building can facilitate wind movement in and around it to improve the urban microclimate.

Considering the context of cities where the high humidity level, acute shortage of land is a burning issue, the solutions mentioned above are not feasible. As of today, most of the buildings in cities of the developing nations are built without any professional input and custom made passive design solution for every single building is a farfetched dream. Rather the protection of existing landscape by facilitating urban forestry, increasing the surface albedo by applying reflective materials especially on horizontal surface and plantation of shade providing trees along the road and around the buildings seem to be a more implementable solution. Among all known strategies of urban climate mitigation, a few, befitting the present context are discussed below.

Implementation of Urban Green Infrastructure:

‘Green infrastructure’ (GI) is a term used to delineate a network of greenways, parks, and untransformed open spaces, which are basic modules of urban environments (Benedict and McMahon 2006). (Kambites and Owen 2006, 484) specified that green infrastructure denotes “connected networks of multifunctional, predominately unbuilt, space that supports both ecological and social activities and processes”. These systems provide assorted psychological, economic, social, and environmental benefits to urban individuals and communities (Forest Research 2010); (Manning 2011), and are essential in city planning and design (Walmsley 2006). Green infrastructure focuses on strategic planning to identify and protect wetlands, forests, and other natural components that deliver crucial ecosystem services.

GI includes the community "greening," in which trees and plants are used tactically for stormwater management and other functions in urban areas. Urban greening ranges from planting streetside trees, installation of high albedo surfaces and rain gardens to installation of green roofs and planters on high-rise building balconies. Urban greening is very important to mitigate the extremities of urban climate and it provides several types of additional benefits to the urban community including richer biodiversity, pleasant visual experience, reduction of stormwater runoff and more groundwater recharge.

Green roofs:

Installetion of green roof can passively cool the air above it and the indoor space below, (Köhler, 2004) (Teemusk and Mander, 2009) reduces the stormwater runoff, tackles air pollution by absorbing the pollutants and Suspended Particulate Matters (SPMs) and so on. The higher reflectivity of the foliage of the trees compared to common roof materials results in lesser absorption of radiated heat. Their higher emissivity also facilitate long-wave radiation and so radiant cooling (Gaffin et al., 2005) (Gaffin et al., 2006).Green-roof shades the roof slab by obstructing solar radiation. It offers thermal insulation to obstruct heat absorbed at the upper surface toward the roof slab (Lazzarin et al., 2005) (Getter et al., 2011).

Use of High Albedo Surface:

Roofs and pavements constitute around 60% of urban surfaces in many urban areas (Akbari et al., 2003) (Rose et al., 2003) (Akbari and Rose 2001). It is also demonstrated in many studies that an increase of roof reflectivity from 10-20% to 60% can generate energy savings excess of 20% in many cities. Increase of albedo of roofs and pavements can improve the air quality and reduce the summertime temperature in urban areas (Taha 2001) (Taha et al. 2000) (Rosenfeld et al. 1998). Due to the increased reflectance of urban surfaces some amount of incoming solar radiation can be reflected back and can counter global warming also (Kaarsberg and Akbari, 2006).but this strategy can only work in the case where the solar radiation is reflected back to the space and not entrapped between the building due to multiple reflections.

Promotion of Urban Forestry:

Urban forests can ameliorate the urban climate by restricting direct solar radiation, facilitating wind movement, removing SPMs and pollutants by the means of bioretention. It can lower the overall temperature of the surrounding by at least 2 ^{0}C-8 ^{0}C by the means of increased evapo-transpiration (Oke, T.R., 1987), (Taha et al, 1989). The shade provided by urban trees can be the single most important parameter to increase the overall thermal comfort as the direct solar radiation has the maximum impact on the surface energy balance (Taylor and Guthrie, 2008). The most favourable design solution is a layout where the buildings and trees together mutually shade the open spaces and roads (Emmanuel and Johansson, 2006), (Erell, 2008).

Policy Level Mitigation Strategies

Planning policies, guidelines and development control regulations actually determines the urban geometry. Though there is a subtle linkage between policy framing and urban physics, appropriate planning and development control regulations can facilitate the solutions that came out from simulation of various city models. At the same time, proper implementation of those guidelines should also be ensured.

Urban geometry has a strong influence on urban climate and the comfort level. It has been observed that a compact urban form with very deep street canyons and lower sky view factor (SVF) can create lower temperature (Cool Island) providing shade to the pedestrians in hot dry climate (Pearlmutter et.al. 1999) (Givoni,1998). On the contrary, dispersed urban forms create an extremely uncomfortable environment in the summer. So urban physics can indirectly guide the framing of building bylaws of a city depending upon its climate.

From the above discussion it is understood that urban physics not only gives the researchers an in depth knowledge of the problems regarding urban climate but also helps to find out the solutions for the same. The advancements in this field of research will certainly help to build better cities with better living experience.

INTEGRATION IN URBAN DESIGN

The comfort level of cities are highly compromised due to their high pollution level, formation of UHI, and reduced thermal comfort. Framing the Urban design guidelines according to the findings of the researches following the principles of urban physics can can lead to the optimum urban setup. Taking the case of a city in warm humid climate, it can be observed that the stagnant air mass inside the city helps to form UHI, rises the humidity level and concentrating the pollutants and SPMs which altogether deteriorates the urban experience. But improvement of wind movement inside the city can substantially improve the scenario. Strategic placement of the tall buildings in the urban fabric can extensively improve the wind flow in the city. But placing the tall building in a dense pattern restricting the wind penetration inside the city is not recommend in this particular case. So setting the building bylaws in favour of higher FAR and lower ground coverage in some strategic plots and designing the urban area in accordance with it can be very helpful to improve the outdoor comfort and reduce the outdoor temperature which results in substantial energy savings.

But this same urban setup can become incompatible in the case of cold and windy cities. The opposite approach, i.e. clustering of tall building in the path of prevailing wind restricting the wind flow can reduce the pedestrian level wind movement to a comfortable level and prevent the conduction heat loss from building skin. Appropriate and contextual urban design guidelines understanding the principle of urban physics can thus improve the urban experience and reduce the energy demand as well.

In the case of a number of tropical and subtropical coastal cities, moist air comes from the seaside.

The hot urban area underneath heats up the moist air and it rapidly goes up followed by sudden cooling and formation of dense clouds. But the wind drives the clouds on the other side and heavy rainfall happens in the opposite side of the city of the direction of that incoming moist air from the sea. This unequal heavy sudden rainfall results in unprecedented high intensity urban flooding in those cities. Cities like Kolkata, Mumbai, Puri, Kochi, Surat are some common example of this incident in India. The urban poor or those who live in slums are mainly affected by urban flood especially in cities like Kolkata and Mumbai where the slums are located in low lying ecologically fragile areas

There is a need to access the probability and extents of occurrences of these incidents and design the urban area accordingly facilitating prolonged runoff time using urban green infrastructure, more permeable surfaces, more urban greenery and improving the efficiency of stormwater drainage. This can reduce the chances of vulnerability of the services and the inhabitants as well. Therefore many of the urban design principles for sustainable and climate resilient development of the cities require the inputs from urban physics for betterment of their performance.

THE INDIAN SCENARIO

Since the economic reforms started in 1991, Indian economy is growing at a fast pace. Due to migration from rural to urban areas, India's urban population is expected to reach 472 million in 2020 and 611 million in 2030 compared to 325 million in 2005 reaching a share of 41% of the total population resulting in urban sprawl and densification (MGI 2010). To accommodate the migrating population, the construction industry is also growing at a fast rate contributing an average 6.5% of GDP (JLLM 2007).

Indian cities grow in a ridiculous way by inclusion of urban fringes in the municipal areas. When a city starts to grow, the land price of its surrounding village areas go up and development of the rural areas start according to the rules and regulation of the rural areas having narrow roads and lack of public amenities. It does not support any future improvement due to high built up areas and virtually no open space. When these peri-urban settlements are included in the urban municipal areas, the problem increases many fold due to the further increased population pressure. These areas may be retrofitted with some basic services and amenities, but the situation remains the same. These densely packed buildings (mostly without mandatory open spaces) creates a havoc impact on the urban climate because of complete extinction of greenery, extensive hard paved surfaces and the least space for wind movement.

In most of the cases, Indian cities only have municipal building byelaws which only deals with one individual building but they do not have any comprehensive strategy or guidelines for developing the public spaces considering the outdoor comfort and convenience in the urban realm. The existing building bylaws are often disobeyed which creates problems in wind movement, water percolation etc. Even the buildings in the National Capital Territory of New Delhi, comply with building codes less than 35% of the time (WB & IFC, 2009). Considering the unsustainable growth of the urban areas in India, a number of policies are introduced to facilitate the energy efficiency and green building as a control and regulatory measures including appliance ratings and certifications. But almost all the measures deal with an individual building. No visionary guideline has not been developed considering a neighbourhood level or city level.

Though in March 2011, BEE asked for the compulsory enactment of ECBC at the local level in eight states starting in 2012: Delhi, Maharashtra, Uttar Pradesh, Haryana, Tamil Nadu, Andhra Pradesh, Karnataka, and West Bengal (PTI, 2011).

The data on existing building stock in India are incomplete and estimates about the total floor space, number of units and typology of building (commercial, residential or industrial) vary considerably. With this limitation, the following facts and figures should be viewed as approximation. The total building stock in India has experienced an annual average growth of 6% between 1990 and 2005 resulting the doubling of floor space from 4 to 8 billion m2. From 2005 to 2030, the average growth is expected to be 6.6% resulting 22 billion m2 in 2020 and 41 billion m2 in 2030. The growth pattern represents that almost 70% of the buildings that will exist in 2030 have not been built yet which actually leaves a window of opportunity to make substantial improvement of urban climate. (The World Bank, 2010). There is an urgent need to develop an urban development guidelines with a strong emphasis on the mitigation strategies of climatological and environmental impacts of urban development.

It is an agreed upon fact that Indian cities need much more attention for their extreme and as well as diverse character and as most of the future cities are yet to be built, there is a great scope of implementation of urban physics in designing Indian cities. Though a lot of researches has been carried out but the real life implementation of urban physics in urban design is yet to gain its momentum in the subcontinent.

CONCLUSION

The amelioration strategies discussed above came only through the research of urban physics and gives a direction to improve the experience of urban areas and explore new areas for improvement. It is evident that most cities suffer due to their air quality (pollution), thermophysical quality (thermal comfort) and water related issues (urban flood, low water table, etc.) (Campbell-Lendrum & Corvalan, 2007). In most of the case they are linked with one another in the urban ecosystem. So, the architects, urban designers and planners need to use urban physics to understand their interrelation for a practically implementable, streamlined and unified approach to start the development of mitigation strategies to deal with the unintended urban climate change.

The development route of world civilization till date has made it very clear that the population growth and urbanization will continue at a very rapid pace. Development of a number of new cities and expansion of the existing ones is a necessity. Therefore, there is an urgent need to develop new sets of urban design guidelines that comply with the research outcomes of urban physics to ensure that the upcoming buildings and the corresponding urban areas go along with today’s most efficient, climate resilient design and planning strategies.

Though the subject, urban physics, comes with a world of opportunities, it has some downside too. The correlation between various factors of urban climate, huge data sets and highly complex mathematical calculation demands profound knowledge of the subject and substantial amount of computational resource to run the simulations. Supply of resources and availability of experienced professionals and a streamlined networking among all the stakeholders is necessary for its success.

Though urban physics mainly deals with a group of buildings, neighbourhoods, urban canyons etc. special emphasis has to be given on the design of individual buildings also as they cumulatively contribute to the overall urban experience. Considering the common trend of having very less building designs with professional inputs in most of the urban areas, the situation is going to deteriorate much more in the foreseeable future. It is very important to get the urban fabric right so that every single building have the capability to extract the maximum environmental potential with or without professional interventions echoing the ethos of traditional Indian design with a fuzzy demarcation of indoor and outdoor.

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