Effects of tall building envelope technologies and design strategies on the urban microclimate in hot arid regions

Sameh Monna¹

T2 – Mitigation Strategies and Techniques

ABSTRACT
The effects of tall building envelopes on urban microclimate are enormous, as tall buildings cast many shadows on the other buildings and streets, the use of green walls and roofs affects the microclimate air temperature, the highly glazed buildings facades can flash brilliant reflections, tall buildings in different orientation can block or channel the wind creating artificial wind patterns, and the massive amount of concrete and pavements contribute to the urban heat island.

This paper is directed to the study of various tall building envelope technologies and design strategies and their influence on the hot arid urban microclimate. The effects of coating materials with high and low albedo on the air temperature, surface temperature and urban heat island, the tall buildings large scale have a significant influence on the urban microclimate due to the large mass of concrete, glass and steel used in tall building envelope; these cause the so called urban heat island. On the other hand, some technologies and design strategies have a positive influence on the urban microclimates, like: the use of green walls and roofs, shading elements, self shading and orientation. It's found that these could decrease the urban heat island in hot arid climate.

KEYWORDS
Urban microclimate, building envelope, tall building, design strategies, technologies

¹ Politecnico di Milano, Building Environment Science and Technology Department (BEST), Milano, Italia, 20133, Via Ponzio, 31, Phone +39 02 2399 6016, Fax +39 2 2399 6020, sameh.monna@mail.polimi.it
1 INTRODUCTION
1.1 Tall and high rise buildings
ASHRAE technical committee for tall buildings defines tall buildings as those higher than 91 m height. "We can define a high-rise building as essentially a tall building with a small footprint and small roof area with tall facades" [Yeang, 1999]. The building can defined to be high or low rise with respect to the height of the surrounding building, for example if the buildings in the city are around 4 stories then 12 stories or more may be a tall buildings. In some cities like New York and Hong Kong the tall buildings are 40 stories plus, the council on tall buildings and urban habitat CTBUH consider 150 meter and above as a high rise building.

Tall buildings have unique engineering facade and systems, these systems make tall building different from low-rise building and need attention in design, construction and use phases. "Special attention needs to be focused on the ecological design of the skyscraper building type more than on other intensive urban building, in which many of the well-known ecologically responsive technical solutions are common" [Yeang, 1999]. The reason that this kind of building has large effect on the built environment and urban microclimate; tall buildings cast many shadows on the other buildings and streets. In addition, the highly glazed buildings facades can flash brilliant reflections, streets lines with tall buildings can block or channel the wind create artificial wind patterns, massive amount of concrete and pavements contribute to the urban heat island and increase the local air temperature. These factors have an effect on the energy demand for tall buildings cooling and heating.

1.2 Environmental effects of height
Because the atmosphere (from the sea level to 11 km) changes with altitude, The temperature decrease with altitude with a rate of 1°C per 150 m, barometric pressure decrease more slowly and wind speed increase with altitude (table 1). These environment factors have a significant effect on the annual total cooling and heating loads for tall buildings [Ellis & Torcellini, 2005]

Table 1. The effect of altitude on air temperature, pressure and wind speed, and the significant effect especially for wind speed that should be taken into consideration for tall buildings design strategies

<table>
<thead>
<tr>
<th>Variable</th>
<th>1.5 m</th>
<th>284 m</th>
<th>Absolute difference</th>
<th>Percent difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature</td>
<td>15°C</td>
<td>13.15°C</td>
<td>1.85°C</td>
<td>12.3%</td>
</tr>
<tr>
<td>Barometric pressure</td>
<td>101 325 Pá</td>
<td>97 960 Pa</td>
<td>3 365</td>
<td>3.3%</td>
</tr>
<tr>
<td>Wind speed</td>
<td>2.46 m·s⁻¹</td>
<td>7.75 m·s⁻¹</td>
<td>5.29 m·s⁻¹</td>
<td>215%</td>
</tr>
</tbody>
</table>

1.2.1 Air temperature
In urban areas the air temperature is higher than the surrounding rural country due to urban traffic, urbanization, and the decreasing of vegetation and trees. The well-known phenomenon of heat island causes the temperature difference, and increases temperature in urban area especially during summer period. The impact of urban heat island on energy demands for cooling is tremendous; the urban heat island is increasing significantly, which negatively impact urban productivity and urban living conditions. The exterior surface temperature of urban buildings can exceed 60°C in summer season causing energy consumption for cooling to be up to 30-40% greater [Chen Zhi et al. 2007]. On the other hand, the air temperature is decreases with altitude as its clear in the above table and this happen in tall buildings, this will influence the energy for cooling, heating and natural ventilation in the upper levels for high rise buildings over 150 m.

1.2.2 Wind pattern
Beside the effect of altitude on wind speed (table 1: the higher wind at the upper levels of tall towers presents a potential opportunity to use it in turbines), the presence of tall buildings effects as shelter deceasing in general the wing speed and allowed the modifying of the airflow. In addition, streets lines with tall buildings can block or channel the wind create artificial wind patterns. On the other hand,
higher wind speed increases the convection coefficient and the amount of infiltration which increase the heat transfer (U value) by 8%.

1.2.3 Solar radiation

Solar radiation is divided in to three regions: the ultraviolet, visible and the infrared rays, and they are considered regions of Short-wave. Most of the ultraviolet region which possesses approximately 6% of the solar spectrum (wavelength range 0.29 μm-0.38 μm) is absorbed by ozone. The visible region (wavelengths 0.38 μm-0.78 μm) has approximately 46% of the entire solar spectrum. The infrared radiation (wavelength range 0.78 μm-2.5 μm) owns approximately 43% of the solar spectrum. Under direct-beam clear-sky the amount of solar radiation increases with altitude for horizontal surfaces. For vertical surfaces, solar radiation composed of direct, diffuse from the sky and diffuse from the ground [ASHRAE 2005], for tall building while the direct and diffuse radiation from the sky are likely increasing, the diffusion radiation from the ground is likely decreasing since there are thicker air mass to travel through. The effect of the modification of solar radiation absorbed, transmitted, and reflected due to the technologies and design strategies, like reflective and high emittance coating materials on the tall buildings energy demand and outdoor comfort have to be evaluated.

2 TALL BUILDING ENVELOPE TECHNOLOGIES AND DESIGN STRATEGIES

2.1 The influence of coating materials;

Building envelopes function as an environmental filter; they form a skin around the building structure and manipulate the influence of the outdoor on the indoor environment, they include the entire building component that separate the indoors from the outdoors, the envelope of the building consist of the exterior walls, roofs and windows. For tall buildings walls cover more than 90% of the envelope and highly influence the outdoor microclimate.

Albedo is the ratio of the value of solar radiation reflected by the building surface to the total value projecting on the building surface [Chen Zhi et al. 2007], the larger the albedo of the surface materials the smaller the irradiation energy which absorbed it. The buildings with high albedo materials can improve the indoor and outdoor thermal environment effectively. A great increase of albedo combined with shading of trees can reduce the energy use for air conditioning by 40% in the cases studied. For example it is found that white coatings with an albedo of 0.72 were 40°C cooler than black coatings with an albedo of 0.08 in the early afternoon of clear summer day [Chen Zhi et al. 2007]. Akbari [2003] found that it would save 33 kW·h·m⁻² of energy per day and 8.4 kW·h·m⁻² per year when the albedo of the roof was changed from 0.26 to 0.72. Simpson and McPherson [1997] monitored the roof temperature on 1/4 scale model buildings and suggested that white roof 0.75 albedo were up to 20°C cooler than grey 0.30 albedo, or silver 0.50 albedo and up to 30°C cooler than brown 0.10 albedo roofs. Synnæfa et al. [2007] estimate the effect of using cool coatings on energy loads and the thermal comfort in residential building in various climatic conditions, and found that using cool materials on the building roof in hot climates could save up to 90% on the cooling loads and decreasing the hours of discomfort for almost up to the same percent.

Table 2. Calculated mean value of albedo for different coating materials [Chen Zhi et al. 2007]

<table>
<thead>
<tr>
<th>Material</th>
<th>Albedo</th>
<th>Material</th>
<th>Albedo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>0.21</td>
<td>Yellow coating</td>
<td>0.54</td>
</tr>
<tr>
<td>Blue coating</td>
<td>0.25</td>
<td>White napped tile</td>
<td>0.71</td>
</tr>
<tr>
<td>Reddish-brown coating</td>
<td>0.36</td>
<td>White smooth tile</td>
<td>0.78</td>
</tr>
<tr>
<td>Deep red tile</td>
<td>0.43</td>
<td>White coating</td>
<td>0.86</td>
</tr>
</tbody>
</table>

Considering the increase of high rise buildings in cities, the heat absorbing and heat releasing of wall facing materials and not only the roofs are one important factor influencing the urban heat environment during summer, that impact the indoor and outdoor microclimate environment. For this reason applying such technologies should be evaluated for tall buildings in hot arid climates. In
conclusion researches show that exterior surface with high albedo remains cooler when exposed to solar radiation because they absorb a little solar radiation and reflect more to the space. In addition wall facing materials with high albedo could control the temperature of walls effectively and thereby control the indoor temperature. Increasing the solar reflectance is typically more beneficial in hot climates where cooling load dominates most of the year. Special attention should be given to tall building envelope coating materials in hot arid climates due to its large surface exposed to the solar radiation and its effect on the urban heat island, indoor environments and cooling loads.

2.2 The influence of large scale and height

The urban environment imposes additional environmental factors because of shadings and reflection from the surrounding buildings. The large scale of tall buildings can result in excessive input data [Ellis & Torcellini, 2005]. In recent studies the built form, especially the envelope, was also found to have a significant effect on the microclimate behaviour. The envelope ratio or the ratio of the open ground area to the envelope area has an effect on the heat environment, studies show that the smaller the envelope ratio the cooler the built up unit, at maximum the built form effect relative to meteorological reference station is about 0.75 K in street houses and as a large as -2.4 K in closed courtyard at 15:00 [Shashua-Bar et al. 2006]. It can be seen that the tall buildings can have a positive effect due to shade it provide in hot climates. Other factor is the building heights, as the temperature decreases by height and the wind speed is increased this could affect the cooling loads and internal thermal comfort on the upper floors and allows passive ventilation. The taller the building in hot climate the greater the decrease in temperature, air density, and potential moisture and the higher the reduction in cooling energy use. Further studies should be done to evaluate the effect of this factor on the cooling load and outdoor comfort for tall buildings in hot arid climate.

2.3 The influence of green walls and green roofs

Urban spaces are expanded dramatically; the large modern cities, their structure, materials and general lack of vegetation affect the climatic characteristics of urban spaces causing a significant rise of the urban environment temperature known as the heat island effect especially in climate with a hot season. A recent study [Alexandri & Jones 2008] on the effect of green walls and green roofs on temperature decreases in different climates (Fig. 1) shows that air and surface temperature lower significantly in al climates examined when walls and roofs covered with vegetation. Surface temperature decreases on the south wall from 18.5°C maximum and 14.3°C daytime average for Riyadh to 9.8°C maximum and 5.6°C daytime average for Moscow. For the green wall case, air temperature decreases reaches 5.1°C maximum and 3.4°C daytime average for Riyadh and 2.6°C maximum and 1.7°C daytime average for Moscow.

We can conclude that the hotter and drier the climate is the more important the effect of green roofs and green walls on the heat environment and improves outdoor and indoor thermal comfort. On the other hand, it can decrease cooling loads demands inside the buildings due to microclimate.

Figure 1: On the left, air temperature decreases in canyon due to green walls, and on the right air temperature decrease in canyon due to south oriented walls covered with green, the various results in different climate zones show that the highest influence was for hot arid climate. Source: [Alexandri & Jones 2008]
modification. Due to the same study in Riyadh for example the high cooling loads decrease of the magnitude of 90% by applying green roofs and walls. The study shows also that for all climate examined, green walls has a stronger effect than green roofs inside the canyon, while green roofs has a greater effects at roof level and the urban scale.

2.4 The influence of shading and orientation

Minimizing the effect solar radiation within the hot urban environment may often be desirable in urban design criterion, the effect of buildings orientation and buildings heights are crucial factors on shading in hot arid climates due to high altitude solar radiation and high air temperature. After exposing the building to summer solar radiation for a certain period the building itself acts as a heat source and to the rising of the air temperature including the inside temperature [Akbari et al. 1997]. Bourbia and Awbi [2004] indicated that in hot arid climates, the air temperature of the north-south orientation street during day is lower than other sites and that the peak street temperature was 2.5-3.5 K lower than the reference temperature of the meteorological recording. While the air temperature of the east-west street was higher by up to 4 K than the north-south orientation street. In conclusion, the decrease of air temperature can be achieved by correct orientation of building for shading, while ensuring adequate sky view factor in order to moderate the harness of the climate.

Solar access to the street can be decreased by increasing the height to width ratio, floor and wall shading fraction increase with increasing the height to width ratio [Bourbia & Awbi 2004]. Todhunder [1990] considers that the micro scale urban geometry, like the street to building height and width relationships, their orientation and shading potential of urban mass are more important than the albedo and surface characteristics effects.

3 CONCLUSION

From the study above it can be concluded that technologies and design strategies for tall buildings have different influence on the hot arid urban microclimate. Green walls and green roofs, high albedo materials, shading strategies, building height to width and building orientation have a positive effect on the inside and outside air temperature in hot arid climate. On the other hand, factors like huge mass, glazing and low albedo materials have a negative influence. Most of these technologies and design strategies and their effects on the urban microclimate are examined for low and medium rise buildings, for these reason further studies are necessary to calculate the effect of tall building envelope technologies and design strategies on the urban microclimates. On the table below, the evaluation of various technologies and design strategies and their influence on the hot arid urban microclimate as high (+), medium (0) and low (-).

Table 3. The effects of building envelope technologies and design strategies on the outdoor comfort and cooling loads in hot arid climate.

<table>
<thead>
<tr>
<th>Technologies and design strategies</th>
<th>Outdoor comfort</th>
<th>indoor comfort/Cooling load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coating materials</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>Large scale and height</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Green walls and green roofs</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Shading and orientation</td>
<td>+</td>
<td>0</td>
</tr>
</tbody>
</table>

4 ACKNOWLEDGEMENT

The author acknowledge the support from Gabriele Masera and Tiziana Poli, Building Environment Science and Technology BEST Department, Politecnico di Milano.

REFERENCES


