Causes of Urban Heat Island in Singapore:
An investigation using computational fluid dynamics (CFD)

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ABSTRACT: In low-latitude cities like Singapore, urban heat islands contribute to the urban dweller's summer discomfort and significantly increased air conditioning loads. This study investigates the key factors causing urban heart island in Singapore. The possibilities of improving heat extraction rate by optimizing air flow in selected hot spots were explored The effect of building geometry and the location of air conditioning condensers on the outdoor air temperature was investigated using Computational Fluid Dynamics (CFD) simulations. It was found that strategically placing a few blocks of high-rise towers will actually help to enhance the velocity within the canyon thereby reducing the air temperature. Air-conditioning units spaced widely apart do not contribute much to the heat built up inside a canyon when the geometry is simple and as long as there is some wind flow within the canyon.
Keywords: urban heat island, CFD, geometry, facade materials, temperature, velocity

INTRODUCTION

Increasing urbanisation and industrialisation has caused the urban environment to deteriorate. The urban climate and the environmental efficiency of buildings are influenced by the deficiencies in proper development control [1]. As a consequence of changes in the heat balance, air temperatures in densely built urban areas are higher than the temperatures of the surrounding country. This phenomenon, known as Urban Heat Island (UHI), is a reflection of the totality of microclimatic changes brought about by man-made alterations of the urban surface [2]. In high-latitude cities with cooler weather, heat islands can be an asset in reducing heating loads, but in mid and low-latitude cities, heat islands contribute to the urban dweller's summer discomfort and significantly higher air conditioning loads. The effect of building is considered as one of the main reasons for urban heat island effect. Building masses increase the thermal capacity, which has a direct bearing on the city temperature. They reduce wind speed and radiate heat through the building fabric and also in the form of air-conditioning equipments. The heat that is absorbed during the day by the buildings, roads and other construction in an urban area is re-emitted after sunset, creating high temperature differences between urban and rural areas. Many research works have been conducted in USA, Australia, Greece and Japan to study the UHI effect in many cities. But studies are relatively lacking in the low tropics, particularly with respect to quantitative evaluation. In Singapore, with the current trend of having higher density and high-rise buildings as well as the increasing usage of air-conditioning, it is essential that research should be carried out to study the severity and effects of this phenomenon and what measures could be implemented to ameliorate such effects.

The urban heat island phenomenon is due to many factors, the most important of which are summarized as follows [3]:

1. The canyon radiative geometry that contributes to the decrease in long-wave radiation loss from within the street canyon due to the complex exchange between buildings and the screening of the skyline;
2. The thermal properties of materials, which increase storage of sensible heat in the fabric of the city;
3. The anthropogenic heat released from combustion of fuels and animal metabolism;
4. The urban greenhouse, which contributes to the increase in the incoming long-wave radiation from the polluted and warmer urban atmosphere;
5. The canyon radiative geometry, which decreases the effective albedo of the system because of the multiple reflection of short-wave radiation between the canyon surfaces;
6. The reduction of evaporating surfaces in the city, which means that more energy is put into sensible heat and less into latent heat; and
7. The reduced turbulent transfer of heat from within streets.

The urban canyon is a more useful city unit for investigation in the UHI study. It describes the conditions of a long street with tall buildings on both sides. The distribution of the ambient air in a canyon greatly influences the energy consumption of the buildings. The temperature in a canyon is influenced by the temperature of the canyon surfaces, because energy is transferred through convective process. Results from simultaneous measurements performed in three sets of canyon in Athens pointed out that the air temperature measured in the middle of the canyon is not influenced by the orientation of the street either during the day or during the night. This leads to the conclusion that air temperature in the canyon is not greatly influenced by the canyon configuration and is mainly controlled by the air-flow process [1].

URBAN HEAT ISLAND IN SINGAPORE

A combination of measurement strategies were employed to find the severity of the urban heat island and it has confirmed the occurrence of the UHI effect in Singapore. Based on the data derived from mobile survey, the CBD area showed the highest temperatures. The maximum temperature difference of 4°C was observed between the vegetated area and the CBD area. The possible causes of temperature increase in the CBD area are unsuitable use of materials, lack of ventilation resulted from improper building-street layouts and orientation and impact of heat rejection from the air conditioning systems.

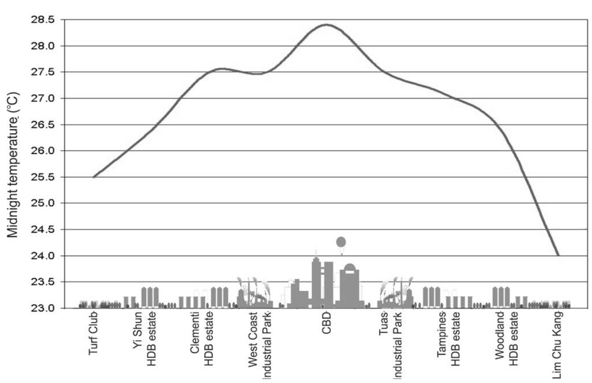

Figure 1: Sketch of urban heat island profile in of Singapore

As streets usually cover more than a quarter of the urban area, canyon-street layout plays an important role in creating the urban climate. It directly influences the air temperature, moisture and wind flow within the streets as well as the urban surrounding area. Natural ventilation of buildings located in urban canyons is significantly reduced because of the decrease of the wind velocity inside the canyons. Another cause for the heat build up is anthropogenic heat, the main source of which is vehicle transport and heat discharge from air conditioners. The energy consumption of air conditioners is closely related to the climate of the city. The heat emitted by the air conditioners in summer will induce a rise in the ambient air temperature. Also the rise in ambient air temperature will increase the energy consumption of air conditioners. This paper mainly focuses on the impact of geometry modifications and heat rejection from air conditioning condensers.

METHODOLOGY

Computational Fluid Dynamics (CFD) is used as the main tool for analysis and this study makes use of the software, CFX-5.6 [4] which is based on finite volume technique. In this technique, the region of interest is divided into small sub regions called control volumes. The boundary conditions required for the CFD simulations were mainly obtained from the weather data and field measurements. The inlet boundary condition was expressed in the form of power law wind profile as explained below to simulate the atmospheric boundary layer.

Power law:

$$\frac{U}{U_{ref}} = \left(\frac{Z}{Z_{ref}}\right)^{a}$$

Where, reference height z_{ref} = 10m, coefficient of roughness for city centre a =0.4

The wind speed set was based on the data obtained from the Singapore Meteorological station over 18 years. Since the mean wind speeds at the meteorological stations were recorded at 10m height, this data was corrected by incorporating the Power law to estimate the wind speed at 60 m height. The air temperature was assumed to be 30°C. The outlet was modeled as free pressure boundary with zero relative static pressure. An infrared thermometer equipped with a laser beam (measurement accuracy ±2%) was used to measure the surface temperature of the exterior facades of the building. The infrared radiation emitted from the measuring object is directed and converted to an electrical signal by the imaging sensor and displayed as a colour or black and white thermal image. Measured temperature can be corrected by applying the emissivity of the measured object in the emissivity setting. These values ranging from 32°C to 40°C were assigned for the external surface of the buildings as fixed temperature boundary conditions. Here the wall boundary is fixed at a specified temperature T_w. The heat flux into the domain is calculated by $q_w = h_c(T_w - T_{nw})$ where T_{nw} is the near wall temperature and h_c involves the use of turbulent wall functions.

EFFECT OF GEOMETRY

The urban wind is one that can be dominated and modified by urban design. The main urban design elements which can modify the wind conditions are the overall density of the urban area, size and height of the individual buildings, existence of high-rise buildings and the orientation and width of the streets [5]. Characteristics of canyon geometries, expressed in terms of height-to-width (H/W) and length-to-height (L/H) ratio, are known to produce three principal air flow regimes: 'isolated roughness'; 'wake interference'; and 'skimming flow' [6]. In deep canyons, the air circulation inside the canyon is not only due to the ambient wind flow, but is the resultant of three specific mechanisms: the ambient air flow above the canyon; the vertical stratification of the air inside the canyon which can reach values up to 6K; and the mechanism of advection from the building corners that result from end effects [7].

To have a general understanding of the influence of high-rise towers on the thermal environment numerical simulations were conducted using simple models. Two models were compared: one without high-rise towers; and another by incorporating a few high-rise towers. The effect of these towers on the air flow with respect to different H/W ratios was explored. Subsequently, a part of the existing CBD area was selected for the study. A series of CFD simulations have been carried out by varying the width of the streets and the height of the tall building towers to investigate the effect of these parameters on the velocity as well as temperature patterns within the canyons.

For the parametric modelling, a canyon having a height of 18m and length of 250m was selected. This is typical of the canyons found in the CBD area. No high-rise towers were included in the first model which is named as Model 1(Figure 2). Another model, Model 2 was created by including the high-rise towers to explore the effect of these towers on the air flow profile (Figure 3). The H/W ratio was varied from 1.5 to 0.4. Wind speed of 4m/s, based on the meteorological data was used for this study.

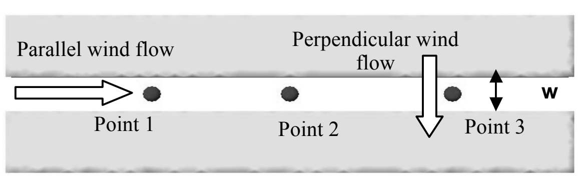

Figure 2: Plan of Model 1 and measurement locations

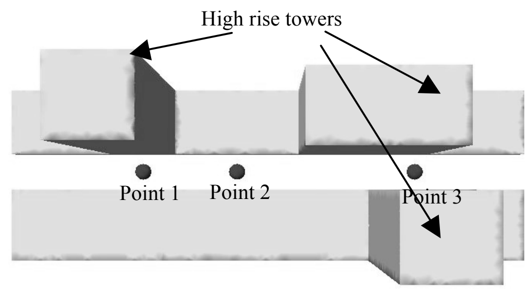

Figure 3: Plan of Model 2 and measurement locations

For parallel wind flow, the velocities at lower levels were enhanced by the channeling effect by the buildings, in the case of canyons with higher H/W ratios. For canyons with lower H/W ratios, unobstructed flow was observed. At higher levels, the channeling effect was found to be not very significant. The velocity first increases with decrease in H/W ratio, and then reduces due to the flow separation at the centre. Here, the unobstructed flow occurs at much lower H/W ratios. The channeling effect observed at the lower levels in the absence of the high-rise towers existed for even smaller H/W ratios with the introduction of high rise towers. This means unobstructed flow occurred at larger widths.

Figures 4 and 5 show the comparison of velocities and temperatures at 1.5m height as well as 15m height for different cases.

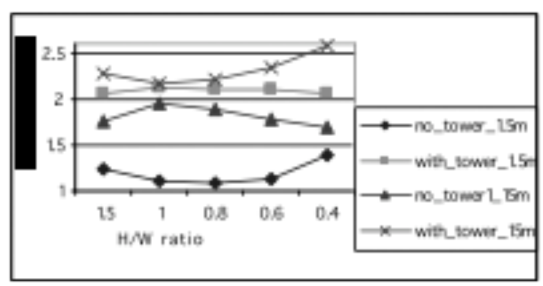

Figure4: Velocities with and without high rise towers (wind flow parallel)

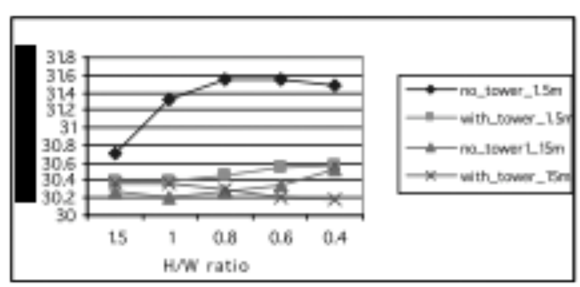

Figure 5: Temperatures with and without of high rise towers (wind flow perpendicular)

The velocities at the three Points within the canyon were highly enhanced by the presence of high-rise towers when the wind flow is parallel as well as perpendicular to the canyon. For parallel flow, the velocity has been increased by up to 90% and the temperature has been reduced by up to 1°C with the introduction of high-rise towers. For perpendicular flow, the velocity has been increased up to 10 times and the temperature has been reduced by 1.1°C. The high-rise towers at the canyon entrance will influence the velocities at locations deep inside the canyon length even at the lower level. For perpendicular flow, with the presence of high-rise towers, the velocities were much higher, up to one order of magnitude. The transition to wake interference flow occurred at a larger H/W ratio. The temperature generally decreased with the increase in velocity. The velocities as well as temperatures of the lower levels were highly influenced by the high temperature of the road surface. The temperatures were much higher near the ground. But the introduction of high rise towers led to strong airflow at the lower level thus decreasing the temperature. The length of the canyon, height of the high-rise towers as well as the spacing between the high-rise towers are the other important parameters which can influence the air flow pattern.

The part of the CBD area under exploration covers a region of 600m X 400m. The area consists of densely populated high-rise buildings and deep street canyons. Canyons are numbered from I to IV. Temperature at these locations were noted from the results of the CFD simulation and these were compared to the temperature measured at the field. Table 1 shows the dimension of the canyons. All the 4 canyons under study were asymmetric with varying building heights on the two sides. The width of the road (W) comprise two side walks and other set backs. The vicinity can be mainly divided into two: the lower area up to height of 24m consisting of continuous canyons; and the higher area which has high rise building towers up to a maximum height of 250m located randomly above the continuous canyons. 12 numbers of locations were identified for the analysis. A series of simulations were conducted by varying the width of the streets as well as the height of the high-rise building towers. Widths of four streets were varied as described in Table 2. The heights of the lower parts of the buildings were kept constant.

Table 1: Dimension of canyons

Canyon no	Mean ht of lower continuous canyons (H)m	Width (W) m	H/W ratio	Max.ht of high rise towers (m)	Min. ht of high rise towers (m)
I	19	30	0.63	180	128
II	21	14	1.5	180	76
III	21	24	0.88	170	44
IV	20	30	0.66	90	46

Table 2: Different geometric modifications

Different cases	Variations
Base case	Existing
Case A	10% width increase
Case B	25% width increase
Case C	50% width increase
Case D	$2/3^{rd}$ height for high rise towers
Case E	$1/3^{rd}$ height for high rise towers

Analysis showed that fFor most of the Points, maximum temperatures were observed near the ground due to the convective flow from the road surface to the adjacent air. The lower and higher levels of the base case had similar pattern for velocity and temperature near high-rise buildings. The temperature variations amongst different locations were much smaller at higher levels compared to the lower levels. High wind speeds were observed within the lower level as velocity was enhanced by the channelling effect along the streets. However, locations just in front of the high rise buildings had increasing velocities with the increase in height. The effect of street's width modification in the lower continuous canyon was different from the effect above the canyons. It was observed that H/W ratio of 0.6 to 0.7 gave rise to maximum velocity at the centre of the canyon. The adoption of this optimum H/W ratio increased the velocity up to 35% and reduced the corresponding temperature by up to 0.7°C. Modifying the neighbouring street geometry enhanced the wind speed and lowered the temperature at the narrow lanes. Reducing the height of the high-rise towers reduced the wind speed at most of the locations and also resulted in higher temperatures. This shows that a limited number of the high-rise towers strategically placed above the continuous canyons will not always cause higher temperature.

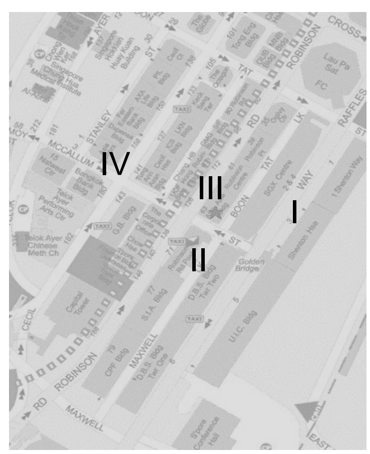

Figure 6: Plan of the CBD area under study

AIR CONDITIONING CONDENSERS

The main source of building related anthropogenic heat is air conditioners. Though air conditioning can improve the indoor thermal environment of a building, waste heat is dumped into the atmosphere making the urban thermal environment worse. The effect of heat dissipation from the condensing units can be unfavourable. Arrays of condensing units installed on tall buildings can cause thermal buoyancy as a consequence of heat dissipation from these condensing units. This results in an upward air movement. Santamouris *et.al* [8] found that for a representative building, the cooling load almost doubled in the central Athens area, while peak electricity load may be tripled for higher set point temperatures. In parallel, the minimum COP values of the air conditioners in central Athens area is reduced by up to 25%.

In this study, the air conditioning condensers were modeled and their locations were varied in order to determine their effect on the temperature profile. Simulations were conducted to investigate the influence of heat rejected from the air conditioning condensers inside the canyon. The sides of condenser unit were assumed to be around 1m and for accurate prediction, each of this has to be finely divided into a number of mesh elements. As a result, the number of mesh elements in the model increased tremendously. A simple canyon namely Model 1, with length 120m, width 12m and height 18m was selected for the preliminary study. A number of condenser units were placed inside the canyons. The number of units was limited due to the memory restrictions. Subsequently a canyon including high-rise towers was simulated. Four types of layouts as explained below were tested by varying the positioning of the condensers.

1. Layout 1 - Condensers within the canyon at a level equal to half of the building height (see Figure 7);
2. Layout 2 - Condensers at the roof top
3. Layout 3 - Condensers vertically arranged at each floor of the high-rise towers; and
4. Layout 4 - This is a very deep canyon with a height of 80m, and condensers are arranged vertically above one another at each floor.

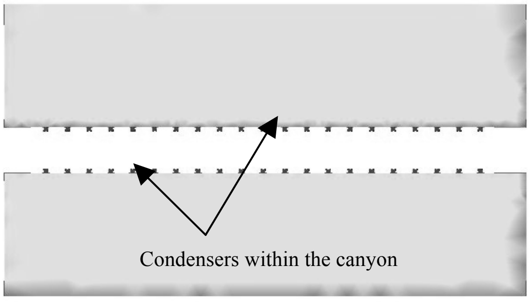

Figure 7: Plan of condenser Layout 1

Each condensing unit was assumed to have a heat dissipation rate of 4.5kW. The horizontal spacing between each unit was maintained as 5m. Volumetric heat energy was specified to the enclosed cells to represent condenser heat dissipation. Enough spacing was provided to eliminate the edge effect and the entire domain was having a size of 1500L x 1200W x 1300H. Two different wind speeds were tested: 4m/s to represent the high wind speed condition; and 0.1m/s to represent the low wind speed condition. Both parallel and perpendicular wind directions were tested.

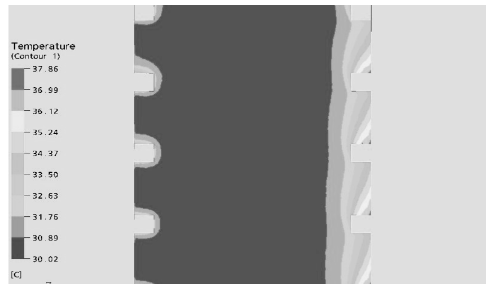

Figure 8: Temperature contours for Layout 3 for parallel wind at 0.1m/s

Figure 8 shows an enlarged view of the temperature distribution for Layout 3. From the series of simulations conducted, it was concluded that air conditioning units spaced widely apart do not contribute much to the heat built up inside a canyon when the geometry is simple and as long as there is some wind flow within the canyon. It is only the immediate surroundings to the condenser units that were affected. Earlier studies in Hong Kong had shown that condensers placed at narrow re-entrants of apartment buildings can cause significant heat built up due to inadequate air flow [9]. Very high on-coil temperature not only leads to energy wastage but also affects the equipment operation. Similar narrow spaces do exist in some parts of the CBD area. However, the capacity of the computing resources does not permit the modeling of a larger area as the number of mesh elements will be too huge. In the case of Layout 4, where the condensing units are arranged vertically on a canyon with very high H/W ratio, it was observed that there is a significant change in the thermal environment especially when the wind flows perpendicular to the canyon. Thermal buoyancy, as a consequence of heat dissipation from these condensing units, leads to an upward air movement. The resultant temperature near the condensers was as high as 38°C. It was also found that when condensers were arranged vertically on high-rise towers, temperature in between the towers was higher for higher wind speed compared to lower wind speed with wind flowing perpendicular to the canyon.

DISCUSSION AND CONCLUSION

A comprehensive assessment was carried out to identify the potential causes of urban heat island in Singapore. The contribution of various factors which affect the microclimate of the urban environment was quantitatively evaluated so as to determine and select the most promising ones for implementation and incorporation in urban design and planning decisions. Air flow pattern within the canyon inclusive of high-rise towers has been well addressed and the common belief that high-rise towers always cause obstruction to the air flow has been re-evaluated. The relationship between air temperature and parameters like street's width, height and wind velocity was evaluated. Also the correlation of air temperature and local air velocity was established.

From the series of parametric studies by modifying the urban canyon geometry, it was found that strategically placing a few blocks of high-rise towers will actually help to enhance the velocity within the canyon when the wind flow in parallel or perpendicular to the canyon. In addition, the temperature was lower when high-rise towers were introduced. For parallel flow, the velocity was increased by up to 90% and the temperature was reduced by up to 1°C with the introduction of high-rise towers. For perpendicular flow, the velocity was increased up to 10 times and the temperature was reduced by 1.1°C. The velocities as well as temperatures at the lower level were highly influenced by the high temperature of the road surface. However, when the wind flow was perpendicular, the introduction of high-rise towers caused higher air flow at the lower level thus decreasing the temperature. It is to be noted that, the lengths of the canyon, height of the high rise towers as well as the spacing between the high-rise towers are other important parameters which need further in depth study.

The results of the CBD area simulations showed high temperatures at narrow lanes and low temperature at wider streets. The limited geometry modification did not cause much significant change in the velocity and temperature. H/W ratio of 0.6 to 0.7 gave rise to maximum velocity at the centre of the canyon. Adopting this optimum H/W ratio increased the velocity up to 35% and reduced the corresponding temperature by up to 0.7°C. Modifying the neighbouring street geometry enhanced the wind speed and lowered the temperature of narrow lanes. Reducing the height of the high-rise towers reduced the wind speed at most of the locations and also resulted in higher temperatures. This shows that a few numbers of high-rise towers strategically placed above the continuous canyons may not always cause temperature rise.

Air-conditioning units spaced widely apart did not contribute much to the heat built up inside a canyon when the geometry is simple and as long as there is some wind flow within the canyon. It is only the immediate surroundings to the condenser units that were affected. Also, most of the commercial buildings in the central business district have central air-conditioning where heat dissipation occurs through cooling towers. However, high density residential buildings have window and split air conditioning systems, the condensers of which dissipate heat to the atmosphere. Very high on-coil temperature not only leads to energy wastage but also affects the equipment operation and also consumes more energy to cool down the buildings to the specified temperature setting.

In this study, a comprehensive assessment has been carried out to identify the potential causes of urban heat island in Singapore. The fundamental objective is to provide a general guidance to avoid the deterioration of the urban thermal environment. The results are expected to serve as design guidelines for a sustainable urban development which will ensure rational energy management and conservation.

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