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EFFECT OF SKY SCRAPERS ON NATURAL VENTILATION PATTERNS AND HUMAN COMFORT INDEX IN LOW-RISEBUILDINGS - A CFD ANALYSIS OVER CENTRAL MUMBAI

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ABSTRACT
Mumbai, the financial capital of India and one of the world's largest Mega Cities by the sea, is witnessing a massive construction boom. This can be attributed to the rapid economic growth as well as increase in population density. The number of skyscrapers has escalated to 140 (as of 2012), highest in any Indian city, with several more in the pipeline. It is also home to 1480 high-rise buildings. These towering, sharp-edged structures produce great amount of frictional drag and create turbulence in the boundary layer, significantly impacting the low-rise buildings lying in their wake. A CFD analysis to simulate air flow patterns around Tardeo (Latitude: 18°58'21.95" N, Longitude: 72°48'44.19" E) in Mumbai, has been conducted using ANSYS CFX to obtain pressure and velocity profiles- these product modeling simulations are expected to inform green architects engaged in sustainable design enhancements.

Keywords: Human Comfort Index, natural ventilation, skyscrapers, computational fluid dynamics, sustainable design, product modeling and simulation.

INTRODUCTION
Comfort has always been of primeval importance to man, providing him with a sense of ease and satisfaction within his environment. This is achieved mainly by well- designed houses with plenty of windows, promoting natural ventilation. The "HawaMahal" in Jaipur, built in 1799 serves a good example for a well-ventilated structure, primarily due to its pyramidal shape and small width of the upper three stories. These features promote cross-ventilation inside the structure, facilitating smooth flow around it, thereby leaving a very small region of wake. With advancement in technology, man furthered his pursuit to achieve comfort by inventing Heating, Ventilation and Air-conditioning devices (HVAC) like air conditioners, heaters, etc. But of late, owing to their high power consumption, these devices are in dire need of replacement, making natural ventilation highly popular in architecture.

We have based our study in Mumbai, one of the largest megacities by the sea. Being an island city, it enjoys a prodigious sea breeze, with the south westerly monsoons dominating the flow from June to September. Owing to its unplanned construction, Mumbai is an amalgam of high and low-rise buildings. It is home to roughly 18.41 million people (as per the latest census of 2011) and this number is predicted to cross 22 million by the end of 2013. This massive incubation has ignited a simultaneous need for commercial and housing establishments. Mumbai chose to build high rather than wide, due to spatial constraints and this, has led to a massive increase in the number of skyscrapers from less than 50 in 2001 to 174 in 2011. This simultaneous presence of skyscrapers as well as low-risers provided us with an opportunity to analyze the effect of these skyscrapers on the ventilation of low-lying buildings around them.

MODELING DOMAIN
Tardeo, a residential-commercial locality in south Mumbai, has been chosen as our area of study (Figure-1). It houses the Imperial Towers, standing tall at 885ft (270m), at latitude of 18058'21.95"N and a longitude of 72048'44.19". As of record, these towers are the second tallest structures in Mumbai, the first being the Palais Royale. An adjacent low-rise building - the Kamal Mahal – is the focus of our analysis for thermal comfort. It is a 7-storey residential structure. We have modeled an approximate layout with two 3-BHK flats on each floor, along with adjoining buildings. The area under consideration was modeled in Solid Works with dimensions measured from Google earth.

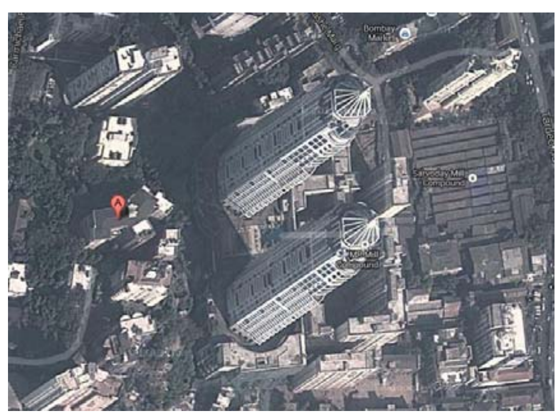

Figure-1. Google Earth view of Tardeo and Kamal Mahal.

The distance of Kamal Mahal from the western coast-line of Mumbai along its axis was measured to be 856.96m. Also, it was observed that the Imperial Towers were situated at an angle of 60 degrees from the axis of Kamal Mahal. This makes the south-westerly winds fall at

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an angle of 75 degrees to the Kamal Mahal and 135 degrees to the Imperial Towers, respectively. The winds change direction three times annually, the dominant wind directions being South-West from June to September, North-East from October to February; and West from March to May. A detailed annual wind- rose diagram for the city of Mumbai can be seen in Figure-2.

Figure-2. Annual Windrose diagram for Mumbai at an altitude of 10m.

COMPUTATIONAL FLUID DYNAMICS ANALYSIS

Apart from being structurally tall, skyscrapers are also enormously wide. This results in the formation of low pressure and velocity areas on the leeward side, which in turn affect the natural ventilation of low-rise buildings lying in its wake [1]. As wind flows around these buildings, they tend to detach from its surface (boundary layer separation) which may reattach to the surface depending upon the length of the structure. A study of this detachment and reattachment was performed for rectangular prisms of varying aspect ratio [2]. The flow around such an area is often disrupted by additional structures likes trees, billboards etc. which further promotes the need to use HVAC.

A CFD simulation of Tardeo was carried out on ANSYS CFX to find out the exact pressure distribution around the low-rise buildings. A coupled analysis was chosen over a decoupled one as it has shown more accurate results [3]. The standard k- turbulence model was used with an input velocity of 3.41 ms^{-1} at a reference height of 10 m in the North- East direction. The inlet boundary conditions were set as [4]:

$$U(y) = \frac{u^*_{ABL}}{\mathcal{K}} \ln\left(\frac{y}{y_0}\right)$$

$$k(y) = \frac{u^{*2}_{ABL}}{\sqrt{C_\mu}}$$

$$\varepsilon(y) = \frac{u^{*3}_{ABL}}{\mathcal{K} y}$$

$$K_{S,\,ABL} = 29.6 y_0$$

where,

U = inlet velocity
y = vertical height
u^*_{ABL} = friction velocity = 0.24ms^{-1}
$\mathcal{K}$ = von Karman constant = 0.41
y_0 = roughness length = 0.03m
k = turbulent kinetic energy
C_μ constant = 0.09
ε = turbulent dissipation rate
$K_{S,\,ABL}$ sand grain roughness height for Atmospheric boundary layer (ABL)

The simulated results for velocity and pressure are shown in Figure-3 and Figure-4 respectively. On the windward side of the skyscrapers, we notice stagnation pressures (in red) in the order of 20Pa (Figure-4). At the same location, velocities reach near zero (in blue) and the flow is diverted around the buildings, leading to an increased velocity (in orange) of 6ms^{-1} (Figure-3). These high speed winds are a major cause of pedestrian discomfort [5].

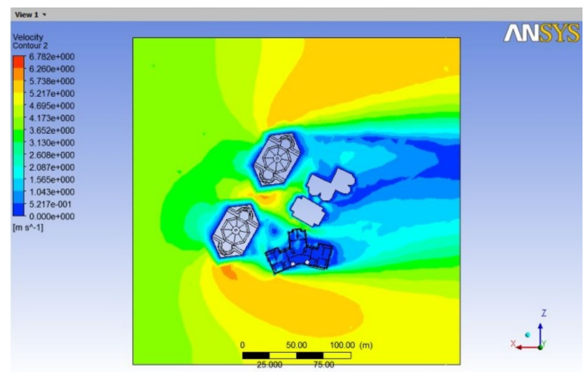

Figure-3. Velocity contours around skyscrapers and adjacent buildings.

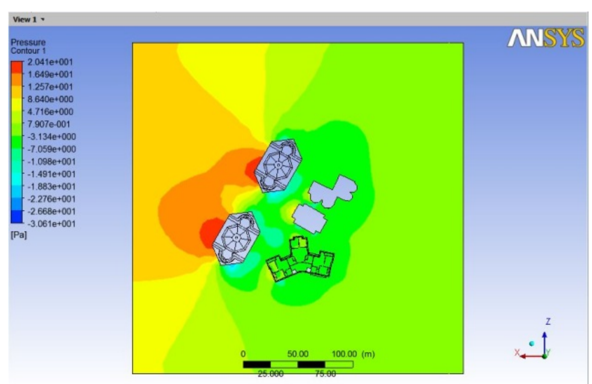

Figure-4. Pressure contours around skyscrapers and adjacent buildings.

Gauge pressures varied from -7.059Pa to -3.134Pa around Kamal Mahal (Figure-6). These low pressures can be attributed to the formation of a wake. A wake is a region behind an object, in this case the skyscrapers, which cause the formation of eddies as a fluid flows around it. These eddies are of low velocities (in blue), varying from 1.565ms^{-1} to 2.087 ms^{-1}, as can be seen in Figure-5. These low values indicate that the skyscrapers have reduced the wind velocities in and around them.

The pressures (in green, Figure-6) inside Kamal Mahal were found to be uniform at -3Pa and have significantly reduced the wind velocities inside the building to zero (in blue, Figure-5). This can be ascribed to the lack of a pressure gradient required for cross ventilation. By increasing the distance between the skyscrapers and the low-rise building from a mere 25m to 100m will significantly help in increasing the scale of natural ventilation. From Figure-3, we notice that further downstream from the building, there is an increase in wind velocity as the atmospheric boundary layer re-stabilizes. Introducing devices such as wind-catchers at strategic locations near the low-pressure regions can enable a significant improvement in indoor ventilation. These devices typically act as nozzles, facilitating a pressure driven influx of air from the bulk flow around the building.

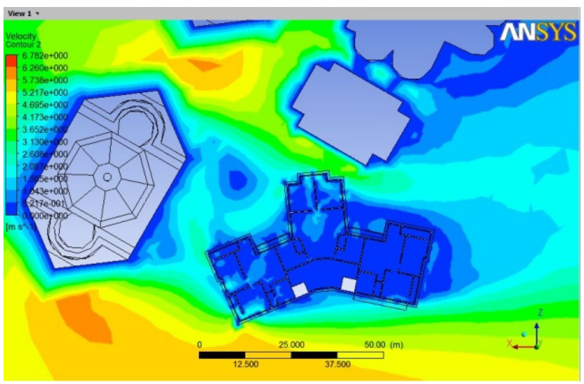

Figure-5. Velocity contours around Kamal Mahal.

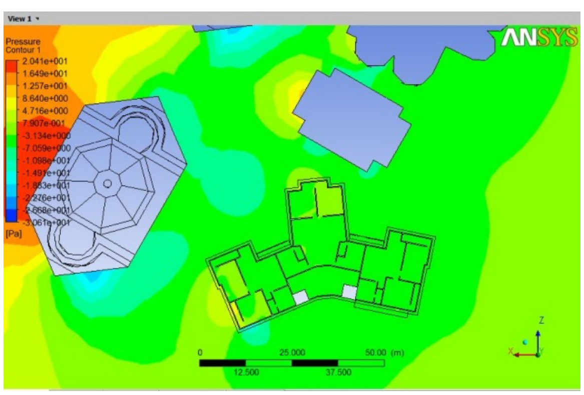

Figure-6. Pressure contours around Kamal Mahal.

Skyscrapers are generally very appealing to the eye and showcase a nation's wealth. They also exhibit a large housing capacity without consuming a lot of ground area. While this mitigates space-constraint issues in a city, it can also give rise to several other prominent issues like pedestrian discomfort, as well as reduced wind-driven ventilation in a low-rise building. This in turn leads to an increased use of artificial ventilation like fans and air conditioners culminating in electricity consumption.

CONCLUSIONS

Sustainable designs require a great deal of planning and modeling. Particularly in the metro cities of India, housing millions of people within limited available land is a challenge in itself. The problem is doubly complicated because of the energy crunch that the country is facing. The saving grace however is the plentiful availability of uninterrupted sunshine and the free flow of winds in our cities particularly over Mumbai. A design analysis involving optimal heat and mass transfer through ambient winds inside living quarters of Mumbai has been undertaken. A careful CFD analysis of pressure and temperature distributions inside low-rise buildings adjacent to towering skyscrapers revealed many interesting caveats- poor planning and location of skyscrapers have a significant impact on wind driven ventilation in low-rise buildings.

This study suggests that in order to increase indoor comfort, skyscrapers need to be placed at carefully considered distances so that nearby low-rise buildings do not lie immediately within their wake region- in this instance it was found to be 100m. Also, the construction of aerodynamically shaped buildings will help significantly in reducing this distance. Moreover, the installation of wind catchers at strategic locations in low-rise buildings shows promising results.

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