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Computational Fluid Dynamics Study on Wind, Solar Effect and Pollutant Dispersion in Masdar City

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Abstract

Advanced architectural designs of street canyons facilitate the improvement of thermal comfort in urban cities. A clear demonstration is found in Masdar City Abu Dhabi, a growing sustainable city powered by renewable energy. While thermal comfort is important, air quality should also be maintained. This work investigates pollution dispersion patterns and effects of solar radiation in Masdar City. A two-dimensional model of the city cross-section is used for simulations while adopting the *k*-ε model in ANSYS FLUENT. The effect of solar radiation is examined at three times of the day: morning, noon, and evening. For wind, both constant and uniform wind profiles are considered. The main pollutants considered in this study are carbon dioxide and water vapour (humid air) in the form of transport species. Results show that the canyon maintains thermal comfort in the morning and evening; at noon however, temperature rises in the canyon to about 35°C. For pollutants coming from an external source, the bottom of the canyon has less concentration of pollutants. Conversely, in the case of pollutants emanating from within the canyon (Masdar City), the concentration of pollutants is high hence indicating that they do not easily escape. Overall, while the structure in Masdar City ensures thermal comfort, it might be difficult for pollutants and humid air to escape.

Introduction

The study of thermal comfort in an urban city has become an important topic recently. The aim to achieve thermal comfort with architectural modification has become a significant target for many architectural firms. Although architects have been trying to improve the performances of the building from the inside, a few have considered improving the external influences on the urban environment. Advancement in this research area will not only create a pleasant living environment, but also help cut down cost of electricity for lighting, heating, and cooling.

With the advent of computer technology, the “air pollution model” has developed from, on the page calculation, with tables and charts to computational models run on high performance computers. Also known as “dispersion models”, they help in predicting concentration of a pollutant source, based on knowledge of the emission characteristics, terrain and past and current weather data. Several parameters affect the pollutant distribution in urban canyons, such as the wind flow speed, building shape, canyon aspect ratio, the air and building temperature difference, etc. [2]. CFD modelling is an excellent method of studying flow and dispersion in urban street canyons as it allows the study of flow characteristics and concentration patterns at a building resolving scale. The effect of building geometry and dimensions without thermal effects has been widely investigated in wind tunnel experiments and by means of numerical models [2, 3, 14]. Sini [13] and Kim [9] emphasized the role of thermal effects which is derived from the shift in solar heating of building walls and the ground surface during the day in street canyon. In-canyon flow and transport abilities are induced by temperature difference. Xie et al. [15] evaluated the effect of flow in street canyons having walls with different temperatures. Santese et al. [12] compared CFD simulations of urban street canyons with heated walls against wind tunnel data; they reported a decent agreement regarding the qualitative behaviour of temperature profiles using k-ε turbulence model.

In more recent literature, the effect of cooling roof on air quality in an urban street canyon was investigated [8, 11]. It was shown that the air quality in the street canyon was improved marginally due to the cooler air entering into the street canyon. Furthermore, various countries have investigated how the air quality is affected in their respective street canyons. These include: Florence, Italy [5], Seattle, USA [4], and Campinas, Brazil [1].

One city that has taken an initiative in developing thermal comfort through its innovative urban canyon design is Masdar City, winner of Condė Nadt Traveler Innovation & Design Award [10]. Its unique location (24°25′45″N 54°37′6″E) – heart of the UAE, makes it a great challenge for such an achievement. The city was designed by the British architectural firm Foster and Partners in collaboration with the environmental consultancy Mott MacDonald. Its unique infrastructure makes it an interesting subject of study. Studies on the wind patterns in Masdar City are few [6, 7]. This paper analyses Masdar City cross-section (2D) from a fluid dynamics perspective. Particularly, wind, solar, pollution and humidity effects around the city are considered. The results aid in predicting the behaviour of the Masdar City canyon.

Methodology

Geometry

The geometry of Masdar City was made based on an actual engineering drawing as seen in figure 1 which represents three-storey clustered buildings. The discretised model mesh is shown in Figure 2. Quadrilateral (rectangular) elements were used in meshing. Critical areas such as the area surrounding the buildings have clustering with appropriate boundary layer; thus, capturing the steep thermal and velocity gradients and hence more accurate results. The domain was made large enough so that outlet pressure conditions can be applied without interference with the results. The velocity-inlet was assigned to the left side and a pressure-outlet was assigned to the right and top side.

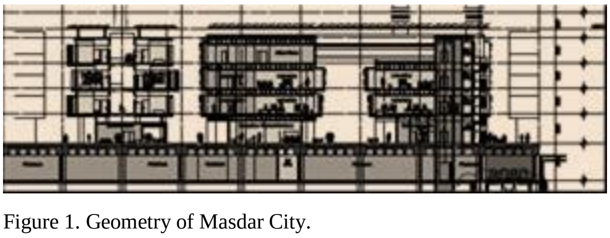

Figure 1. Geometry of Masdar City.

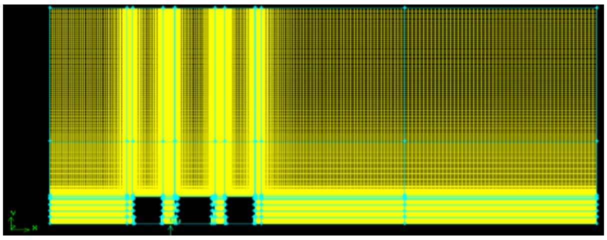

Figure 2. Meshed model of the cross-section of Masdar City.

Simulation set up and Governing Equations

The system is governed by the steady Navier-Stokes equation coupled with the energy equation. These equations are written as:

$$\frac{\partial \rho}{\partial t}+\nabla\bullet(\rho u)=0 \qquad (1)$$

$$\rho\frac{Du}{Dt}=-\frac{\partial p}{\partial x}+\frac{\partial \tau_{xx}}{\partial x}+\frac{\partial \tau_{yx}}{\partial x}+\frac{\partial \tau_{zx}}{\partial x}+\rho f_x \qquad (2)$$

$$\rho\frac{Dv}{Dt}=-\frac{\partial p}{\partial y}+\frac{\partial \tau_{xx}}{\partial y}+\frac{\partial \tau_{yx}}{\partial y}+\frac{\partial \tau_{zx}}{\partial y}+\rho f_y \qquad (3)$$

$$\frac{\partial}{\partial t}(\rho E)+\nabla\bullet\left(\vec{v}(\rho E+p)\right)=\nabla\bullet\left(k_{eff}\nabla T-\sum h_j\vec{J}_j+\left(\bar{\bar{\tau}}_{eff}\bullet\vec{v}\right)\right)+S_h \qquad (4)$$

Equation (1) represents the continuity equation while equations. (2) and (3) represent the momentum equation for fluid flow in the x and y directions respectively. Equation (4), on the other hand, is the heat equation. ANSYS FLUENT software was used for simulation and the common k-ε turbulent model was chosen for this study.

The following are the assumptions that are taken into account:

- Open System *(Control Volume)*
- Model is two-dimensional *(no flow in z-direction)*
- No slip and no penetration conditions are applied on the walls of buildings and the ground *(viscous flow)*
- Pressure gradient is zero at the domain outlet
- Steady-state flow
- The density-pressure-temperature coupling follows the ideal gas flow

Regarding boundary conditions, the kinematics and thermal conditions exist in addition to turbulence. The wind speed in Masdar City ranges from 3 m/s to 8 m/s [6]. In this study, 3m/s *(Low Speed)* and 8m/s *(High Speed)* are considered. The inputs of the wind profile is of two kinds – constant wind and function profile. The latter, according to the terrain description, can be written with power law as:

$$U=U_{\infty}\left(\frac{y}{h}\right)^{\frac{1}{7}} \qquad (5)$$

Two methods can be used for the thermal conditions or solar radiation – either assigning a higher temperature or placing a heat flux on the solar-affected boundary. Assigning higher temperature value was used in this work. Three periods of the day were chosen: Morning *(2-hours after sun rise)*, Noon *(12pm)*, and Afternoon *(2-hours before sun set)*.

As for the pollutants and/or emissions, two different cases are used in simulating species in Masdar City. The first involves the inlet of multiple species, i.e. inlet flow predominated by air. Another attempt is also carried out considering the ground in between the buildings as the source of the emission. Table 1 shows the values used for simulations.

Simulation Type	Species	Representation of Species	Mole Fraction
Species released with air at inlet	CO_2	Pollution	0.1
	H_2O	Humidity	0.1
	N_2	Air	0.8
Species released from the ground	CO_2	Pollution	0.5
	H_2O	Humidity	0.5

Table 1. Simulation Conditions

Results and discussion

Flow Field

The first study was carried out to investigate the wind flow within Masdar City. From this, a clear wind profile can be observed. Four cases were considered: Constant low speed *(3m/s)*, constant high speed *(8 m/s)*, profile low speed *(3m/s)*, and profile high speed *(8 m/s)*. The results of these cases are presented in Figures 3-6.

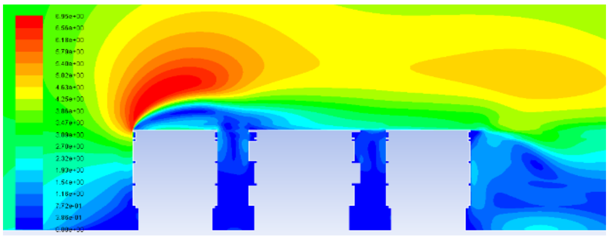

Figure 3. Low Speed (3 m/s) over Masdar City.

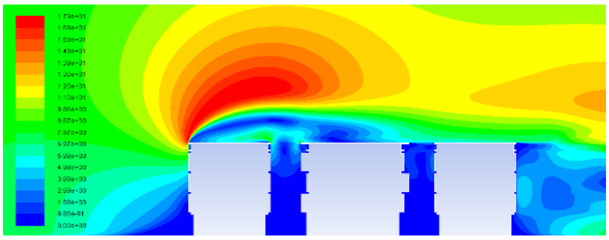

Figure 4. High Speed (8 m/s) over Masdar City.

The figures (3 and 4) show that very limited activities occur in the canyon region. This is primarily due to the high aspect ratio. The wind velocity on the top of the first canyon is 1.7 m/s and 2.68 m/s for low and high speeds respectively. As for the top surface of the second canyon, the wind speed is recorded to be 0.571 m/s and 1.19 m/s for low and high wind speeds respectively. An interesting observation to note is that the wind profile of the first canyon is relatively more active than the second canyon in terms of thermal comfort, i.e. more flow agitation and hence avoidance of thermal soaking compared to the second canyon. This is due to the boundary layer that is created on top of the building.

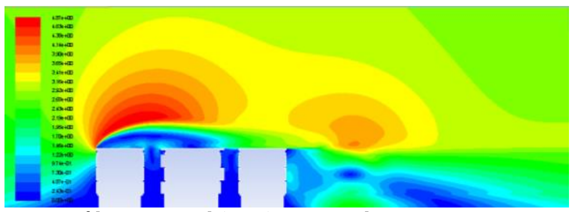

Figure 5. Profile Low Speed (3m/s) over Masdar City.

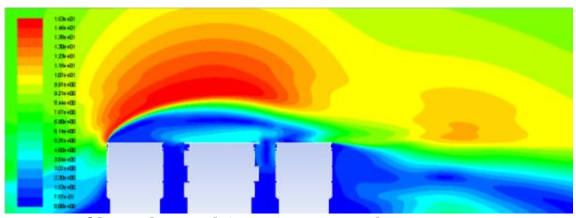

Figure 6. Profile High Speed (8 m/s) over Masdar City.

There is no major difference in the constant inlet-velocity and the profile inlet-velocity near the canyon region. In the case of low speed, there is slight movement of wind in the upper part of the first canyon. When the speed is high, there is relatively more movement of wind in the second canyon. This is due to the formation of the boundary layer on the top of the building. Again, it is observed that there is no major wind motion in the bottom of the canyon, i.e. stagnant wind.

The study of wind pattern is of utmost importance because it describes how heat is distributed and how pollutants are spread.

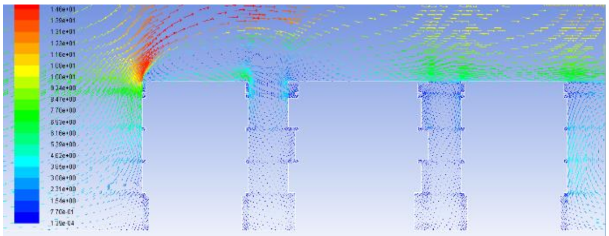
Figure 7. Wind flow Vectors

Figure 7 depicts the velocity vectors of the air. As air comes in contact with the first wall, the vectors turn their direction parallel to the wall. At this point, a boundary layer is created. On top of the first canyon, there is a vortex that is formed as a result of the boundary layer. This vortex enables some of the air to flow into the first canyon. In the second canyon, the velocity vectors are parallel to the roof of the buildings, hence less air flows into the second canyon.

Wind Flow with Solar Effect

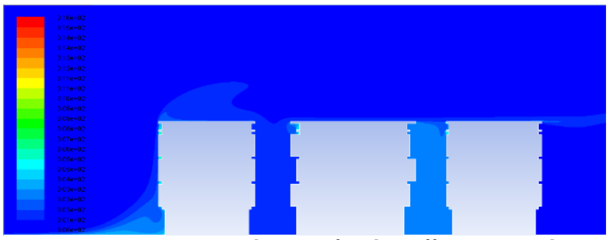
Figure 8. Temperature Distribution of Solar Effect on Masdar City (Morning, Sun location left, Temperature Difference, Speed: 8m/s).

Figure 8 presents the temperature distribution at morning time. It is obvious that the temperature in the canyon is less as compared to the areas that are effected by the sun. The reason for this is because of the high aspect ratio, which provides shade. Another key point to note is that the temperature at the second canyon is higher than the first canyon. This is due to the wind profile discussed earlier. Lastly, there is high temperature observed at the top windows which are facing the sun. These window designs make it hard for temperature to dissipate.

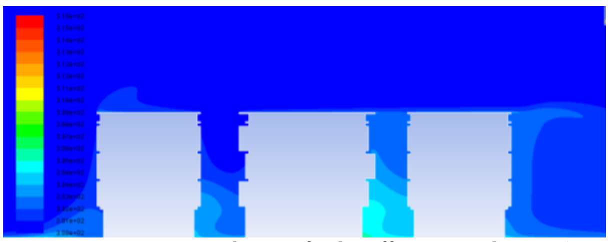
Figure 9. Temperature Distribution of Solar Effect on Masdar City (Noon, Sun location at Top, Temperature Difference, Speed: 8m/s)

Figure 9 shows the effect of the sun at noon time. The ground along with the roofs are heated up. From the results we can conclude that the second canyon has a higher overall temperature as compared to the first canyon at noon time. Moreover, the basement of the canyon has the maximum temperature. Furthermore, the top windows are shaded by the roofs, hence, they are relativity cooler. Lastly, there is a vortex being created by the wind on the right hand side. This vortex picks up heat from the ground and heats up the wall.

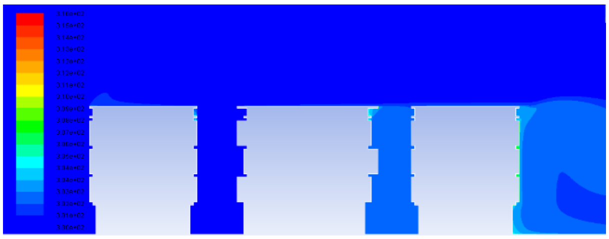
Figure 10. Temperature Distribution of Solar Effect on Masdar City (Afternoon, Sun location Right, Temperature Difference, Speed: 8m/s)

Figure 10 presents the effect of the sun at evening time. The simulation results are quite similar to that of the morning. The second canyon has a higher temperature as compared to the first one. There is a thermal vortex being created at the right side of the domain. This is due to the wind pattern.

Wind and Species Flow

The release of CO_2 and H_2O from the grounds between buildings demonstrates a real life situation in which a car, or an emission source, is located in the middle of the canyon and the exhaust is emitting CO_2. However, when the species are being released from the inlet with the air, it demonstrates another real life situation in which the pollutants or humidity are directed towards Masdar city by the wind.

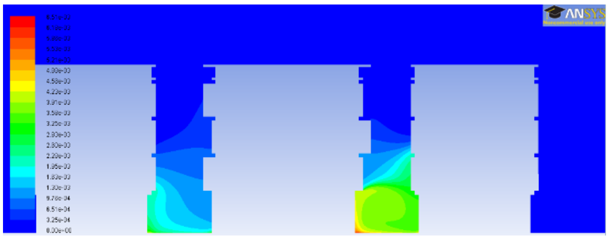
Figure 11. Molar Concentration of CO_2 (8 m/s). Species Release from Ground.

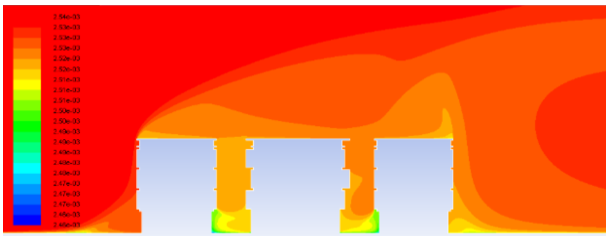
Figure 12. Molar Concentration of CO_2 (8 m/s). Species Release from Inlet.

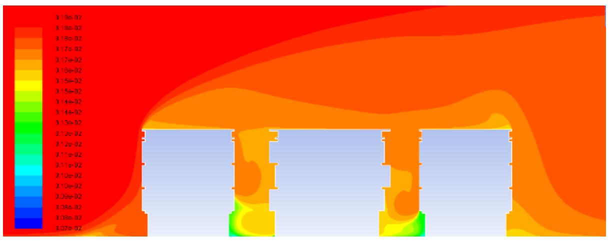
Figure 13. Molar Concentration of N_2 (8 m/s). Species Release from Inlet.

In the first case, figures 11 and 14, the results clearly depict that the species are concentrated mainly in the canyon. The atmosphere is at zero concentration. Moreover, the second canyon has a higher concentration as compared to the first canyon.
In case 2, figures 12, 13 and 15, there is less concentration of CO_2 in the canyon as compared to the atmosphere. For the high wind

velocity, the concentration of CO_2 and N_2 increases in the canyon. The concentration of N_2 is around 33% more than CO_2,
The overall results represent the behaviour of a high aspect ratio building: species from outside cannot get in and species from inside cannot get out.

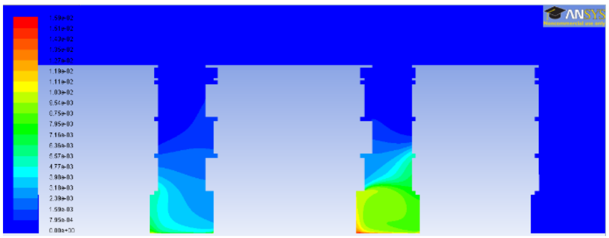

Figure 14. Molar Concentration of H_2O (8 m/s). Species Release from Ground.

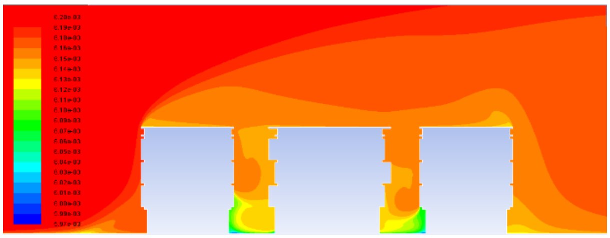

Figure 15. Molar Concentration of CO_2 (8 m/s). Species Release from Inlet.

Conclusion

This work clearly demonstrates the nature of air flow in Masdar City under various conditions. Its high aspect ratio protects it during the day from the sun, but makes it difficult for pollutants or humid air within it to escape.

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