Jurnal Alam Bina, Jilid 8, No.1, 2006.

Possibility of Using Computational Fluid Dynamics (CFD) for Urban Canyon Studies in Tropical Climate

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ABSTRACT: *This paper gives an overview of research methods for urban street canyon studies, from the commonly used field experiments and scaled models methods to numerical simulation models. Review of field experiments and scaled models showed identical weaknesses in dealing with urban canyon studies i.e. cost, time consuming and data or information obtained is rather limited or specific and often do not yield all of the designers' requirement. Numerical simulation on the other hand is an effective tool of understanding the complicated processes within the urban canopy layer. Numerical simulations using Computational Fluid Dynamics (CFD) is reviewed. CFD is well-known for its ability for evaluating either internal or external air flow and pollutant dispersion. In this paper instead, the possibility of using this model for urban canyon thermal environment studies in tropical climate is emphasized.*
Key word: CFD, Urban Canyon, Numerical Simulation

Introduction

In recent years, there is a growing interest in internal and external microclimate performance analysis of the built environment. According to Alamdari (1994), due to new design standards in either indoor or outdoor air quality, thermal comfort and safety, and awareness of new technology, modeling or numerical simulation of indoor and outdoor microclimate using high performance computer-aided system are even more pronounced. In urban studies, field experiment (Yoshida et al, 1991; Arnfield, 1994) and scaled models (Pearlmutter, 2005; Gayev & Savory, 1999) has been regarded to have performed more realistic predictions of the air movement, containment concentration, temperature and pressure distribution in or around buildings.

However, since 1970s a number of sophisticated dynamic thermal energy software have been developed (Alamdari, 1994), and in the last two decades, microclimate models based on Computational Fluid Dynamics (CFD) which takes the advantage of speed and power capabilities of new computers, are being used as an efficient tool for air movement, thermal comfort, and smoke or other pollutant movement analysis. In urban canyon studies however, CFD applications are mostly used in studying air flow (Bonneaud et al, 2001), pollutant dispersion (Chan et al, 2001) and traffic emission (Xie et al, 2005), and not so much on urban canyon thermal environment e.g. air temperature distribution, mean radiant temperature, surface temperature etc. The application of CFD in the context of thermal environment of the urban canyon in the tropical climate is the aim of this study. Existing methods as well as CFD's application in urban canyon studies will also be reviewed.

Field Experiment

Field measurement has been regarded to provide the most direct evidence of the canyon energy balance (Nunez & Oke, 1977). In finding the interaction between urban canyon geometry and incident solar radiation, Bourbia and Awbi (2004) performed a field measurement in the urban street canyon in El-Qued City, a hot and arid climate city in Algeria. The measurements were conducted in summer (July/August 1996 and 1997) and winter (December/January 1996 and 1997), a duration of approximately two years to complete, whereas the measurement instruments required include double-shielded and aspirated type-T thermometers, thermometers type Pro 7010/9070 and thermistor temperature sensors case type TEMP-02-2-T02-016 enclosed in an aluminium casing.

For Santanouris et al (1999), measurements of airflow inside and outside canyon and air and surface temperature inside canyon of a deep pedestrian in Athens, Greece, took him 7 continuous days (day and night period). And the instruments used include miniature ambient air thermistor sensors, infrared thermometer equipped with a laser beam, and 3-propellor (nrg) axis anemometer. In the case of Pearlmutter et al (1999), the parameters monitored are even more, including air temperature, relative humidity, wind speed and direction, global radiation, net radiation and radiant surface temperature. Pearlmutter's microclimate analysis is performed at several low rise urban street canyon of the Negev region of Israel, which is also an arid climate. Continuous 24 hour monitoring is required during summer (June till August) and winter (December till February) over a one year period. In this particular study alone, the instruments used include PT-100 sensors, Campbell RH probe, Met One Sensors, Kipp and Zonen pyranometer, Siemann-Ersking net radiometers and Teletemp IR thermometer.

The above review shows that although field measurement has the advantage of portraying accurate results, it is however very time-consuming and costly. Moreover, it can only be applied for specific range of geometries, orientation, Height to Width ratio and Sky view Factor. Besides, the huge number of urban variables and processes (Ali-Toudert, 2005) and the complexity of actual cities (Pearlmutter, 2005) makes it impractical to directly measure the effects of systematic variations i.e. street canyon geometry.

Scaled Model

Urban canyon airflow and pollutant dispersion studies utilizing scaled model are quite common. Most researchers (Wang, 1996; Pitts and Wards, 1983) suggested it is the best way in studying ventilation. These are done using Wind Tunnel in Laboratories: physical model and its surroundings were constructed and placed in the wind tunnel where they are subjected to a controlled wind flow. Pressure sensor taps are installed at various points on the model. In modeling of the motion of air within the urban environment, Gayev and Savory (1999) utilized an idealized two dimensional street canyon in which the internal roughness is represented by an array of vertical cylinders. The results provide a deeper understanding of pollutant dispersion of an urban canyon. Although wind tunnel can provide controlled dispersion conditions, it is an expensive research tool and difficult to set up, often used in the development t and validation of mathematical models. According to Alamdari (1994), data and information obtained using wind tunnel is also rather limited and often does not yield the designer's entire requirement.

Urban canyon thermal studies using scaled models, however, are not that popular among the researchers. This may be due to the comprehensive procedure, time factor as well as the limitations in available equipment and budget, although the results can correlate well with full-scale observations (Pearlmutter et al, 2005), and since it is carried out under actual climatic conditions, it reduces uncertainty faced by other forms of modeling, besides offering a wide range of configuration. One of the example is performed by Pearlmutter et al (2005) in a desert region in the arid region of Southern Israel, in order to evaluate the influence of street canyon geometry on microclimatic conditions and pedestrian energy exchange within the urban canopy. The model is composed of 'scaled schematic' buildings arranged in linear rows. These buildings are made of 200mm x 200mm x 400mm hollow concrete masonry blocks set on a finely leveled and compacted bare loess soil that stretches 250m in prevailing wind direction.

Numerical Simulation

In recent years, numerical simulation has been the favorable method among researchers in studying urban canyon microclimate. Besides being an effective method of understanding the many complicated causal mechanisms of urban heat island (Sakakibara, 1996), it is a method 'perfectly suited to dealing with the complexities and non-linearities of urban climate systems' (Arnfield, 2003). Bornstein (1986) has classified heat-island numerical models into two categories: the urban canopy layer (UCL) models and urban boundary layer (UBL) models. This paper will concentrate only at the UCL models.

3D model ENVI-met developed by Bruse (1998) has been utilized by Ali-Toudert (2005) to simulate the microclimatic changes within urban environments in a high and temporal resolution. ENVI-met is one of the first models that seeks to reproduce major processes in the atmosphere that affect the microclimate, including simulation of wind flows, turbulence. Radiation fluxes, temperature and humidity. This model is also free and downloadable through the internet.

Another popular UCL model is the Street Cluster Thermal Time Constant (CTTC) model. CTTC model is suitable to predict UCL diurnal climatic variations (Swaid and Hoffman, 1990/1991; Sharlin and Hoffman, 1984), impacts of anthropogenic factors (Swaid, 1993; Elnahas, 1997) and urban design alternatives (Bar-El, 1989; Moseri, 1990). Shashua-Bar and Hoffman (2003) uses CTTC to assess thermal effects of alternative architectural designs of the flanking buildings and inner courtyards. In this case, the CTTC model is able to incorporate several parameters related directly to the physical structure of building forms (building density, shade areas, the cluster geometry etc.). A modified CTTC model, the Green CTTC Model has been used by Shashua-Bar, Hoffman and Tzamir (2005). This modified model is a tool for quantifying the integrated thermal effects of built forms and vegetation on UCL climate ion design built-up alternatives. In Shashua-Bar's study, the built form and the vegetation effects were estimated for 86 cases of street and closed courtyards, with and without colonnade, at 1500 hours in summer near the Mediterranean Sea Coast. Another extension of CTTC model has been created by Elnahas and Williamson (1997) to operate at hourly time intervals and to include the dependence of total solar radiation absorption, instead of direct radiation modification of outgoing long-wave radiation loss by the inclusion of cloud cover, thermal effects of vegetation in the urban site; and the contribution of anthropogenic heat. URBANm, created by Williamson and Erell (2001) retain this extension of CTTC calculation technique but incorporated better data handling and improved algorithms for shading, long-wave radiation and wind effects. This model is still under development but will enable the transformation of reference site climate data to site-specific climate data.

Herbert (2002) uses a combination of interlinked sub-models including the wind field, dispersion and energy models to simulate diurnal temperature distribution in and around a dry urban canyon. This study aims to show the effects of changing canyon geometries on the model output. The advantage of this simulation allows Herbert to locate his model at any position on the Earth's lands mass, to specify thermal properties of the objects or surfaces comprising the canyon, besides being a powerful tool in city planning and for urban canyon research generally. However, this model is limited to dry canyons and cloudless skies (Herbert, 2002).

In Malaysia, Salleh (1994) uses the URBAN3 model which is an example of UCL model that simulated energy exchanges in urban canyon. Salleh approximates the physical structure of a city by a finite number of rectangular blocks intermixed with streets, parking lots and parks. The blocks are translated into 3D coordinates which are used in a separate program called 'OBSTRUCT' to generate the distances and heights of all possible obstructions in the neighbourhood.

CFD Application in Urban Canyon Studies

Computational Fluid Dynamics or CFD is a general term used to describe the analysis of systems including fluid flow, heat transfer and associated phenomena by means of computer-based numerical methods (Xie et al, 2005). CFD is a numerical simulation method, based on the Navier-Stokes equations established by Claude Navier and then George Stoke. According to Xie (2005), CFD is increasingly applied to the simulation of atmospheric problems, due to its suitability for use in passive energy design (because of many variables involved), and its ability to model various parameters that affect thermal comfort.

During early adaptation of CFD to the building Services industry, many models were set up for internal environments and verified experimentally (MacLeod and Waskett, 1996). However, there is a certain amount of skepticism on CFD's application in the external environment due to problems associated with setting up the boundary conditions i.e. the ever-changing ambient conditions, which also exist when physical modeling the environment e.g. in a wind tunnel. Though, due to CFD's many benefits including reducing or eliminating the need for physical modeling, quick and easy investigation of alternative designs and instilling confidence in the proposed design (MacLeod and Waskett, 1996), CFD is still a popular tool among researchers even in external microclimate, especially usage of Reynolds averaged Navier-Stokes (RANS) flow equation model in simulating airflow and pollutant dispersion in street canyon (Xie et al, 2005).

Bonneaud et al (2001) performed CFD simulation with N3S code to evaluate the natural ventilation potential of different shapes of the dense housing in Cayenne, French Guyana; Xie et al (2005) simulates emission from vehicle exhaust in a street canyon within an urban environment using standard k-e turbulence model (also considered RANS model); and similar model is used by Chan et al (2001) to find out various critical canyon configurations to avoid the contamination by pollutants.

There are many CFD software available such as COMIS, CONTAM96, PHEONICS, FLUENT and FLOVENT. In this paper, only FLOVENT will be discussed due to its availability and ability to perform air temperature distribution simulation. FLOVENT is a commercially developed code, specially designed and developed for the building industry. It calculates the resultant temperature index recommended in CIBSE, using predicted field values of air velocity and temperature, and mean radiant temperature (Alamdari, 1994). Studies using this application are very limited, and mostly emphasize on indoor climatic conditions such as air movement and thermal comfort assessment, smoke and pollutant movement analysis. Hence this paper attempts to use CFD FLOVENT for urban canyon thermal study. Following is a discussion of a pilot testing using this particular software application.

Pilot Testing Using CFD Flovent

The pilot testing is based on a field experiment carried out by Salleh (1994) in Kuala Lumpur, Malaysia. The aim of Salleh's study was to investigate whether deeper or shallower urban street canyon provides better comfort enhancement for the pedestrian in the tropics. This is done by comparing the Urban Canyon Height to Width Ratio (H/W) or two urban street canyon which is the Damansara urban canyon and Melawati urban canyon. And in this paper, the pilot testing is aimed at comparing the air temperature of CFD FLOVENT simulation and the air temperature provided by Salleh's field experiment in Damansara Urban Canyon on 29/06/1987 and Melawati Urban Canyon on 02/07/1987.

Models of the two canyons are created directly using the drawing board window provided with the software using 1:1 scale. The Damansara Urban Canyon (H/W ratio 3:1) and Melawati Urban Canyon (H/W ratio 1:1) models together with their position in the overall Domain Solution is shown in Figure 1 and 2 respectively. Both models are orientated towards North-South direction.

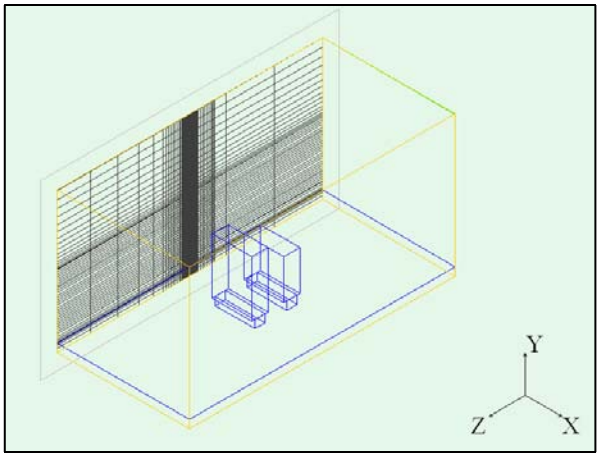


Figure 1: The position of Damansara Urban Canyon Model (29/06/1987) within the Flovent's overall Domain Solution.

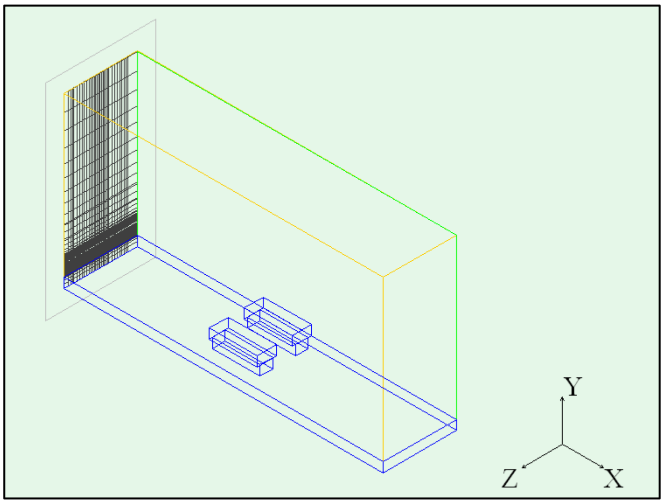


Figure 2: The position of Melawati Urban Canyon Model (02/07/1987) within the Flovent's overall Domain Solution.

Monitor points for both the models are positioned 1.5m (human height) above ground at the center of the canyon. This is the air temperature measuring point, as in the case of the field measurement by Salleh. In FLOVENT, Cartesian type of grid system is utilized. The grid distribution will eventually affects the numerical accuracy of the simulation. See Figure 3 and 4 for the detailed grid constraints applied in both the models.

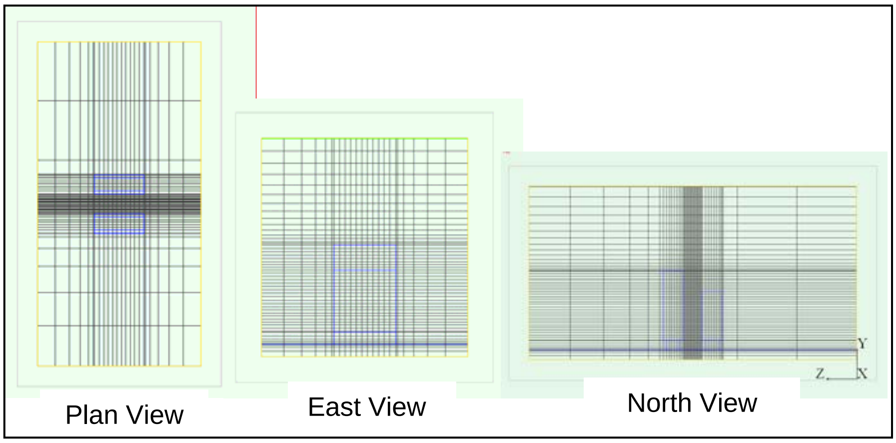


Figure 3: Grid distributions for Damansara Urban Canyon Model (29/06/1987)

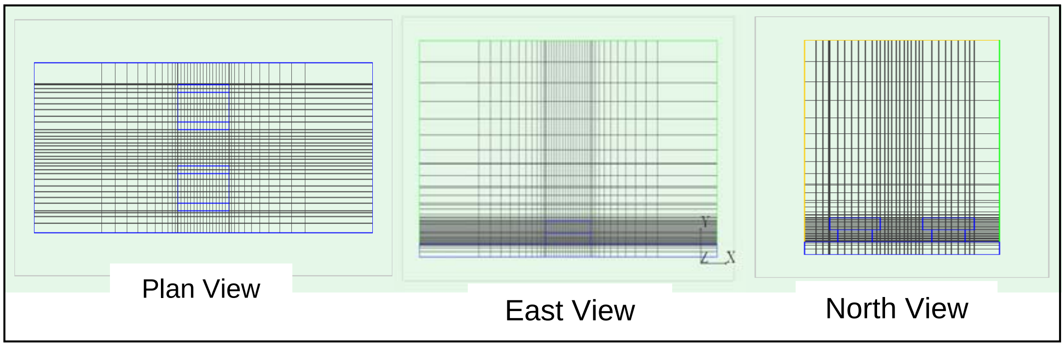
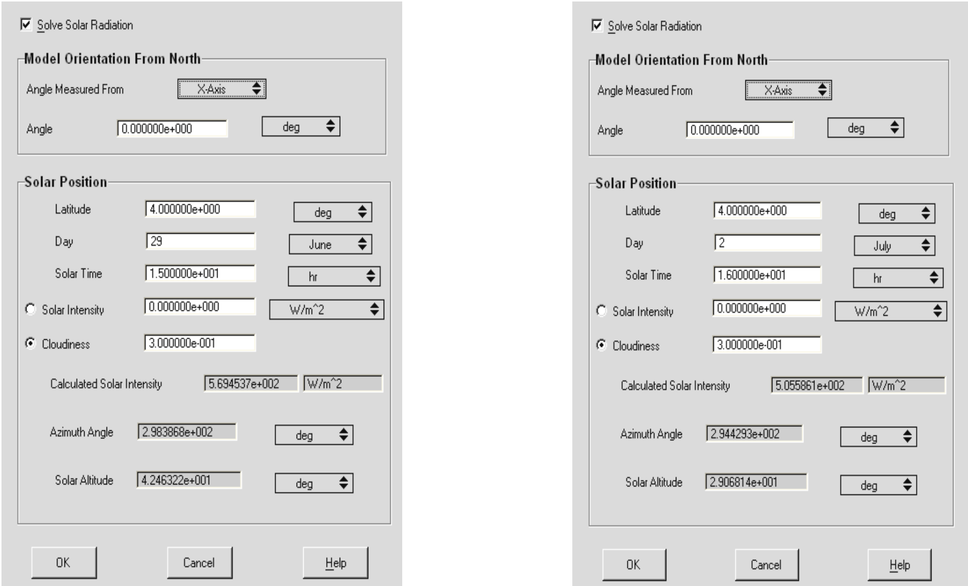


Figure 4: Grid distributions for Melawati Urban Canyon Model (02/07/1987)

The simulation conditions including material properties (wall=brick; ground=gravel; roof=concrete) and climatic conditions (Figure 5), are based on Salleh's field experiment and data collected.



Damansara Melawati

Figure 5: Part of 'Damansara' and 'Melawati' Urban Canyon Model's boundary condition setting up.

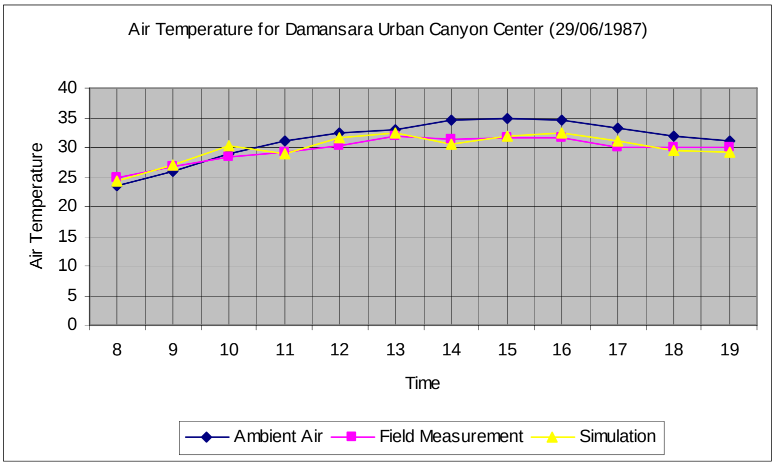


Figure 6: Air temperature from Petaling Jaya metereological station, field measurement and simulation for Damansara Urban Canyon Center (29/06/1987)

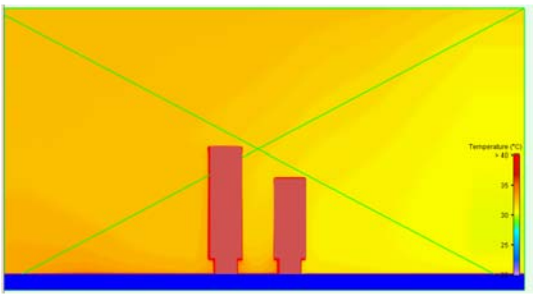


Figure 7: Graphical output of FLOVENT simulation for Damansara Urban Canyon Center at 1300h (29/06/1987)

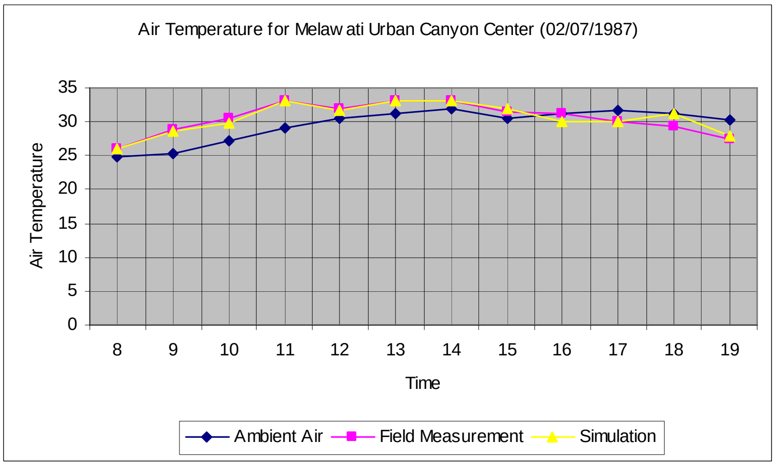


Figure 8: Air temperature from Petaling Jaya metereological station, field measurement and simulation for Melawati Urban Canyon Center (02/07/1987)

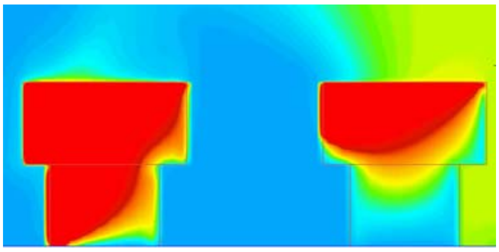


Figure 9: Graphical output of FLOVENT simulation for Melawati Urban Canyon Center at 0800h (02/07/1987)

The results from both simulations (Figure 6 & 8) showed that the average differences between the results of measurement and simulation for air temperature at 1.5m above ground was only 1%. The results suggest that CFD FLOVENT is not only capable of simulating air flow or pollutant dispersion, but also the thermal environment (in this case air temperature) in the external environment i.e. urban street canyon in the tropics.

Conclusion

Review of various methodologies above revealed that field measurements and scaled models are beneficial in terms of site-specific evaluation of urban canyon microclimate. However, in terms of evaluation of various canyon configurations, numerical simulations are more reliable. Computational Fluid Dynamics (CFD) has been used in numerous air flow and pollutant dispersion in urban canyon studies, but none on thermal i.e. temperature distribution studies. However, when the results of air temperature from CFD FLOVENT simulation was compared with the measured results of Salleh's previous study, a satisfactory correspondence was found.

A more holistic evaluation of the thermal environment using CFD should include heat flux and distribution of air temperature and humidity of urban canyon. Besides heat conduction of building walls and grounds and the radiation heat exchange between them should also be simulated. On the other hand, various canyon configurations in a tropical climate should also be studied due to scarcity of such studies in these areas, in order to achieve an optimum urban street canyon configuration that is thermally comfortable for users.

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