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A Review of the Impact of Urban Block Form on Urban Microclimate

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Abstract

Along with the advancement of urbanization, urban spatial form changed dramatically, and causes a series of many urban problems, in which the deterioration of urban climate environment has seriously affected the daily life of urban residents. In the past two decades, heat island phenomenon rises the temperature of cities, air pollution near and around buildings is an important environmental problem. This paper provides a review of research on the impact of urban block form on thermal environment, pollutant dispersion and air ventilation. A discussion of these studies reflects the impact of urban block form parameters on thermal comfortable conditions and better air quality and reviews existing methods and techniques to predict air ventilation assessment on a neighbourhood scale. This study is useful for urban designers and architects who are responsible for decision-making during the design phase.

Keywords:	Urban blocks; Block form; Thermal comfort; Pollutant dispersion; Air ventilation

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1. Introduction

After the industrial revolution, the use of fossil fuels for providing all kinds of comfortable working and living conditions have grown. Cities use a big amount of energy resources and account for over 70% of global carbon emissions [1-2]. Built environment and human activity make cities several degrees warmer than rural and suburban areas. This temperature difference between urban and rural areas is called the urban heat island (UHI) effect [3]. Air pollution near and around buildings in city is increasing. Dispersion of pollution represents an important environmental problem with respect to human health. This topic especially in the urban environment is concerned with the transportation of pollutants and temperature mitigation in the lower atmospheric boundary layer by the wind flows [4-6].

Architects [7] and urban planners [8] have concentrated on the relation between energy consumption and neighbourhood form since the 19th century. The relationship between buildings and their surroundings is an interdisciplinary challenge for architects, urban engineers and meteorologists [9]. Originally, meteorologist were interested in the effect of urbanization on climate change, urban planners studied the impact of urban morphology on the energy use of and thermal comfort in buildings and urban environments [10-12] and the architects considered energy and comfort mostly on the building scale [13-14]. However, planners and architects understood that it was not enough to solely focus on individual buildings but that it is important to broaden the analysis.

The thermal behaviour of buildings is altered when buildings are laid in a cluster[16].Urban geometry affects the amount of solar radiation on the building envelope and also the micro climate and air flow pattern around buildings[17].The position of neighbouring units and building morphology influence directly the amenity from both the indoor and outdoor environment [18]. Orientation and neighbourhood patterns not only affect solar access but also air flow patterns and wind speed. Furthermore, the placements of buildings within the site and land use patterns strongly influence the outdoor air and radiant temperature of the micro climate created by city blocks [19].

This paper will review the literature on the effect of urban block form on air ventilation and try to give an overview of studies that focused on urban blocks instead of urban scale. The environmental impact of urban block form will be investigated from three perspectives: the thermal impact of urban blocks, pollutant dispersion in urban blocks and the effect of block form on air ventilation. Each perspective comprises in two sections: first, evaluation parameters and second, methods and techniques.

2. Methodology

This article systematically reviews recent research on the effect of urban block form on thermal environment and air quality. The interrelationship between urban block morphology and climate has been the subject of many papers. Most publications can be classified in three main categories. Studies that

(1) Investigate the influence of urban block form to mitigate urban heat island effect [3, 20-25].

(2) Focus on issues of controlling measures of air pollution based on urban block form [26-32].

(3) Evaluate the effect of urban block form on air ventilation performance [33-40].

This systematic research review tries to classify all studies about this topic but it should be underlined that some studies tend to overlap because some of the researchers studied multiple parameters simultaneously.

3. Thermal environment impact of urban block form

The knowledge that now exists about the thermal environment impact of the neighbourhood can help increase thermal comfort in buildings through the application of passive heating, cooling, ventilation, and day lighting strategies [41]. Despite various efforts in mitigating the UHI effect, the effectiveness of the mitigation strategies cannot be evaluated with a high level of certainty due to weakness of current models in their design and prediction stages [42]. This implies that the developed tools should precisely include a series of complex phenomena occurring in a city and avoid unrealistic assumptions as well as the intensive computational calculations [43].

3.1. Factors affecting the thermal environment

The shape of a building, the ratio of a street's height to its width, orientation, pedestrian sidewalk, building block configuration, street design, urban corridors and green spaces are among parameters influencing the heat removal from the surfaces of building. Therefore, the airflow detail plays a key role in understanding how heat is exchanged between a street canyon and its environment. In many studies, the MCM models are the selected technique in investigating airflow details [44, 45].

Using higher albedo materials and green surfaces decreases solar gain of a buildings' skin, resulting in moderation of the UHI. Thermal conductivity and thermal capacitance are the main additional parameters that affect the thermal performance of urban building materials .The thermal capacity of the paving materials has a similar impact on the maximum and minimum surface temperatures like the thermal conductivity. High thermal capacity decreases the average maximum surface but at the same time increases the average minimum one. Thus, urban-scale models are highly preferred when the studies are intended to represent the impact of an extensive deployment of cool or green materials on an urban climate [46, 47].

3.2. Health and comfort

Outdoor thermal and wind comfort during the exacerbated UHI by the local heat waves is a widely investigated subject[48].In most of the studies, air temperature, moisture, and solar radiation in a city's courtyards, green-spaces, sidewalks and ponds are monitored with mobile and stationary stations to study the impact of the UHI on pedestrians' comfort[49]. Furthermore, simulation techniques are utilized to estimate the reduction in heat related mortality rate by applying mitigation strategies [50]. Moreover, field surveys are broadly conducted to help researchers to analyze and convert the obtained data sets to comfort indices such as physiological equivalent temperature (PET) [51].

3.3. Thermal analysis techniques and methods

The UHI is warmer greatly than its surrounding rural areas because of the urban constructive materials and the urban geometry. Several models and simulation techniques have been developed to study and describe the energy performance of buildings in relation to their surrounding micro-climate [52]. However, most of these studies have been conducted by building designers who focused on buildings as individual blocks neglecting to the urban context in which the building is placed [53].

Most building simulation software is designed to concentrate on buildings and systems design. Most of these neglect the importance of the impact of the surrounding on the thermal behaviour of a building, as a result of which the effect of building block geometry on urban micro-climate [54].Many studies thus focus on monitoring and modelling this spatial-temporal variation. Since the complexity and diversity of the contributing parameters cannot be easily modelled by deterministic approaches, the majority of models are developed based on the stochastic techniques such as regression method, which are supported by enormous data sets obtained from remote sensing imagery [55-57].The majority of the studies confirm relationships between surface/air temperature and corresponding urban land characteristics.

Multiscale models are formed from integration of different types of models in order to cover the existing gap between them. A higher resolution results in a large-scale area can be achieved using these models although the coupling technique still requires special considerations in balancing mass and heat among the models. For example, [58] obtained a better accuracy by integrating BEM, UCM, and MM models to estimate summer waste heat emissions from anthropogenic activities. Prediction of the UHI impact on future indoor and outdoor air temperature helps to adapt new strategies and policies in the design and retrofit of existing and planned buildings. Stochastic models developed based on ANN and regression techniques are more utilized in the projection of future temperature within the cities in accordance to their built area [59, 60]. In general, these models exhibit a promising performance in prediction of the future UHI.

4. Pollutant dispersion in urban block

This study especially in the urban environment is concerned with the transportation of pollutants in the lower atmospheric boundary layer by the wind flows. Dispersion of pollution represents an important environmental problem with respect to human health. In urban areas, several sources of pollution (e.g. wind-blown dust, vehicle exhaust, toxic and odorous emissions) may be unpleasant and dangerous [61]. Among them, inside cities, where the building density increases, the pollutant emissions can be accumulated between buildings, thus inducing an increase of the contaminant concentration because reduced air flow passes through the zone's boundaries as compared to free-stream flow [62].

4.1. Study parameters

Urban air quality is directly related to the atmospheric boundary layer (ABL) flows and their interactions with obstacles which are themselves strongly dependent on many aspects of meteorology, wind engineering and environmental science[63].The height of the atmospheric boundary layer is an important parameter in the dispersion of air pollution[64,65].It can change both in space and time, and may vary from less than one hundred to several thousand meters depending on the orography, surface cover, season, daytime and weather[66]. The ABL is almost continuously turbulent over its entire depth [67], particularly in urban environment where the main disturbing features are the buildings of different height and shapes. In this particular area (i.e. urban environment), the vertical structure of the atmospheric boundary layer -also called urban boundary layer (UBL) -is composed of a roughness sub-layer (RSL) near the ground and an inertial sub-layer (ISL) above as can be seen in Figure 1.

In recent decades, the efforts of boundary-layer researchers have been directed towards problems of surface-atmosphere interaction over complex surfaces including the homogeneous surface-layer relationships used to describe the mean and turbulence properties [68]. In this regard, for the case of numerical studies, the scientific community advises to assess the effects of horizontal in-homogeneity by performing a simulation in an empty computational domain. For instance, Figure 2, adapted from works of Blocken et al. [69], illustrates the development of the horizontal in-homogeneity within an empty computational domain. For modelling wind engineering problems within the atmospheric surface layer, several authors (e.g. Richards and Hoxey,1993; Blocken et al., 2007; Hargreaves and Wright, 2007; Yanget al., 2009; Cai et al., 2014) pointed out the need of modelling the flow as a homogeneous flow essentially by well reproducing the turbulence profiles including the wind velocity profile[70-74]. Therefore, the velocity profile which varies with the nature of the surface and the magnitude of the wind is one of the most important parameters [75] when modelling the surface boundary layer.

4.2. Methodology and modelling studies

In order to investigate the basic structure of pollutant dispersion around a building, many research studies examining dispersion around a single obstacle have been conducted by field measurements and wind tunnel experiments. Until recently, modelling studies on urban air quality were typically conducted by operational models derived from an integral nature of atmospheric dispersion [76, 77].Based on the studies discussed in the preceding section, some features of near-field pollutant dispersion around buildings can be identified by considering bluff body aerodynamics and atmospheric dispersion. The relationship between these features and reminders of the applicability of Computational Fluid Dynamics (CFD) modelling are explained.

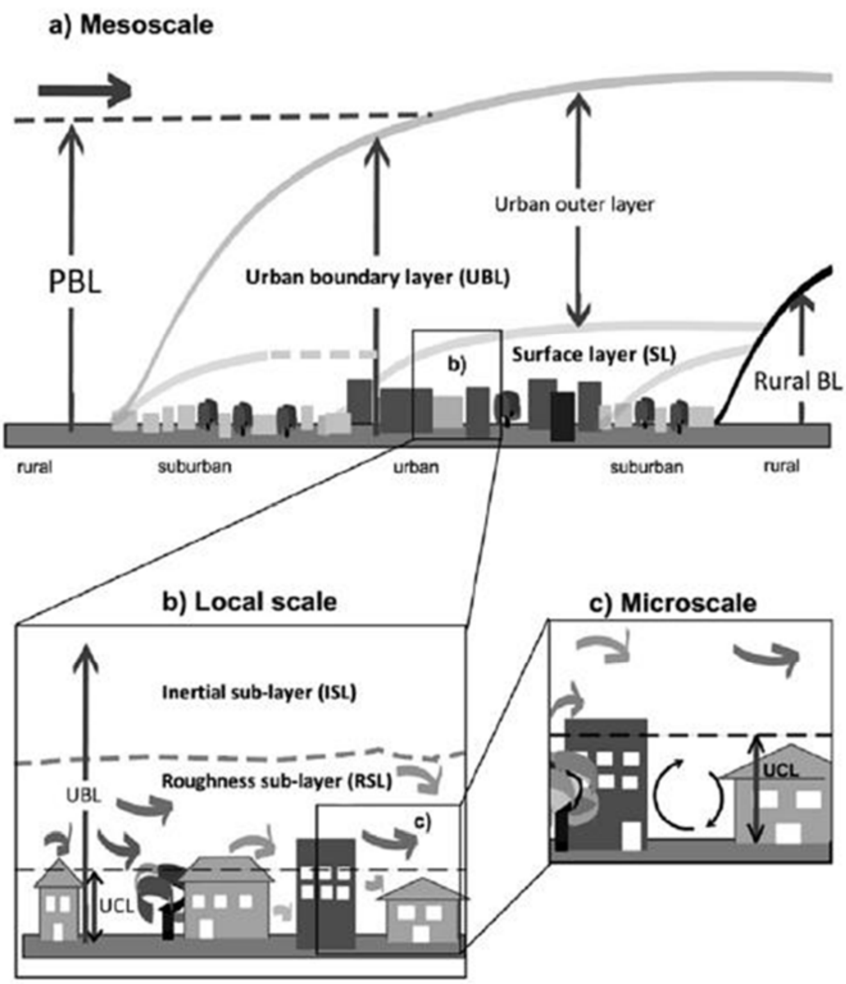

Figure 1. Sketch of urban boundary-layer structure indicating the various sub-layers and their names [72]

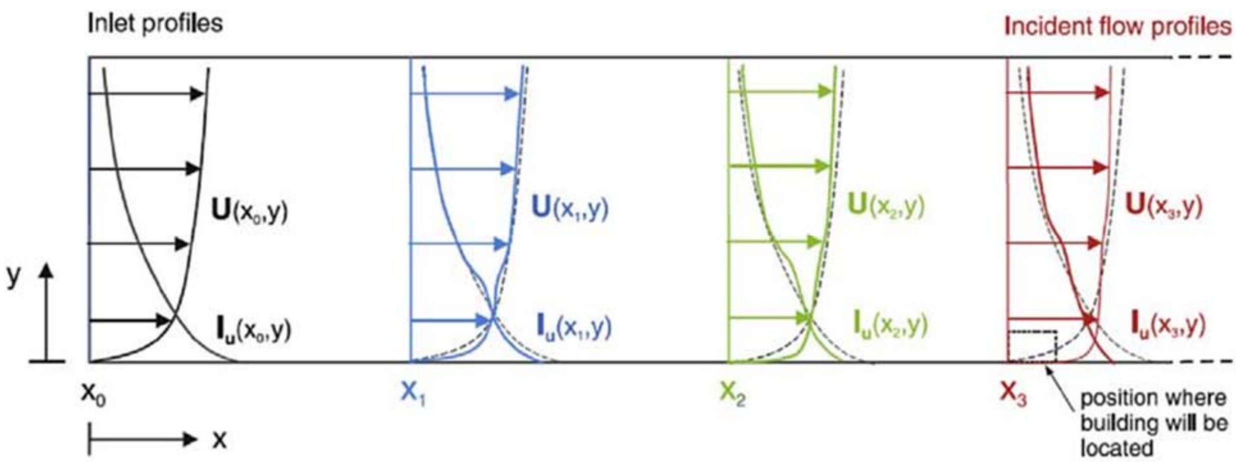

Figure 2. Schematic illustration of the development of an internal boundary layer (horizontal in-homogeneity) in a CFD simulation in an empty domain [72]

There are two important issues with modelling of boundary conditions, i.e., in flow boundary condition and expression of unresolved obstacles, affecting near-field pollutant dispersion in the urban environment. First, previous CFD studies of near-field pollutant dispersion around buildings, conducted with different research purposes, configurations, boundary conditions, and modelling approaches, were reviewed [78, 79].

These delivered an overview of CFD applications to near-field pollutant dispersion in the urban environment in recent years [80]. Next, key features of near-field pollutant dispersion around buildings from previous studies, i.e., three-dimensionality of mean flow, unsteadiness of large-scale flow structure, and anisotropy of turbulent scalar fluxes, were identified and discussed [81, 82].

In the past decade, CFD has become a more accessible tool due to the continued progress of modelling studies and the rapid increase of computational resources. In particular, for the prediction of the pedestrian wind environment, CFD has already been a viable method using several practical guidelines [83, 84]. However, for near-field pollutant dispersion around buildings, it is still needed to discern the applicability of CFD further with paying careful attention to the above quote [85].

5. Air ventilation in urban blocks

Air flow around buildings has a direct effect on the indoor and outdoor thermal comfort and air quality and on the energy use of buildings. Prediction of air flow and ventilation can be affected by several factors. Some of the factors relate to the climate and weather which include wind speed and wind direction. One of the most essential sources of power for indoor natural ventilation is the wind pressure difference over the building and pressure fluctuations on the facade. This pressure difference can help the air to come inside and move through the building. The arrangement of adjacent buildings in relation to wind direction strongly influences natural ventilation [86, 87].

Other factors which affect ventilation relating to the urban layout are topography, street depth and neighbourhood layout. Investigating the air flow inside an urban canyon is a big topic which can be divided into several scales. Studies which investigate air flow patterns on an urban scale are categorized into four dimensional ranges: regional (up to 100 or 200 km), city (up to 10 or 20 km), neighbourhood (up to 1 or 2 km), and street scale (less than 100–200 m) [88]. Factors that relate to the building design are the facade, the size and location of openings, the geometry and orientation of the building [86, 89, 90].

5.1. Air ventilation assessment parameters

There are several factors related to building form and neighbourhood that affect air ventilation:

(1) Urban density;

(2) Orientation of the building's façade;

(3) Building outlines and streets (ratio of building heights to the street widths).

Urban design parameters (street width and urban density) and building design parameters (Orientation of the building's facade and building outlines design) have important effects on air ventilation to the urban canyon and into buildings. Other factors which affect ventilation relating to the urban layout are topography, street depth and neighbourhood layout. Investigating the air flow inside an urban canyon is a big topic which can be divided into several scales.

Concentrating on the air flow inside a building without investigating the effect of the adjacent neighbourhood on the wind pressure coefficient on the building's facade cannot be helpful to better understand the whole process of natural ventilation [87]. When considering air flow and ventilation disperse on the scale of streets, the geometry of canyons (height-to-width ratio) is the main factor [91, 92]. In deep street canyons, variations in wind speed can be important leading to significant temperature differences over the street canyon (approximately 5°C). This temperature difference may have a great impact on the heating and cooling loads of buildings [93].Besides the height-to-width ratio, the building arrangement is one of the important parameters for improved wind flow and should be considered by city planners and architects.

Besides the height-to-width ratio, the building arrangement is one of the important parameters for improved wind flow and should be considered by city planners and architects. Zhang et al. [94] evaluated the effects of three different building arrangements on wind pattern. The numerical results also showed that changing the wind direction from perpendicular to the facades to 45° incidence has significant effect on the flow field (Figure 3). The orientation of buildings in relation to prevailing wind directions another factor that affects urban block ventilation. Jóź wiak et al. experimented to study the influence of wind direction on natural ventilation [95]. They concluded that there are significant differences in pressure distributions with and without modelling the boundary layer and the neighbourhood (Figure 4).Furthermore, Bady et al. [96,97] used a wind tunnel to investigate the indoor natural ventilation in terms of wind pressures on the surfaces of cubic buildings of a street located within a high density urban area. Thapar and Yannas [98] investigated the impact of ventilation and vegetation in providing a comfortable microclimate of urban square in hot and humid climate.

In all the literature reviewed, the wind pressure on and wind pressure coefficient of the facade of buildings were studied. The main purpose is to understand the effect of surrounding buildings on the potential of air flow inside the building. It seems that studies that research the influence of neighbourhood layout on wind pressure (coefficients) and at the same time study air flow patterns inside buildings are very limited.

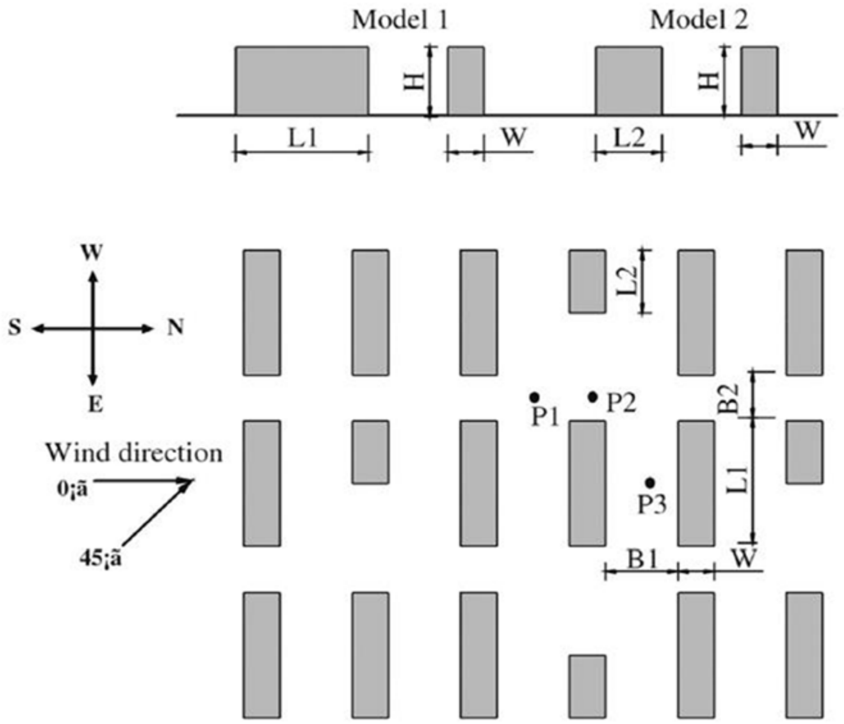

Figure 3. The ratios examined by Zhang et al [87]

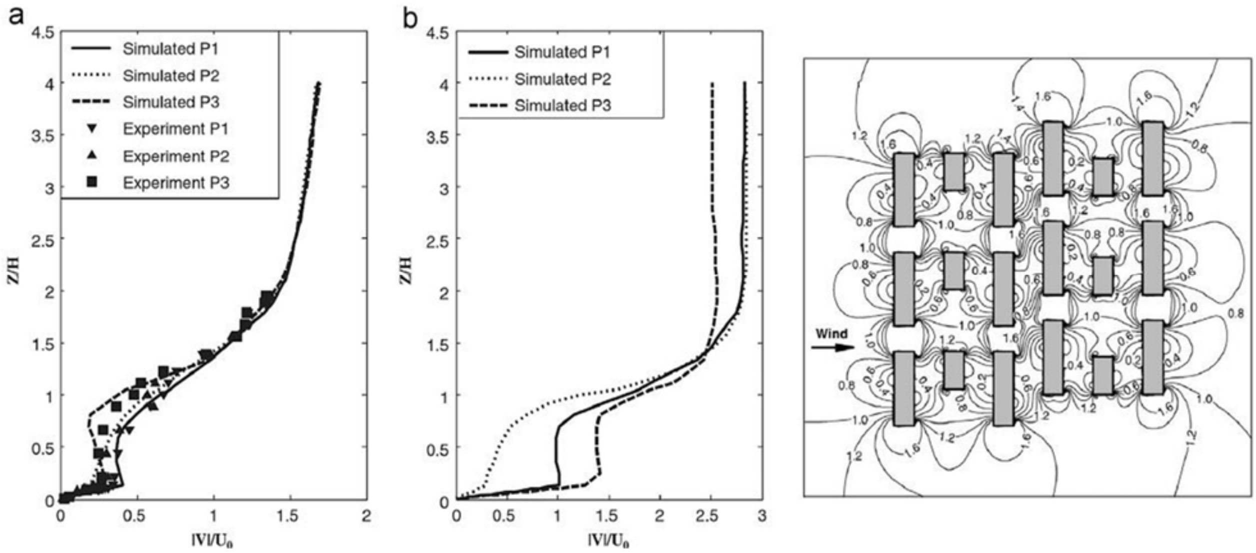

Figure 4. Experimental and numerical normalized wind velocity: (a) S–N wind and
(b) computed normalized velocity field at 2 m from the ground level for S–N wind direction [94]

5.2. Methods and technical guide for air ventilation assessment

There are three common techniques to predict and study wind flow:

(1) Field measurements;

(2) Laboratory-scale physical modelling (wind tunnel);

(3) Computational fluid dynamics (CFD) [99].

Traditionally, the analysis and evaluation of the wind environment mainly depended on wind tunnel tests. Wind tunnel studies of pedestrian-level wind conditions focus on determining the mean wind speed and turbulence intensity at pedestrian height (full scale height 1.75 or 2 m). Wind tunnel tests are generally point measurements with Laser Doppler Anemometry (LDA) or Hot Wire Anemometry (HWA) [100].

Nowadays, numerical simulation (often called computational fluid dynamics, (CFD) has been widely accepted owing to the tremendous progress of computer capabilities in recent years, and the advances in numerical modelling. Johnson and Hunter [101] performed numerical studies on urban canyons using the k-e turbulence model and made a preliminary comparison of wind tunnel results with numerical models He and Song [102] used large eddy simulation (LES) approach to compute and evaluate the pedestrian wind environment under different geometry and wind conditions. They concluded that the numerical model was accurate by comparing numerical results with a number of standard wind tunnel tests. Zhang et al. [87] compared computational results with experimental data for vertical velocity profiles (Fig. 3). They concluded that computational results are generally in good agreement with the experimental data for the locations experimentally tested. The results also showed that the numerical method is a more economical and faster tool to evaluate the wind environment.

6. Conclusion

This paper reviewed studies that considered research on the effect of urban block form on urban microclimate. Furthermore, indicators and methods in each group of studies were discussed. This paper showed that it is difficult to study the impact of the neighbourhood on thermal behaviour of a building because it is hard to describe all relevant indicators simultaneously. As a result, there are limitations in the methods and techniques that describe on air ventilation in relation to their surrounding micro-climate. Finally, most of the works in this field focused on air ventilation because it is the most important parameter and there are more methods to estimate thermal environment and air quality on an urban scale. From these literature review, it seems that studies that research the influence of neighbourhood layout on wind pressure (coefficients) and at the same time study air flow patterns inside buildings are very limited.

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