World Academy of Science, Engineering and Technology
International Journal of Urban and Civil Engineering
Vol:11, No:7, 2017

Using Manipulating Urban Layouts to Enhance Ventilation and Thermal Comfort in Street Canyons

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Open Science Index, Urban and Civil Engineering Vol:11, No:7, 2017 publications.waset.org/10007484.pdf

Abstract**—**High density of high rise buildings in urban areas lead to a deteriorative Urban Heat Island Effect, gradually. This study focuses on discussing the relationship between urban layout and ventilation comfort in street canyons. This study takes Songjiang Nanjing Rd. area of Taipei, Taiwan as an example to evaluate the wind environment comfort index by field measurement and Computational Fluid Dynamics (CFD) to improve both the quality and quantity of the environment. In this study, different factors including street blocks size, the width of buildings, street width ratio and the direction of the wind were used to discuss the potential of ventilation. The environmental wind field was measured by the environmental testing equipment, Testo 480. Evaluation of blocks sizes, the width of buildings, street width ratio and the direction of the wind was made under the condition of constant floor area with the help of Stimulation CFD to adjust research methods for optimizing regional wind environment. The results of this study showed the width of buildings influences the efficiency of outdoor ventilation; improvement of the efficiency of ventilation with large street width was also shown. The study found that Block width and H/D value and PR value has a close relationship. Furthermore, this study showed a significant relationship between the alteration of street block geometry and outdoor comfortableness.

Keywords**—**Urban ventilation path, ventilation efficiency indices, CFD, building layout.

I. INTRODUCTION

RAPID global climate change and increasing urban heat-island effects have affected the quality of urban environments and the comfort levels of their residents. Heat islands are generally formed by the overtly concentrated high-rise buildings in urban areas, which lead to insufficient open spaces and a lack of wind paths; these air conditions impair the dissipation of highly concentrated waste heat from automobiles. Several studies have confirmed that adequate urban wind environments can effectively reduce urban heat-island effects [1]-[3] and increase environmental quality. Mu Li Zhi Zi et al. [4] indicated that one of the most critical factors for urban heat islands is wind speed. In recent years, climate factors (e.g., urban wind environments and temperature), urban street ventilation, control of architectural forms and surface treatments, ventilation paths, and green space systems have become major topics in urban planning for improving the overall urban environmental system. Ignatius et al., Allergrini et al., and Blocken et al. [5]-[7] have offered their suggestions on urban ventilation. Ignatius et al. [5] examined the effects of urban texture variations (i.e., changes in urban density and form) on urban ventilation and thermal comfort and provided a relatively comprehensive urban microclimate analysis by demonstrating the significant influence of space between adjacent buildings on the energy performance of urban buildings. In 2015, to study the effects of urban morphology, Allegrini et al. [6] used CFD and building energy simulations to anazlye urban heat fluxes for various air temperatures and wind fields, revealing the strong influences of buoyancy at low wind speeds on heat fluxes and air temperatures. In the same year, Blocken et al. [7] indicated the importance of wind environment for healthy and livable urban areas; they regarded wind speed and direction as two crucial elements strongly affected by urban morphology, and identified the effect of plan area density and building height on urban wind environments by using two sets of urban configurations that involve rectangular buildings with an equal plan area as well as adopting parallel streets of equal and unequal street widths. To argue for the beneficial contribution of wind fields to air pollutant dilution, Hang et al. [8] described a correlation between the geometry of high-rise urban buildings, air pollutants, and urban block form (characterized by various street widths, plan area densities, urban configurations, and building heights) by simulating idealized urban configurations. Yuan et al. [9] examined the relationship between air pollution dispersion, building porosity, wind environment, and pedestrian-level wind, evaluated the potential importance of urban design strategies, and developed a set of principles for designing high-density urban areas by simulating eight scenarios using various building geometries and levels of urban permeability. Abd Razak et al. [10] investigated the effects of urban geometries and building heights on urban air flows by using the parameters of plan area ratio and building aspect ratio, and analyzed five types of idealized uniform block arrays consisting of rectangular blocks with a staggered layout and different aspect ratios and an array with nonuniform heights. In 2013, when studying the interaction between urban ventilation and indoor air flow, Xiao, Bao-Yi et al. [11] employed CFD for assessing ventilation flow in buildings, which could be derived by simulating Air Change per Hour (ACH) and the volume flow rate through an inlet or the conventional concentration decay method.

The aforementioned studies have confirmed that changing urban geometries can affect the urban wind environment and air quality, reduce the demand for air conditioning facilities, and reduce building energy consumption. Therefore, the ventilation performance of urban blocks has become a topic worthy of discussion in subtropical Taiwan. Urban ventilation paths are where indoor and outdoor air flow exchange. Natural ventilation is caused by ambient temperature differences

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between indoor and outdoor spaces that generate upward air streams directed by the local prevailing winds. Wind environment evaluation has already become a major trend for developing sustainable cities, with sustainable urban design serving as an effective tool for urban governance. Improving the overall urban environment and creating adequate urban wind environments by formulating appropriate urban design principles has become a major concern for environmental planning and urban design projects.

Songjiang Nanjing District in Taipei City, Taiwan was selected as the study area. A Testo 480 multifunction ventilation and air conditioning (VAC) measuring instrument was employed to measure the environmental wind fields of this district. A set of design principles for Taipei City's wind environment was determined by using ANSYS Fluent software to perform numerical simulations on the study area under a constant total floor area and varying ratios of block width, building width, and street width. The simulation results were verified by CFD software that compared the observed and estimated wind speed and air temperature data. The natural ventilation behavior and management of the ventilation paths in the study area were evaluated in terms of air changes per hour (ACH), also known as air change rate. Multiple systems of urban ventilation paths were analyzed and their ventilation performance levels were quantified by using physiological equivalent temperature (PET) as an indicator of comfort level in the context of urban ventilation.

II. METHODOLOGY

A. Study Area

Songjiang Nanjing District (25°03′N, 120°42′E) was selected as the study area (see Fig. 1); within that area, the effects of different urban morphologies and block widths on outdoor ventilation were examined by comparing the observed and simulated data of the block arrays. The physical measurement experiment lasted from August 20, 2016 to January 20, 2017; that is, from summer to winter. Due to insufficient research budgets and human resources, the measurement sessions were limited to a period of 9:00–18:00, which was divided into three subperiods (i.e., 9:00–11:30, 13:00–15:30, and 17:00–19:30). Data were averaged every 10 minutes to calculate the average wind speed and wind direction with respect to a measuring point. To verify the effect of block form on urban warming, 12 sampling stations in the study area recorded measurements during the three subperiods every day. The locations of the sampling stations are illustrated in Fig. 1.

Data were collected using a Testo 480 multifunction VAC measuring instruments and three types of probes, namely a bendable hot-wire thermal flow velocity probe (integrated with temperature and humidity sensors), a hot-bulb thermal flow velocity probe, and a globe probe for measuring radiant heat (Fig. 2). The measurement time was divided into three subperiods to reflect diurnal temperature variations and thereby accurately record the changes in the physical environment of the study area. The observed data were used to verify the accuracy of the CFD simulation results.

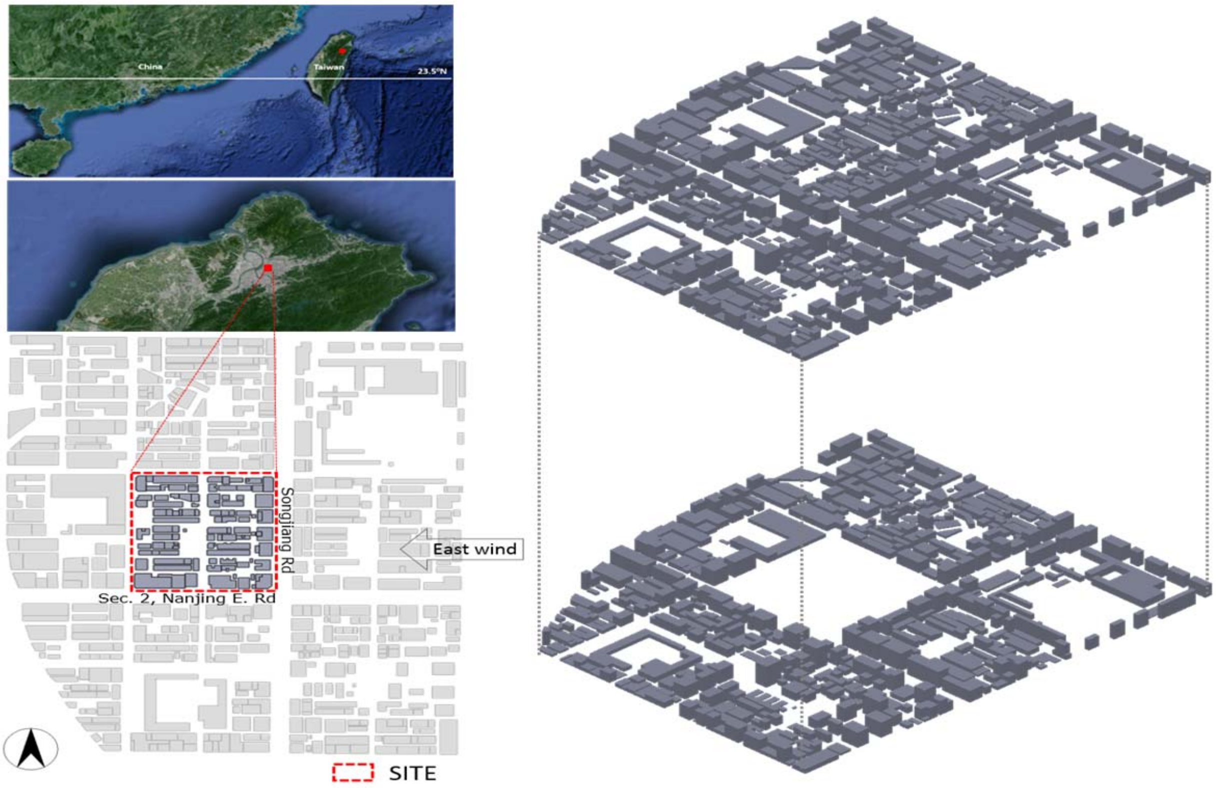
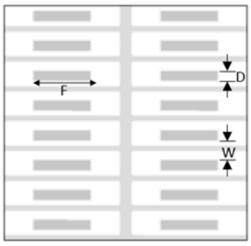
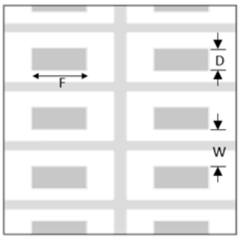
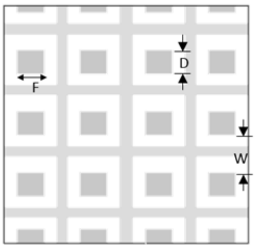


Fig. 1 The location of Songjiang Nanjing area, Taipei City, Taiwan

Fig. 2 Measuring instruments and precision introduction

TABLE I
SIMULATION PARAMETERS DESCRIPTION OF 3 CASES

Type	Diagram	D/F	H/W	H/D	W/D
Layout 1		4	1.95	3	1.53
Layout 2		2	0.97	1.5	1.53
Layout 3		1	0.97	1. 5	1.53

* H: building height (45m), D: building width of windward side; W: the distance between the two houses, F: building depth of windward side.

The real-world block arrays, consisting of blocks in 1,076 m × 925 m, did not comply with the current wind environment regulations in Taiwan because the buildings had high-rise geometries. Using an equal total floor area, this study employed three building layouts with various building parameters (Fig. 3). Layout 1 consisted of 16 rectangular buildings, each measuring 15 m × 60 m, with an equal building width (*D*) of 15 m. Layout 2 consisted of 10 rectangular buildings, each measuring 30 m × 60 m, with an equal building width (*D*) of 30 m. Layout 3 consisted of 20 square buildings, each measuring 30 m × 30 m, with an equal building width (*D*) of 30 m. These three layouts were used to measure outdoor comfort levels for various building widths. Simulation data were collected to examine the impact of natural ventilation performance on urban environments and compared with the collected data to verify the accuracy of the simulation.

B. Simulation Program

ANSYS Fluent software was used in this study to perform CFD simulations. Meteorological data regarding 2005–2014 (i.e., prevailing wind direction, average wind speed, and average air temperature) were obtained from the Xinyi weather station (station code: C0AC70) of the Central Weather Bureau and employed as reference data for analysis of the basic microclimate of the study area. Only the data collected in summer and winter were used to calculate the average wind speed and air temperature in the 10-year period (average wind speed in summer: 2.0 m/s, average air temperature in summer: 29.1 °C, average wind speed in winter: 2.6 m/s, and average air temperature in summer: 17.1 °C). The wind was most frequently from the east. These reference data were substituted into equations of momentum to derive the estimated wind speed and pressure data, which were then used to understand the effects of changes in the urban wind environment.

An area of 6000 m × 4000 m × 400 m was set as the simulation range for the study region (Songjiang Nanjing District), which was divided with computational grids to increase simulation accuracy. The total number of grid volumes ranged between 39,563,273 and 45,969,251. The grid quality ranged between 0.83565 and 0.85561, which fell within the acceptable range (0.80–0.94) of the skewness mesh metrics spectrum.

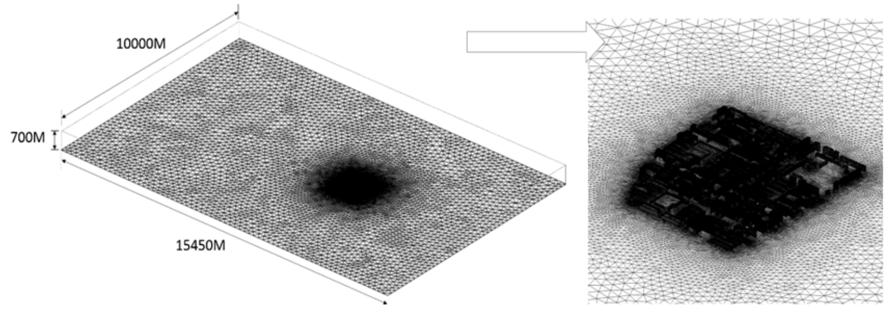


Fig. 3 Songjiang Nanjing area illustrations of numerical simulation model

TABLE II
SONGJIANG NANJING AREA SCHEMATIC OF BOUNDARY CONDITIONS

Item	CFD hypothesis	
Inlet	velocity	ABL Profile
Outlet	pressure	1 atm
Top of region	symmetry	
Side	symmetry	
Wall	wall	log-law of Wall function
Ground plane	wall	Roughness of 0.5m

III. RESULTS AND ANALYSIS

A. Field Measurement and CFD Simulation

The accuracy of the computational analysis was verified by comparing the observed and simulated data. Fig. 4 compares the observed and simulated wind speed and air temperature data collected at the 12 sampling stations in the study area, with wind speed and air temperature errors within ±20% and ±10%, respectively. Errors exceeding 10% were observed for a few of the sampling stations; this can be attributed to the fact that the three-dimensional steady-state Reynolds averaged Navier-Stokes program adopted in this study can more accurately calculate fluid flows at high velocity than at low velocity, which can result in high degrees of distortion and error. This phenomenon shows that CFD software can provide reasonable results for estimating outdoor flow fields.

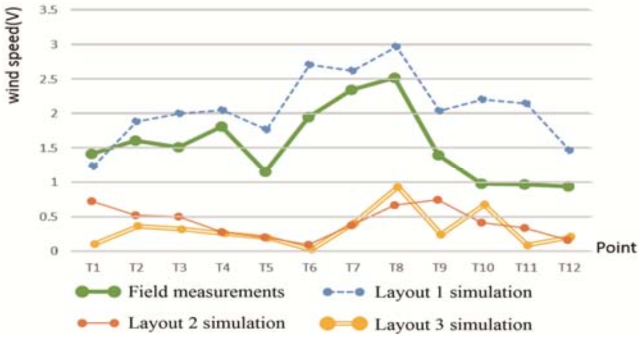


Fig. 4 Each case wind speed line chart

B. Pedestrian Wind Environment at 1.5 m Height Level

Table III displays the simulated average wind speed data at a pedestrian level of 1.5 m collected using the three simulated layouts and the real-world site. In summer, Layout 1 had a prevailing wind direction from the northeast; Layouts 1–3 had average wind speeds of 0.8, 0.7, and 0.6 m/s, respectively. The fact that Layout 3 had the lowest average wind speed may have resulted from a shift in wind direction caused by characteristics of the block array that reduced the velocity of the prevailing wind flowing through the buildings. In winter, Layouts 1–3 had average wind speeds of 0.9, 1.0, and 0.6 m/s, respectively. A comparison of these data indicates that the prevailing winds, squeezed and expanded by the building layouts (with various urban geometries and block scales), pass through the urban blocks and ultimately are mixed with outdoor air on the streets and roads, showing that rectangular buildings aligned parallel to the wind direction can increase air flows and improve ventilation (Table IV).

The three building layouts were analyzed (Fig. 5) using data collected from stations A–C to examine the effects of various block proportions. The D/F ratios of Layouts 1–3 (i.e., 4, 2, and 1, respectively) varied with the variations in building width. Under the premise that the frontages of the buildings were aligned parallel to the wind direction, this study found that a higher D/F ratio signifies a higher wind speed and better ventilation effects, which reduce airway obstruction and ventilation resistance and therefore increase the air-flow volume (Fig. 6).

The urban ventilation path analysis in this study was performed by examining the relationship between the ratio of building height to street width (H/W ratio) and the wind-speed variations in the ventilation paths. The simulated H/W ratios are displayed in Table I, suggesting that a lower H/W ratio (indicating a wider street width) results in a smaller variation in the average wind-speed ratio; a higher H/W ratio (signifying an overtly narrow street width) reduces the speed of the wind entering the ventilation paths, thereby limiting the ventilation effects.

TABLE III
CFD SIMULATION OF WIND VELOCITY ANALYSIS AT 1.5 M HEIGHT LEVEL

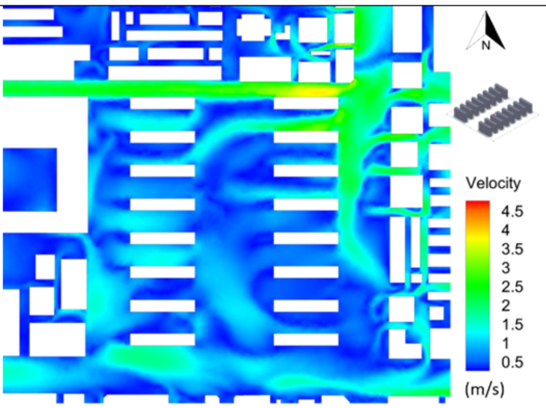
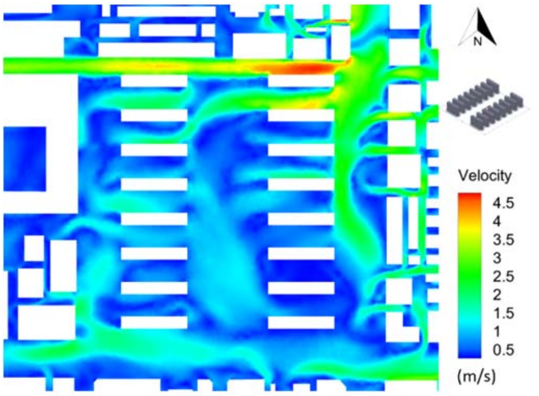
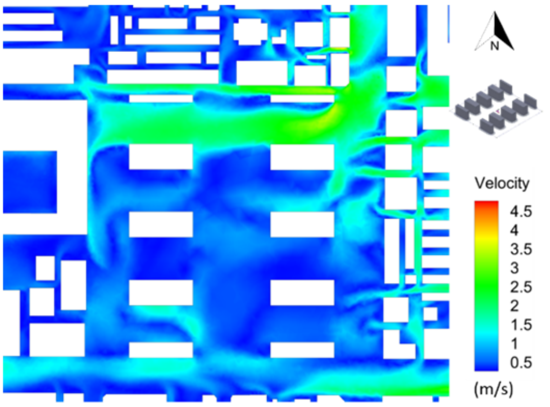
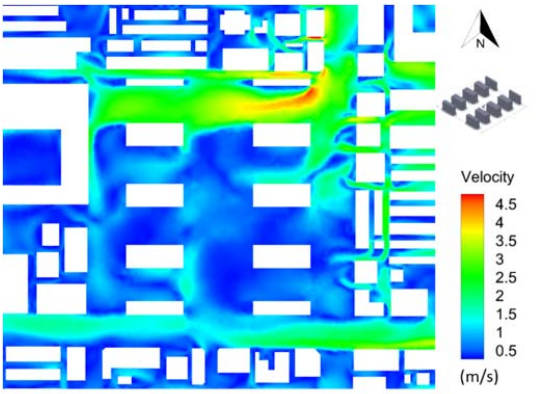
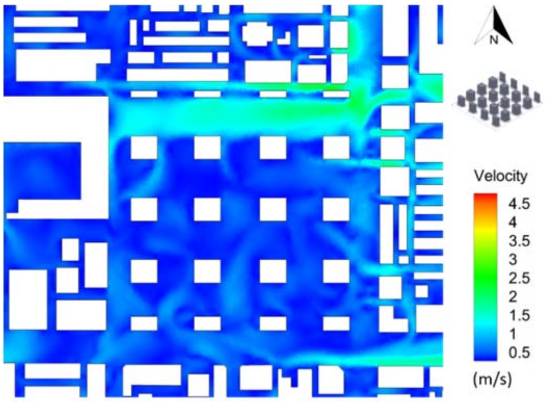
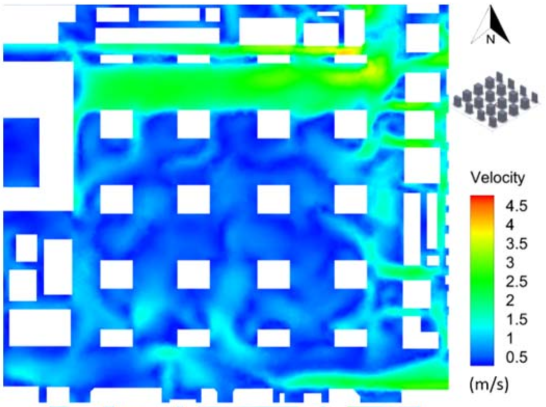
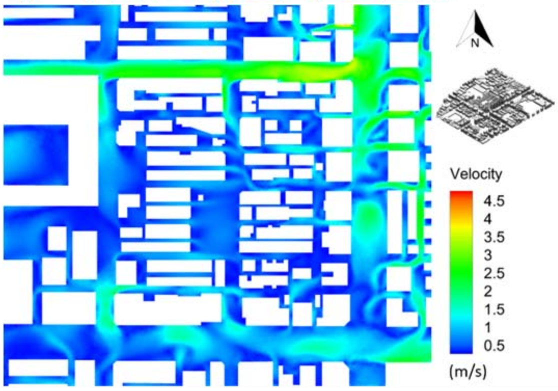
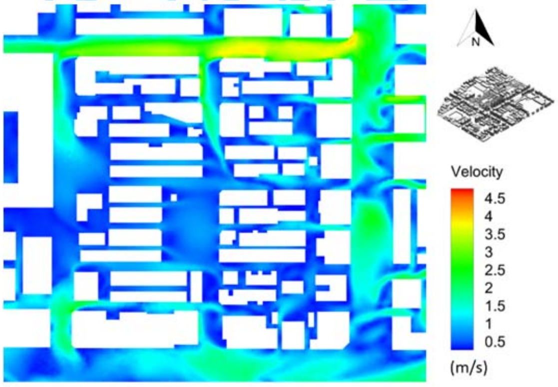
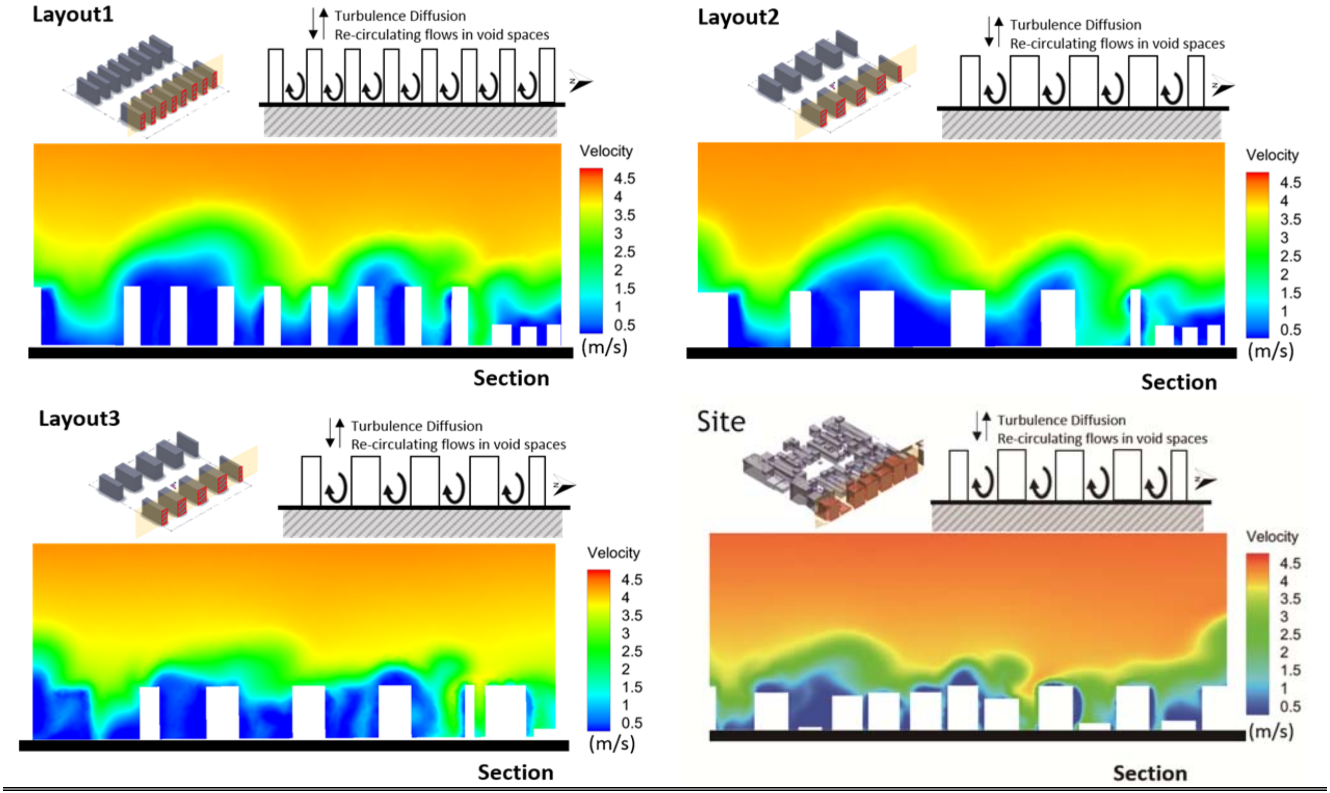
	Summer	Winter
Layout 1		
Layout 2		
Layout 3		
SITE		

TABLE IV
CFD SIMULATION OF WIND VELOCITY ANALYSIS OF LONGITUDINAL SECTION AT 1.5 M HEIGHT LEVEL IN WINTER



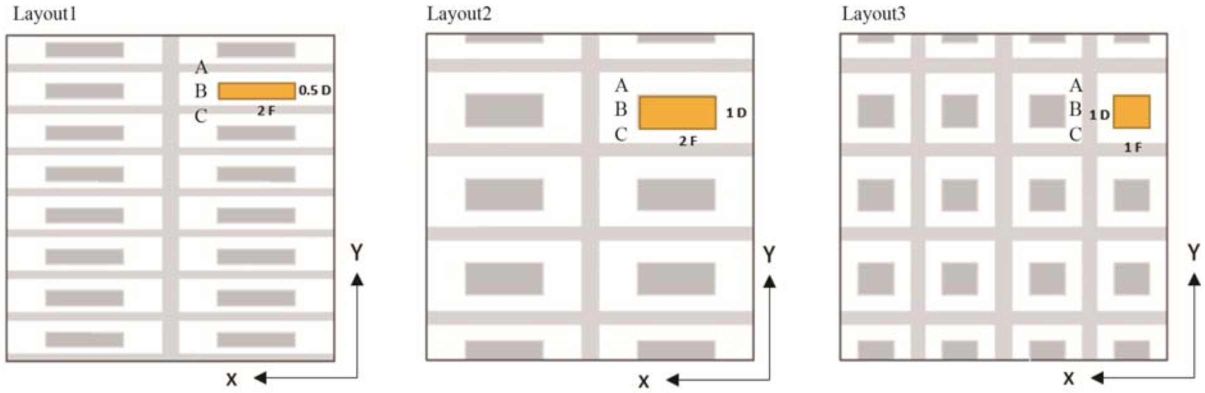


Fig. 5 Each case of D/F analysis comparison chart

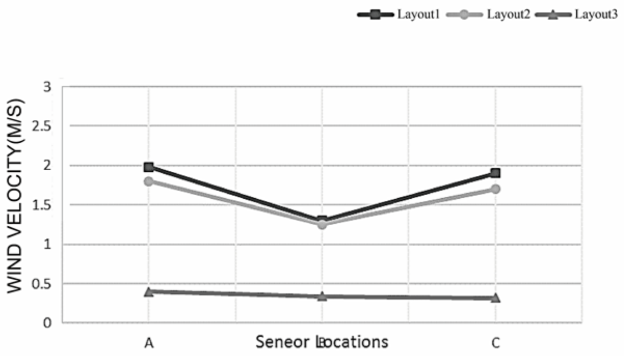


Fig. 6 Wind speed line chart of A.B.C 3 case

A comprehensive comparison of the simulated and observed data demonstrates that, regardless of the block layout, a lower H/W ratio (indicating a wider street width, narrower courtyard width, and a lower building height) leads to smaller variations in the average wind-speed ratio. The data associated with buildings of exceptional width (e.g., a set of row houses) suggest that a high H/W ratio tends to cause greater variation of wind speed in the street canyons. For buildings of narrow width, Layouts 1–3 display a similar trend: a positive correlation between building height and wind speed. Therefore, future urban planning must consider not only the effects of H/W ratio on altering the lateral air flows passing through the inlet, but also the effects of longitudinal air flows.

C. Temperature at 1.5 m Height Level

The simulated data of air temperature at a pedestrian level of 1.5 m indicated average summer air temperatures of 32 °C, 31 °C, and 31 °C for Layouts 1–3, respectively. The actual summer temperature was 33.7 °C, with a mean temperature between 31 °C and 33.7 °C. The high actual temperature can be attributed to the fact that the real-world block layout causes the air to move in loops when passing between the buildings, resulting in lower ACH.

TABLE V
CFD SIMULATION TEMPERATURE ANALYSIS AT 1.5 M HEIGHT LEVEL

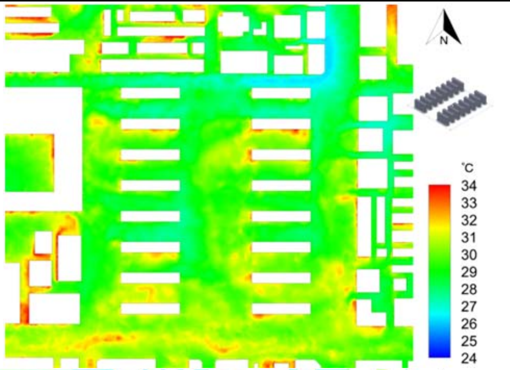
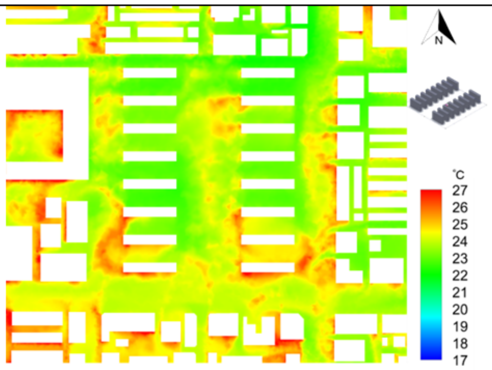
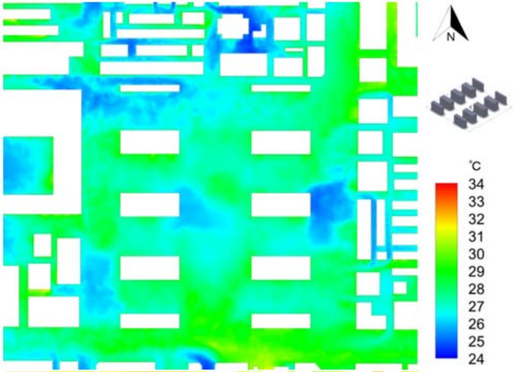
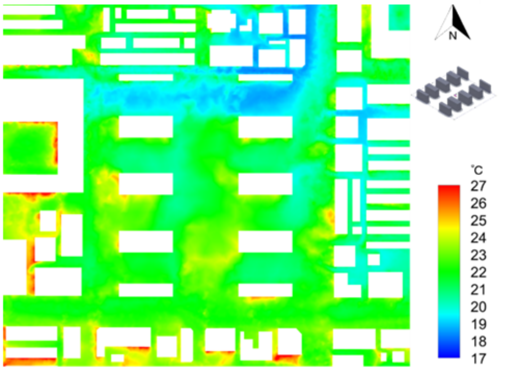
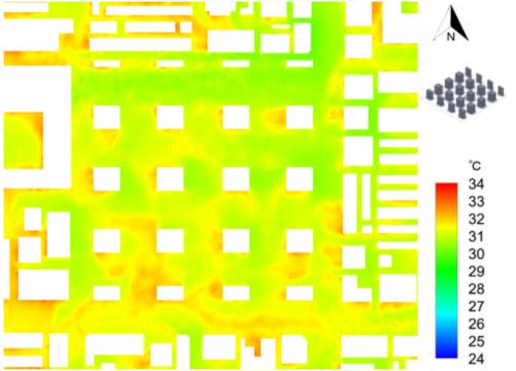
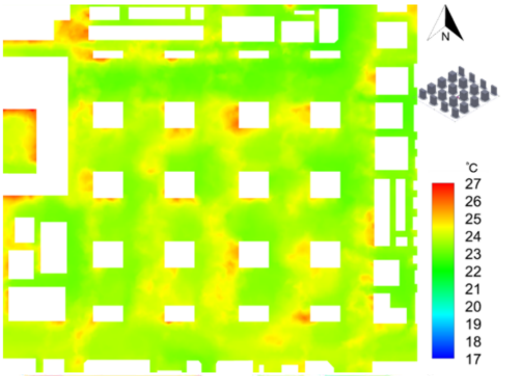
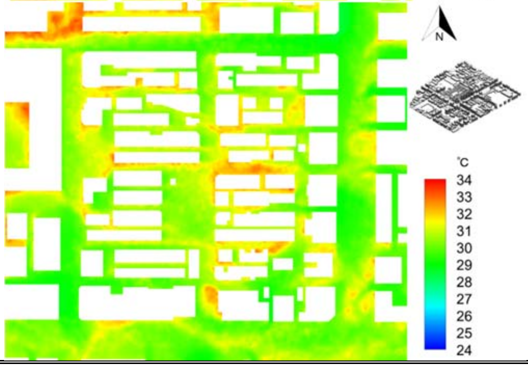
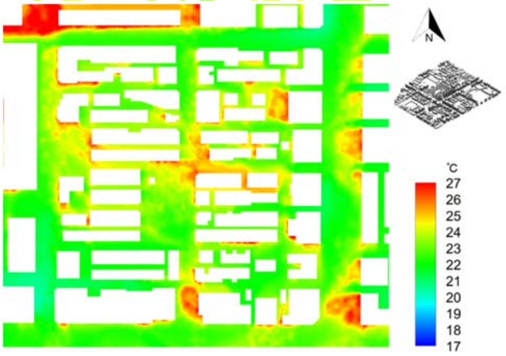
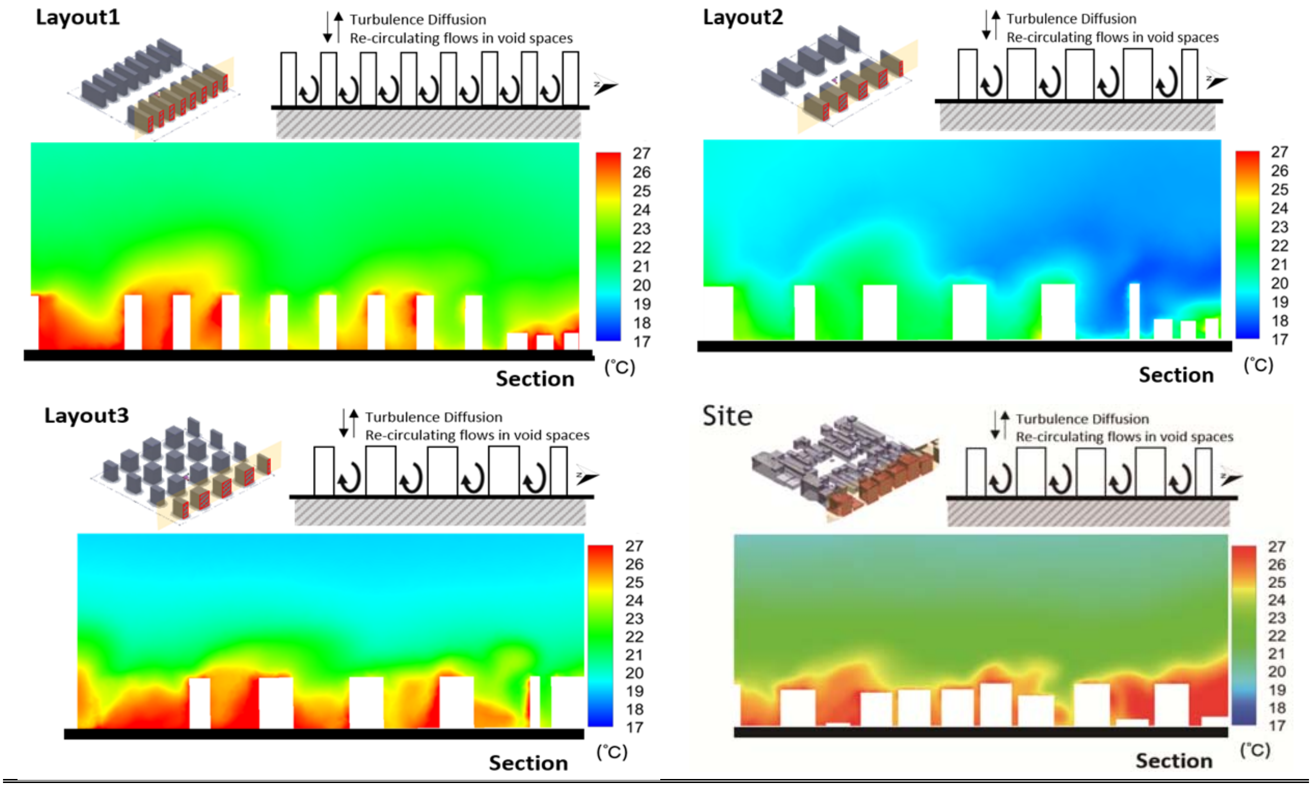
	Summer	Winter
Layout 1		
Layout 2		
Layout 3		
SITE		

TABLE VI
CFD SIMULATION TEMPERATURE ANALYSIS OF LONGITUDINAL SECTION AT 1.5 M HEIGHT LEVEL IN WINTER



D. Air Change per Hour (ACH)

Table VII displays the ACH of the three layouts designed for the study area. ANSYS Fluent software was used to monitor, compile, and analyze the data collected from the sampling stations. The natural ventilation performance levels of the three layouts were evaluated in terms of ACH, which refers to the amount of air added to or removed from an indoor space at a given time divided by the volume of the indoor space (ACH = Q/V).

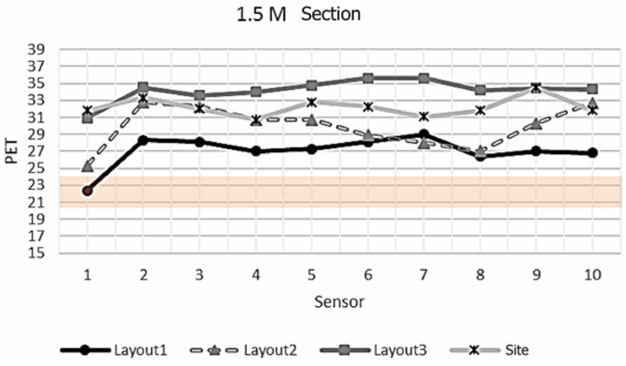
The ACH of Layouts 1–3 are respectively 8.25, 8.08, and 6.85 (h^{-1}). The lower ACH of Layout 3 can be attributed to the variations in ventilation volume caused by differences in building width. Because the ACH value is proportional to the volume of air entering a space, there is a positive relationship between ACH and the newly added air volume. Urban blocks can be aligned in a way that improves urban ventilation efficiency, increases ACH, and increases the quantities of air flowing into the urban ventilation paths. A narrow building width induces convection in the street canyon and increases the ventilation rate by boosting natural ventilation. A comparison of the ACH data suggests a similar trend with wind speed and indicates a ranking of Layout 1 > Layout 2 > Layout 3.

E. Physiological Equivalent Temperature (PET)

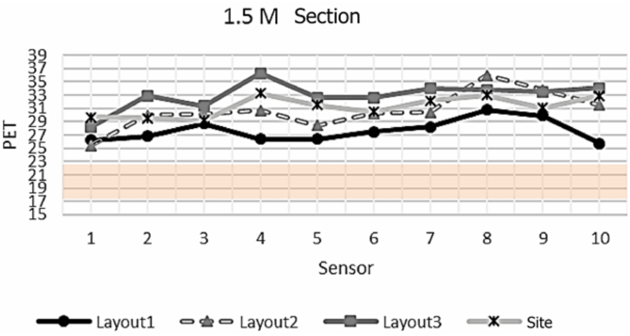
Lin and Matzarakis [12] compared the ranges of thermal comfort perception between residents of Taiwan and residents of Western and Central Europe; the results revealed a thermal comfort range of 26−30°C and 18–23°C (in PET) for the Taiwanese and the Europeans, respectively. This result suggests that the Taiwanese are more tolerant of higher temperature ranges but less tolerant of lower temperature ranges than are Europeans. The orange color in the following diagram marks the thermal comfort range for Taiwanese residents. The present study generated a PET correlation analysis diagram by respectively collecting data at 10 sampling stations along the lateral and longitudinal axes of the study area. The analysis results indicate that, in Layout 1, 95% of the PET data collected at these sampling stations fall within the thermal comfort range of Taiwanese residents. Thus, Layout 1 exhibits the most adequate comfort level, whereas Layout 3 shows the least adequate comfort level.

TABLE VII
COMPARISON OF ACH VALUES OF 3 CASES

Type	Volume flow rate Q (m3/s)	Block Volume (m3)	ACH (h-1)
Layout 1	7643	3335000	8.25
			
Layout 2	7485	3335000	8.08
			
Layout 3	6350	3335000	6.85
			



(A) Longitudinal section of PET at 1.5 m height level



(B) Cross section of PET at 1.5 m height level

Fig. 7 PET at 1.5 m height level (A) Longitudinal section, (B) Cross section

IV. CONCLUSION

ANSYS Fluent software was employed to analyze the results of comparing the simulated and observed wind speed and air temperature data measured at 12 distinct sampling stations in the study area. The analysis outcome indicates wind speed and air temperature errors within ±20% and ±10%, respectively. This suggests that the CFD software was capable of accurately generating simulated data describing outdoor flow fields, which can be used to evaluate a building layout at various conditions of block width, building width, and street width. A preliminary analysis of these data can be helpful for adjusting or modifying existing urban planning projects and thereby obtaining optimized design options.

The prevailing winds, squeezed and expanded by the block layout at various urban geometries and block scales, pass through the building blocks and ultimately mix with the outdoor air on the streets and roads; thus, rectangular buildings aligned parallel to the wind direction can increase air flows and improve ventilation. A smaller block scale (i.e., a lower H/W ratio) leads to smaller variations in the average wind-speed ratio, whereas a wider building width (e.g., row houses with a high H/W ratio) causes greater variations in the wind speed in the street canyons, leading to reduced ventilation effects.

Because the ACH value is proportional to the volume of air entering a space, there is a positive relationship between ACH and the newly added air volume. Alignment of building blocks in a way that improves urban ventilation efficiency increases ACH and the quantities of air entering the urban ventilation paths. A narrow building width induces convection in the street canyon and increases the ventilation rate by boosting natural ventilation. A comparison of the ACH data suggests a similar trend with wind speed and indicates a ranking of Layout 1 > Layout 2 > Layout 3.

This study found that, in addition to lateral air flows, longitudinal air flows can increase air-flow volume. Layouts 1–3 display a positive correlation between building height and wind speed. Therefore, future urban planning must consider not only the effects of H/W ratio on altering the lateral air flows passing through the inlet, but also the effects of longitudinal air flows. In other words, more attention must be paid to the effects of longitudinal air flows in increasing air volume, which suggests that row-house buildings should not be included in urban planning.

The thermal comfort range for Taiwanese residents was previously determined to be 26−30°C (in PET). The results of the present study indicate that, in Layout 1, 95% of the PET data collected at these sampling stations fall within this thermal comfort range. Thus, Layout 1 exhibits the most adequate comfort level whereas Layout 3 the least desirable comfort level. Finally, the present study suggests that regulations for urban ventilation in Taiwan must be established, that natural air flows in urban ventilation paths must be considered, and that urban microclimate analysis must incorporate the concept of PET as an indicator of thermal comfort to ensure accurate calculations of thermal comfort.

ACKNOWLEDGMENT

This paper represents part of the results obtained under the support of the National Science Council, Taiwan, ROC (Contract No. NSC104-2221-E-027-09).

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