EFFECT OF COURTYARD PROPORTION ON NATURAL VENTILATION EFFICIENCY

[1]PARIA SAADATJOO, [2]MOHAMMADJAVAD MAHDAVINEJAD, [3]SHIVA NAJAF KHOSRAVI, [4]NADER KAVEH

[1,2,3,4]Ph.D Candidate of Architecture, Tarbiat Modares University, Associate Professor, Tarbiat Modares University, Master of Energy and Architecture, University of Tehran, Master of Architecture, Tehran Art University
E-mail: [1]paria.saadatjoo@modares.ac.ir, [2]mahdavinejad@modares.ac.ir, [3]Shiva.khosravi@alumni.ut.ac.ir, [4]ader672002@yahoo.com

Abstract- Natural ventilation is considered as one of the most fundamental low cost passive cooling strategies. A major part of building potential in terms of using natural energy resources such as wind depends on its physical characteristics, so architectural decisions at the first step of design process can influence the buildings energy efficiency significantly. Courtyards are just one of the numerous passive cooling strategies in ancient buildings that are currently enjoying great popularity. However various configurations of these components will influence their efficiency in terms of receiving natural ventilation. The main objective of this paper was to investigate the influence of courtyard proportions on their natural ventilation efficiency and to introduce the most effective features in this field. The outcome of these researches could be used as a guideline for architects at the first steps of design process. Investigations indicated that reducing the length of windward side would result in better airflow pattern both inside the courtyard and interior space of a building. So it is suggested to design a courtyard with elongation in the wind direction and minimum windward side length to receive maximum airflow rate and take advantage of natural ventilation.

Keywords- Wind, Natural Ventilation, Architecture, Courtyard.

I. INTRODUCTION

Energy consumption in the building sector is a major concern in the current era. Considering the fact that energy usage in our buildings accounts more than 60% of total buildings energy consumption [1] while the major part of this amount is devoted to ventilation [1,2].Natural ventilation is considered as one of the most fundamental low cost passive cooling strategies [3,4] among other static cooling systems such as Earth cooling, Night sky radiation, Evaporative cooling and etc. Various design strategies can influence the natural ventilation efficiency of buildings significantly. Courtyard as one of the primary components in ancient houses of Iran promoted the thermal during summer by means of various passive cooling strategies combination such as evaporative cooling, night sky radiation, natural ventilation, and etc. although various strategies are applied by courtyards to cool the buildings during hot summer days, the main portion in this field is devoted to natural ventilation. Physical characteristics and architectural features are the main parameters that define a courtyard’s efficiency in terms of trapping wind and making use of natural ventilation. In this research the relation between proportions of courtyards and the wind behavior inside them will be studied.

II. NATURAL VENTILATION AND DESIGN MEASURES

Natural ventilation systems rely on pressure differences to move fresh air through buildings [5]. Pressure difference that ensues from wind or buoyancy effect [6] is created by temperature discrepancy [7,8] or distinction in humidity, [9]. One of the most important way to evaluate the wind load around the building is knowledge of pressure distribution on building walls [10]. Approach-flow conditions and urban surroundings as well as other factors can affect wind-induced pressure distribution [11], building geometry [12] and wind direction [13]. However, the conditions of outdoor air movement will also influence the performance of indoor air by the difference of air pressure applied into a building façade [14,15], so there is a relationship between building design and the utilization of natural ventilation. Building characteristics and their effects on natural ventilation has been an important issue for researchers during the last decade. By Investigating effective parameters the engineers and architects can get valuable information which helps them to design energy efficient, naturally ventilated buildings [16]. There are various classifications of effective design measures on natural ventilation. Aynsley classified these factors into site and local landscaping features, building form and envelope properties, internal planning and room design [17]. Zhou et al divided the effective parameters into 2 main groups; controllable and uncontrollable [18] Siew et al classified the relevant elements into two main groups; physical and Non-physical [19].

III. COOLING STRATEGIES FOR BUILDINGS

To achieve thermal comfort in the summer in a more sustainable way, one should use the three-tier design approach (Fig. 1); Heat Avoidance strategy which tries to minimize heat gain in the building by means of different techniques such as appropriate use of shading, orientation, color, vegetation, insulation, etc. [20]. Passive Cooling that consists of numerous strategies comes true by the application different components in buildings is the second step. Passive cooling also includes the use of air motion to shift the comfort zone to higher temperatures [20]. There are various passive cooling strategies; natural ventilation, induced ventilation, desiccant cooling, night sky radiation, time lag cooling, ground cooling. In a sustainable design process, as described here, this equipment must cool only what heat avoidance and passive cooling could not accomplish. Consequently, the mechanical equipment will be quite small and use only modest amounts [20].

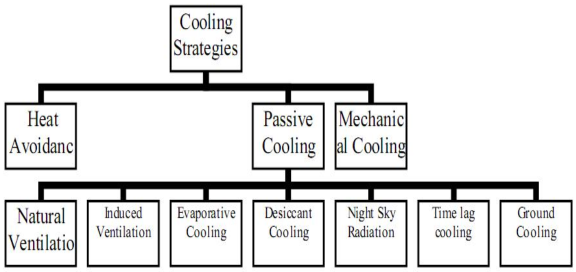


Figure 1. Three-tier design approach for cooling a building.

IV. COURTYARD DESIGN AND NATURAL VENTILATION POTENTIAL

Courtyard building is defined as a building which all spaces are distributed around an internal open area [21] these type of buildings were designed in a confined form, by which they gained the capability to create its own thermal environment [22]. It has the ability of enhancing the building’s microclimate and its internal airflow [23] and thermal buoyancy driven ventilation [24]. The significant difference of the temperature in the courtyard from that of outside [22], the limited fluctuation of indoor conditions [21], and the altered ventilation potential [25], are examples of these abilities. The microclimatic impacts of courtyard makes it a pragmatic air conditioning solution suitable for hot climates, especially when designed in a narrow depth plan. Proper natural ventilation can be achieved with a linear plan form, or by wrapping the building around an open courtyard [6]. Courtyard geometries are crucial aspects to achieve efficient natural ventilation and healthy indoor conditions in a compact urban environment [28]. Some of these geometrical features affecting natural ventilation are mentioned below.

A. Aspect Ratio of the Courtyard

The thermal performance and airflow within the courtyard building depend on its characteristics such as aspect ratio (Hieght/width) [22,25] and its morphological configurations [29]. Littlefair studied the airflow patterns and their thermal effect of courtyards with different aspect ratios [22]. Bittencourt and Peixoto studied the effect of different combination between the aspect ratio of (H/W = 0.5, 0.34, 0.17), various wind directions [26] and the use of pilotis on natural ventilation performance in an open low-rise courtyard building. Taylor (2008) highlighted a study that aimed to investigate the efficiency of cross ventilation in a standard courtyard (H/W= 2) of Jeddah housing in Saudi Arabia and another courtyard model with (H/W = 0.25) [25]. According to Brown and Dekay decreasing the aspect ratio in a long-wind direction has greater effect than decreasing it in cross-wind direction [27]. The horizontal air speed and air flow tests for a cavity ratio of W/H=0.7, 0.5, 0.3, 2.0 and 1 indicated that the courtyard with width to height ratio of 1.0 and 0.7 have the highest potential for natural ventilation due to their geometry that promotes the development of a strong vortex and high velocity magnitudes [28] (Fig. 2).

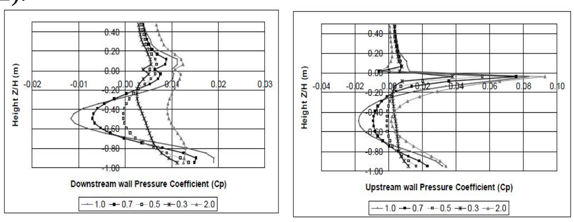


Figure 2. Pressure coefficients of downstream and upstream walls for ratios W/H= 1, 0.7, 0.5, 0.3 and 2 [28].

B. Cavity Profile of the Courtyard

Ok and his colleagues [29] studied the effect of 17 different cavities profile in courtyard mass (Fig. 3) on the airflow within it. The results proved that creating cavities in the surrounding walls could enhance the natural ventilation performance in the courtyard. The results also showed that the closed courtyard had the lowest airflow velocity, while providing two opposite cavities in the courtyard mass could increase the air velocity significantly.

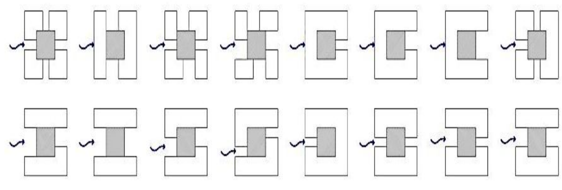


Figure 3. Different morphological cases of courtyard openings studied by Ok et al [29].

C. Section Form of the Courtyard

Surrounding geometry of a courtyard along with its own physical structure plays an important role in determining velocity magnitudes (V/Uref). Investigation of air velocity in cases with various obstructions proved this hypothesis [28] (Fig. 4).

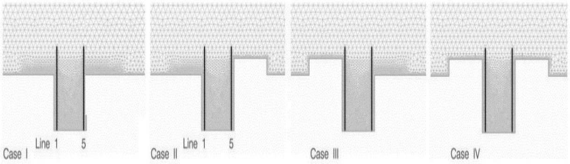


Figure 4. Position of the courtyards' obstructions and lines [28].

The velocity magnitude (V/Uref) of these cases have been compared and the result of these comparisons are illustrated in figures. According to these results case I with no obstructions has the highest velocity magnitude. On the contrary, case III, which has an obstruction on the downstream side, has the lowest values (Fig. 5) [28].

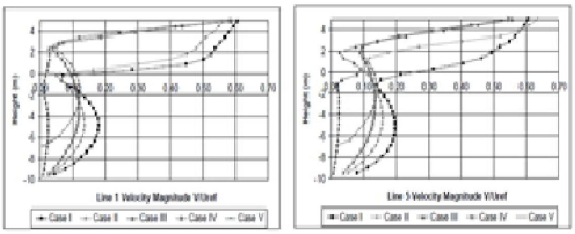


Figure 5. Comparison of velocity magnitude between cavities with different obstacles (on the right) [28].

According to the researches [23,30] which have compared the performance of courtyard and atrium buildings, the courtyards have better performance in terms of natural ventilation. Courtyards are more energy efficient in smaller building heights, while, atrium buildings performed better at greater building heights. The presence of obstructions on the courtyard's top corners provoke a weaker flow inside the cavity and therefore lower velocity magnitudes and potential for natural ventilation.

D. Proportion of the Courtyard

Nowadays most of the modern big cities like Tehran have a very compact morphology with narrow and orthogonal streets. Because of the high density of the building blocks, the crowded dwellings and the lack of natural ventilation, a large number of buildings do not fulfil the requirements for a comfortable and healthy environment. For this reason, high levels of asthma and other respiratory diseases have been reported in the compact urban environments of these modern cities. New buildings inserted in these situations have to be adjusted to the existing compact morphology and, at the same time, provide a comfortable and healthy environment. Efficient natural ventilation by a proper design of the building and courtyard geometry can be a first step to achieve this goal. Although various researches have investigated the effect of numerous courtyard configurations such as its location, section form and wall openings on wind behavior inside the cavities, the relation between courtyard proportions and natural ventilation efficiency remains a state of problem yet. Despite the numerous courtyard types such as L shaped, U shaped, straight form, etc. this research exclusively focuses on U shaped ones and modifies its proportions to find out the effect of this parameter on wind behavior inside the courtyard and rooms. To aim this goal a 225 case with 150 U shaped closed area and 75 open area with 5 different proportions were modeled and analyzed by computational fluid dynamic (CFD).

V. CFD SIMULATION SETUP

A. Outline of the analysis model and cases

To investigate the effect of courtyard proportions on wind behavior inside the open and closed space, we selected a special type among the numerous categories of courtyard buildings. The initial models are all 2 story U shaped buildings with a rectangular courtyard. With a permanent aspect ratio, the proportion of building and consequently the courtyard varies in 5 cases (Fig. 6). The properties of analysis cases are shown in table1. Studies were conducted assuming all conditions such as location and area of openings, wind direction, number of floors and etc. invariant.

Table 1. Analyzed cases and their features.

case	Courtyard Dimensions	Number of floors	Total Floor area	Open space area	Wind direction
A1	7*10.72	2	$150m^2$	$75m^2$	south
A2	8*9.38	2	$150m^2$	$75m^2$	south
A3	9*8.33	2	$150m^2$	$75m^2$	south
A4	10*7.5	2	$150m^2$	$75m^2$	south
A5	11*6.82	2	$150m^2$	$75m^2$	south

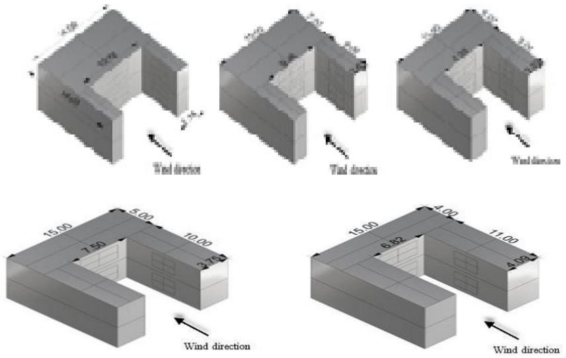


Figure 6. Analyzed cases, their dimensions and wind direction.

B. Analysis Domain and Mesh

In order to model the flow inside the courtyard and room in a more realistic way, both this flow and the external flow around the building were modelled together (rather than, say, using a separate stage to generate the conditions at the inlet aperture). The CFD analysis domain was defined according to the AIJ standards. According to this standard defining an exact domain dimensions to omit reversed flow is an important step. The analysis domain based on referred standard is 135m in the X-direction;75m in the Y-direction; and 36m in the Z-direction, and the center point of models were located in the (37.5,37.5,3) point. The mesh type is Hexa Unstructured and its maximum size in x, y and Z direction is 1 (Fig. 8).

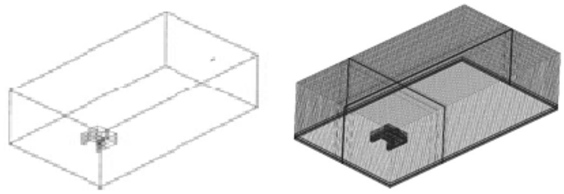


Figure 7. Main domain of the analysis and mesh grid.

C. Boundary Conditions

Standard choices for boundary conditions in this type of problem were used in the simulations. At the upstream (inlet) boundary of the computational domain, vertical profiles for the velocity variables were specified: a logarithmic mean velocity profile, specified using the reference velocity and height and a roughness height z0 ¼ 0.3 m appropriate to an urban boundary layer profile; and turbulence variables (k, ε, u). The downstream face was treated as a constant (zero) pressure boundary; while the top and side boundaries were assigned symmetry conditions (zero gradient). Solid surfaces were specified as no-slip boundaries (Table 2).

The inflow velocity was assumed to be 5.5 at the height of 10m. This amount was proportionated according to the other heights and created a velocity logarithmic diagram. According to the equation 1 the minimum and maximum amount of velocity are 0 and 9.5 in this research. A is assumed 0.36 according to the context.

$$\frac{\bar{V}_Z}{\bar{V}_G}=\left[\frac{Z}{Z_G}\right]^{\alpha} \qquad (1)$$

High-Reynolds-number type quadratic nonlinear k–ε model [4] was used for the turbulence model. k, Turbulent kinetic energy; ε, viscous dissipation were calculated according to the Reynolds number estimated by the Ansys Airpak. This estimated amount is based on the physical features of the model.

Reynolds= 564100, Peclet number= 419193

$I= 0.16\,(Re)^{-1/8}$ Re=0.5×L×V× 10^4 $k=3/2\,(u_{avg}I)^2$ (2)

While I is Turbulence Intensity and Reynolds number is estimated 56100, the amount of Turbulence Kinetic Energy is 0.07926.

$$\varepsilon= C_u^{\,3/4}\times K^{3/2}/l \qquad (3)$$

While C_u is 0.09, the amount of viscous dissipation is about 0.00349. Boundary conditions are shown in Table 2.l= 0.07L

Table 2. Boundary conditions of the models.

Inlet	X velocity- wind algorithmic profile
Outlet Free-slip	Static pressure
Upper and side boundary	Symmetric
Ground and building surface	Wall function
Win ward openings	X velocity- 2.77 m/s at the height of 1.5 m; 4.12 m at the height of 1.5 m.
Lee ward openings	Static pressure

D. Bench Marks

To exactly compare 5 cases in terms of receiving natural wind, we defined 26 bench marks. 19 numbers of these bench marks are located in the courtyard and rest of them inside the building. Wind speed is measured in these points. The location of referred bench marks are shown in table 3 and fig. 8

Table 3. Location of 26 benchmarks.

Point (Courtyard)	X	Y	Z	Point (Courtyard)	X	Y	Z	Point (Interior)	X	Y	Z
P1	32	37.5	1.5	P10	32	35	4.5	P19	34	31	1.5
P2	32	37.5	4.5	P11	35	35	1.5	P20	34	31	4.5
P3	35	37.5	1.5	P12	35	35	4.5	P21	34	44	1.5
P4	35	37.5	4.5	P13	30	40	1.5	P22	34	44	4.5
P5	30	37.5	1.5	P14	30	40	4.5	P23	40	37.5	1.5
P6	30	37.5	4.5	P15	32	40	1.5	P24	40	37.5	4.5
P7	30	35	1.5	P16	32	40	4.5	P25	42	37.5	1.5
P8	30	35	4.5	P17	35	40	1.5	P26	42	37.5	4.5
P9	32	35	1.5	P18	35	40	4.5				

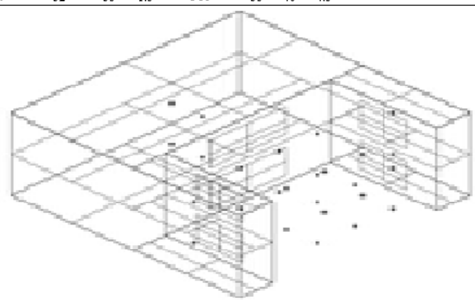
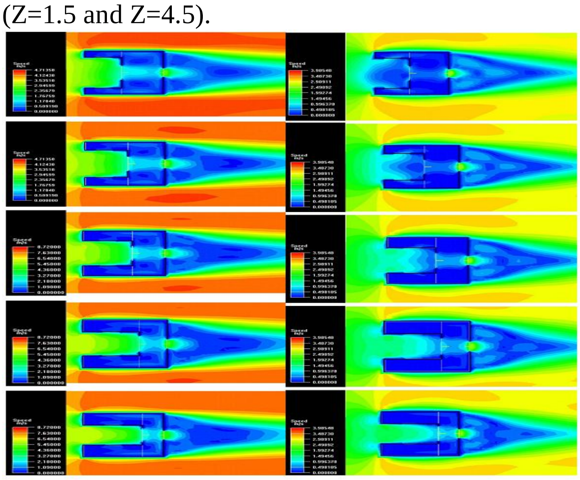


Figure 8. Graphical display of benchmarks.

VI. CFD SIMULATION RESULTS

A. Comparison of the air flow rate

The simulation results of the courtyard proportions effect (horizontal and vertical) on air flow velocity and airflow pattern in the rooms and courtyard are outlined. Finally, the results of the wind direction effect on upward velocity in all configurations are presented. Figures 9-10 shows a plan view of the CFD solution field for 5 cases. As expected, 5 cases with similar aspect ratios and different courtyard and closed space dimensions clearly display the distinct character of the two flow régimes and wind behavior. The plane cut location is illustrated beside each group of contours. The graphical contours illustrate the wind flow rate through one y plane (Y= 37.5) and 2 z planes (Z=1.5 and Z=4.5).



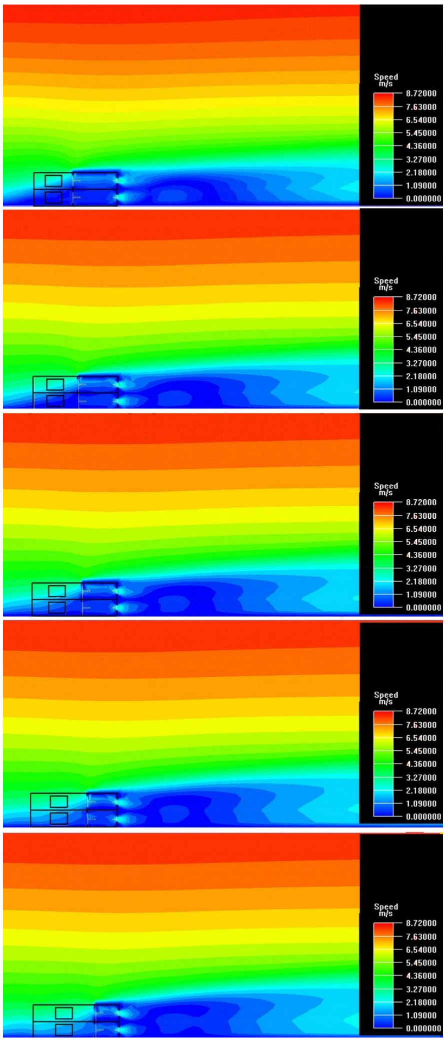


Figure 9-11. Air velocity at the x= 4.5 plane cut. x= 1.5 plane cut and at the y= 37.5 plane cut.

VII. ANALYSIS OF THE CFD RESULTS

The results of the airflow pattern were categorized according to the plane cut and were illustrated in figures. These illustrations indicate the wind flow pattern and wind speed in the position of y=37.5 and z= 1.5 and 4.5 meter.

Horizontal and vertical sections indicate that airspeed in the windward courtyard and interior speed is quite different in 5 cases. It is derived from the contours that airspeed increases by modifying the proportions of the courtyard (decreasing the width and increasing the length). The measured speed at some specific points inside the courtyard and interior space confirms these visualization results. The average wind speed inside the courtyard (Fig. 12) increases gradually and follows an accelerating process. Despite the exterior space, airflow pattern and speed variations inside the rooms follows a different process. According to the measured parameters at 8 bench marks, the airspeed decreases from case1 to case 2 and then increases gradually till case 5.

Although we presented separate results for interior and exterior conditions, it is important to consider these two parameters simultaneously. To reach this aim we calculated the average of 26 bench marks and presented these results in the form of a chart (Fig. 14). Investigations indicated that decreasing the length of windward side of the courtyard will result in a better air stream inside the open space and consequently onside the rooms. That is while increasing the length of this side will result in worse conditions.

Figure 12-14. The average air velocity at exterior benchmarks. The average air velocity at interior benchmarks. The average air velocity at interior and exterior benchmarks

CONCLUSION

Courtyards as one of the numerous passive cooling strategies in ancient buildings are now enjoying great popularity in modern architecture. However various physical configurations of these components will influence their efficiency in terms of receiving natural ventilation. This paper tried to prove that any small change in physical configuration of courtyards such as proportions will influence the air flow pattern and natural ventilation efficiency.

This paper presents a systematic validation of 3-D steady RANS CFD model for 2 story courtyard house with 5 different proportions. The dimension of closed and open space varied in these models while their area and aspect ratio was invariant. RNG k–ε model capable of predicting airflow rate and its pattern was used to analyze the models. The simulation results show that the courtyard proportions, despite a constant area and aspect ratio, is highly affected the flow velocity in the courtyard and consequently the interior. It was found that a rectangular courtyard with minimum windward side show a good performance in terms of receiving wind and natural ventilation.

REFERENCES

[1] Chan H, Riffat SB, And Jie Zhu, "Review of passive solar heating and cooling technologies", Journal of Renewable and Sustainable Energy Reviews. 14, 781-789 (2010).

[2] Zhou L, Haghighat F, "Optimization of ventilation system design and operation in office environment", Building and Environment. 44, 651-656 (2006).

[3] Zhai Z, "Application of computational fluid dynamics in building design: aspects and trends", Indoor and Built Environment. 15, 305-313 (2006).

[4] Su Y, Riffat S, Lin Y, and Khan N, "Experimental and CFD study of ventilation flow rate of a Monodraught TM windcatcher", Energy and Buildings, 40, 1110-1116 (2008).

[5] Walker C, "Methodology for the evaluation of natural ventilation in buildings using a reduced-scale air model", PhD Thesis, Massachusetts Institute of Technology University (2005).

[6] Tommy K, "Natural Ventilation in Buildings Architectural concepts: consequences and possibilities", Doctoral thesis; Norwegian University of Science and Technology (2003).

[7] Feustel H. E, COMIS—an international multi zone air-flow and contaminant transport model, Energy and Buildings. 30(1), 3-18 (1999).

[8] Mistriotis A, Arcidiacono C, Picuno P, Bot G. P. A, Scarascia-Mugnozza, "Computational analysis of ventilation in greenhouses at zero-and lowwind- speeds", Agricultural and Forest Meteorology. 88(1-4), 121-35 (1997).

[9] van Hooff T, Blocken B, "Coupled urban wind flow and indoor natural ventilation modeling on a high resolution grid: A case study for the Amsterdam Arena stadium", Environmental Modeling & Software. 25, 51–65 (2010).

[10] Montazeri H, Blocken B, "CFD simulation of wind-induced pressure coefficients on buildings with and without balconies: Validation and sensitivity analysis", Building and Environment. 60, 137-49 (2013).

[11] Kim YC, Yoshida A, Tamura Y, "Characteristics of surface wind pressures on low-rise building located among large group of surrounding buildings", Eng Struct. 35,18-28 (2012).

[12] Uematsu Y, Isyumov N, "Wind pressures acting on low-rise buildings", Wind Eng Ind Aerodyn. 82, 1-25 (1999).

[13] Levitan ML, Mehta KC, Vann WP, Holmes JD, "Field measurements of pressures on the Texas tech building", J Wind Eng Ind Aerodyn. 38, 227-34 (1991).

[14] Broderick Ch, Chen Q, "A simple interface to CFD codes for building environment simulations", In 7th International IBPSA Conference. Rio de Janeiro. 577-84 (2001).

[15] Ghiaus C, Allard F, "Natural Ventilation in the Urban Environment: Assessment and Design", Buildings Energy and Solar Technology. London: Earthscan (2005).

[16] Shetabivash H, "Investigation of opening position and shape on the natural cross ventilation", Energy & Buildings. Accepted (2014).

[17] Aynsley R, "Natural ventilation in passive design (Tec 2)", in BEDP environmental design guide; The Royal Australian Institute of Architects: Australia (2007).

[18] Zhou C, Wang Z, Chen Q, and Jiang Y, "Design optimization and field demonstration of natural ventilation for high-rise residential buildings. Energy and Buildings". 82, 457-465 (2014).

[19] Siew C. C, Che-Ani A.I, Tawil N. M, Abdullah N. A. G, and Mohd-Tahir M, " Classification of Natural Ventilation Strategies in Optimizing Energy Consumption in Malaysian Office Buildings", The 2nd International Building Control Conference, Procedia Engineering. 20,363 –71 (2011).

[20] Lechner N. Heating, Cooling, lighting. New Jersey: John Wiley & Sons, Inc., Hoboken (2015).

[21] Mansouri, Y, Allard F, and Musy M, "Conceptual implementation of natural ventilation strategy". In Eighth International IBPSA Conference. Building Simulation: Eindhoven, Netherlands, 815-22 (2003).

[22] Littlefair P, Santamouris M, Alvarez S, Dupagne A, Hall D, Teller J, Coronel J.F, and Papanikolaou N, "Environmental site layout planning: solar access, microclimate and passive cooling in urban areas", Building Research Establishment. Ltd (BRE) (2000).

[23] Khan N, Su Y, and Riffat S.B, "A review on wind driven ventilation techniques", Energy and Buildings. 40, 1586-604 (2008).

[24] Edwards B. Sibley M, Hakmi M, and Land P, "Courtyard housing: Past, present and future", New York: Taylor & Francis (2006).

[25] Taylor B, "The first line of defense: Passive design at an urban scale, in Air conditioning and the low carbon cooling challenge", Network for Comfort and Energy Use in Buildings (NCEUB): Cumberland Lodge, Windsor, UK (2008).

[26] Golany G.S, "Ethics and urban design: Culture, form and environment", New York: John Wiley & Sons (1995).

[27] Brown G.Z, Dekay M, "Sun, wind and light:Architectural design strategies", 2nd ed. New York: Chichester: John Wiley & Sons, Inc (2001).

[28] Tabalada A, Blocken B, Carmeliet J, De Troyer F, and Herschure H, "Geometry of building's courtyards to favour natural ventilation: comparison between wind tunnel experiment and numerical simulation", The 2005 World Sustainable Building Conference, Japan: 27 – 29 (2005).

[29] Ok V, Yasa E, and Ozgunler M, "An experimental study of the effect of surface openings on air flow caused by wind in courtyard buildings", Architectural science review. 51(3), 263-68 (2008).

[30] Sharples S, Bensalem R, "Airflow in courtyard and atrium buildings in the urban environment: A wind tunnel study", Solar Energy. 70(3), 237-44 (2001).

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