Design and Performance Comparison of Two Patterns of Wind-catcher for a Semi-enclosed Courtyard

Naima Benkari
Department of civil and architectural engineering, Sultan Qaboos University, Muscat, Sultanate of Oman
Email: nbenkari@squ.edu.om

Ijaz Fazil and Afzal Husain
Department of Mechanical engineering, Sultan Qaboos University, Muscat, Sultanate of Oman
Email: ijaz0001@e.ntu.edu.sg ; afzal19@squ.edu.om

***Abstract*— The main focal point of this work is to provide an enhanced indoor air quality (IAQ) using natural ventilation system called wind-catcher and also to cut the energy consumed by mechanical HVAC systems. This paper looks into the operation of two patterns of wind-catcher in a semi-enclosed courtyard on the top level of the engineering school at Sultan Qaboos University, Oman. The wind speed, direction and roughness length in the region of SQU were used as the inlet and boundary conditions. Computational Fluid Dynamics (CFD) analysis was performed using ANSYS FLUENT with a standard k-epsilon model to generate a homogenous neutral ABL at the inlet. This study provides a comparison of airflow distribution inside the courtyard with two modified wind-catcher designs to provide better indoor air quality. The primary focus is on the air stream distribution. The best possible flow rate of 6056 L/s was achieved for reference velocity 4 m/s at reference height 50m. This rate is more eminent than the minimum requirement suggested by ASHRAE standard 62.1-2013. Also air change per hour (ACH) for the same condition was around 108.**

***Index Terms*—wind-catcher indoor air quality, computational fluid dynamics, air flow rate, air change per hour**

I. Introduction

The disadvantages of the conventional HVAC in buildings include high electricity use, facility and upkeep cost. Besides the application of HVAC solutions in environmental hazards such as high usage of fossil fuels, emission of CFCs, which contribute to ozone layer depletion [1]. It has been reported that 40% of the greenhouse gas emissions are due to the energy consumed in the buildings [2]. So it is necessary to provide significant importance for natural, environmentally friendly and low-cost ventilation to supply fresh air and maintain comfortable indoor temperature. Two important parameters for analyzing the ventilation performance are indoor air quality are ventilation rate (L/s) and air change per hour (ACH) [3]

Manuscript received March 1, 2017; revised August 23, 2017.

Wind-catchers were part of the building in the Middle East over many centuries to provide natural ventilation and cooling. The wind-catcher provides natural ventilation due to wind effect and stack buoyancy effect. Wind effect is the main driving mechanism and is due to the pressure difference on the windward side and leeward side of the wind-catcher. The Wind that enters along the windward side removes the heat from the occupants via convective and evaporative heat transfer and thus results in chilling. Buoyancy effect is the secondary effect in which hot and less dense air moves upward while cold and high dense air moves downward [4-6].

The main objective of this work is to examine the performance of two different shapes of the wind-catcher and their airflow distribution in the courtyard.

II. Working Principle of Wind-catcher

As indicated in the Introduction, wind-catcher operates on a combination of both wind effect and stack buoyancy effect. Fig. 1 shows the working principle of wind-catcher. Generally, wind-catchers are attached to the ceiling to get the free atmospheric air and divert into the indoor.

When the wind hits the wind-catcher as shown in Fig. 1, it creates a high-pressure zone (positive) on the windward side and a low-pressure zone (negative) on the leeward side of the wind-catcher. The Wind intends to match the pressure or in other words flow from high-pressure region to low- pressure region, so it enters via an opening on the windward side and exits through an opening on the leeward side. As a result, fresh air enters through the windward side and hot stale air in the indoor tends to move towards the negative pressure region on the leeward side. This effect is called wind effect and this effect is predominant.

Buoyancy effect is a secondary mechanism and it aids the performance of the wind effect. It is based on the density difference of the fresh air and indoor air due to temperature differences. Generally, cool denser air settles down, and warm and less dense air moves up. As shown in Fig. 1, as the fresh air enters through the opening on

doi: 10.18178/ijmerr.6.5.396-400

the windward side, buoyancy effect aids to move down and also aids in raising the hot indoor to the leeward side.

In this work, since the buoyancy effect is the secondary mechanism, it has been left for future analysis. Besides in most previous studies [7-21], only performance analysis of wind-catcher attached to the ceiling of the indoor with or with-out window outlets was analyzed. In this study, we did try to design the wind-catcher based on requirement and criteria. In our analysis, indoor is not completely sealed on the roof, so it might be difficult to attach wind-catcher on the ceiling and also to create an opening on the leeward side, as hot indoor air instead of raising to the leeward side opening can leave through the openings in the roof. This issue is addressed in more detail in Section 5.

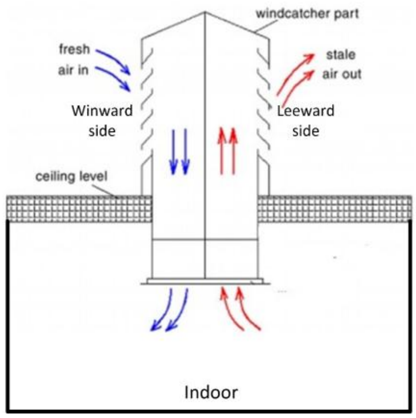

Figure 1: Working principle of wind-catcher [source:10, modified by authors]

III. Wind Data Analysis on the Site of the SQU, Oman

Sultan Qaboos University (SQU) is located in Muscat, Oman. The university is surrounded by small hills, hence the roughness length of this site was chosen to be 0.7m based on the average height of the buildings and suggested value in Burton et al. [22]. Based on the wind data recorded in 2009 by Sultan Al Yahyai in his work [23] and also in his report for an eco-house in SQU (confidential), it was noted that predominant wind speed was 4 m/s and predominant direction was 45^o at the reference height 50m in the site of SQU. Homogenous ABL at the inlet and boundary condition on the ground was employed in the domain using the following equations [24-26].

The governing equation (log law) of the mean wind speed for neutral ABL is given by

$$\bar{u}(z) = \frac{u_*}{K} \ln\left(\frac{z + z_o}{z_o}\right) \tag{1}$$

z is the height above the ground (m)
K is von-Karman constant (=0.4)
u_* is friction velocity (m/s)
z_o is roughness length of the terrain (m)
Turbulent Kinetic energy is given by

$$k = \frac{u_*^2}{\sqrt{C_\mu}} \tag{2}$$

The turbulent dissipation rate is given by

$$\varepsilon = \frac{u_*^3}{K(z + z_o)} \tag{3}$$

In ANSYS FLUENT, roughness length is applied to the ground using the term roughness height and their relationship is provided by

$$k_s = \frac{9.793 * z_o}{C_s} \tag{4}$$

k_s is roughness height (m)
Cs is roughness constant

IV. Geometry and Modelling of Courtyard in the Building of Engineering School in SQU

A courtyard in Sultan Qaboos University chosen for study was of dimension 6.5m*6.5m*4.7m. The courtyard was kept semi-closed on top as shown in Fig. 2. Roof shield of thickness 2cm was supported by truss of diameter 10cm to the side walls. The floor of the courtyard of the building was around 14m from the sea level. The courtyard was constructed in the middle of the staff rooms for relaxation. The courtyard was modelled using AutoCAD. In order to have a better realistic analysis of ABL, the domain of size 400m*200m*50m was created around the building as shown in Fig. 3. Since the building itself is 5^o to the East-West direction and predominant wind direction is 45^o to the East-West direction, the building is rotated 50^o to the inlet of the domain. By this way, the opening of wind-catcher can be easily modelled as normal to the inlet (i.e) incoming air.

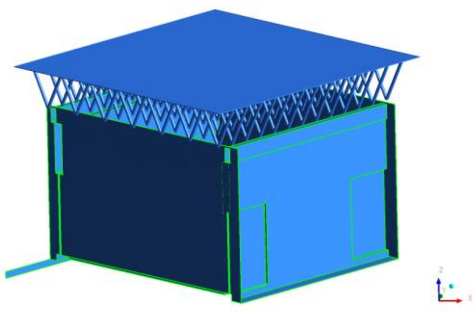

Figure 2. 3D view of courtyard in engineering block in SQU

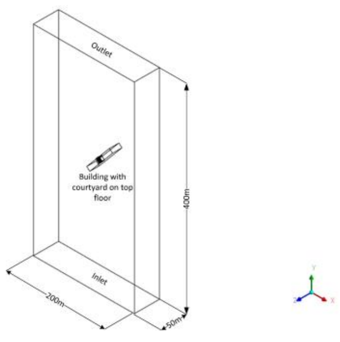

Figure 3. 3D view of domain for ABL analysis of courtyard

V. Different Patterns of Wind-catcher

Vast previous works in the CFD analysis of wind-catcher covers mostly the performance analysis of wind-catcher. In this work, we have concentrated on the suitable design of the wind-catcher in the semi-enclosed courtyard. We did attempt to design a wind-catcher to suit the requirement and also to fulfil the minimum required standard suggested in ASHRAE standard 62.1-2013 [27]. Based on the previous works [7-21], the most suitable ratio of length and width of the wind-catcher shaft to that of the room was found close to be 1:4. As mentioned above, length and width of the courtyard were 6.5m, hence the length and width of the shaft of the wind-catcher were chosen to be 1.625m.

The height of the wind-catcher depends predominantly on the external wind speed which varies with altitude based on Equation 1. Besides it is necessary to get into consideration about the civil aviation rule in Oman that no buildings should exceed 38m. Already the courtyard had been on the 2nd floor which is 14m height from the ground and the height of the courtyard itself was 4.7m. An allowance of 12m was provided to the limit height (38m) and height of the wind-catcher from the ground was maintained to be around 26m on trial and error basis.

In most previous studies, wind-catcher was attached to the roof-top and also the room may or may not include windows in the side walls. But in this case, the structure of wind-catcher can’t be connected to the roof-top as it is very thin and can’t withhold its weight. So the shaft of the wind-catcher is propagated near to the floor of the courtyard and connected to the floor by the supporting poles. Two patterns were initially analysed based on the approach of connecting wind-catcher to the floor as shown in Fig. 4. In the first design (left in Fig. 4) height of the supporting poles was kept to be 0.6m from the ground and in the second design (right in Fig. 4) height is increased to 2.35m (half of the sidewall height) from floor integrated with a revolved curved like structure at the bottom of the wind-catcher for better distribution of air. Traditionally either the top of the wind-catcher will be a flat plate or inclined especially at 45o. In this analysis, a modification was made instead, a curved top (a quarter of a circle with a diameter of the size of the shaft) was used for better distribution of air in the front side of the courtyard which is explained in the results and discussions section.

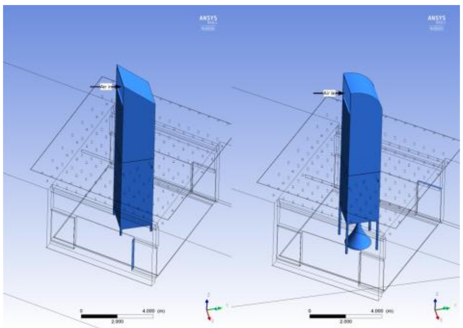

Figure 4. Two Patterns of wind-catcher designed for the courtyard

VI. Computational Meshing and Fluent Setup for Simulations

ANSYS ICEM software was used to create the mesh. Patch independent octree method was used. Global mesh element size was chosen to be 4. Maximum size in the truss was chosen to be 0.025m and maximum size of the mesh elements in the courtyard was chosen to be 0.1m. This assisted in producing a fine mesh in the region of courtyard and wind-catcher. A maximum number of mesh elements were maintained around 25 million. The size of the domain and mesh was chosen based on the many trial and error method. ANSYS FLUENT was used to perform steady state analysis. Boundary conditions applied at the inlet and ground was based on the Equations from 1 to 4, symmetry was used on lateral walls, outflow at the outlet and constant shear stress on the top wall.

VII. Results and Discussions

Two CFD analyses of the courtyard with designed wind-catchers performed in this study were discussed in this section.

A. Comparison of Two Cases

In this courtyard without wind-catcher, it was noticed that though the atmospheric air at considerable velocity enters through openings near the truss at the top, instead of circulating considerably inside the courtyard it just passes through the truss and exits through other openings. In addition, this external airflow forms a layer which might cause difficulty for the stale air in the courtyard to go out thus ACH would be reduced. The purpose of this courtyard was to provide relaxation for the staffs and to provide adequate fresh air. But this design didn’t suit the requirement which motivated to design a wind-catcher for this courtyard.

Fig. 5 shows streamlines from the entrance of air on the top of the wind-catcher to the courtyard for both the patterns (left is for 1st design and right for 2nd design). Though the 1st design provided an adequate volume of air for ventilation, from Fig. 5 it can be noticed that there was an uneven distribution of the air. The Huge volume of the air with higher velocity is found behind the wind-catcher (i.e) rear side of the courtyard while in the front side seldom air gets circulated. Overall this model even though it fulfills the requirement, but results in uneven distribution of the wind in the courtyard. Also it can be noticed that from Fig. 5 that air is directed like a jet to the floor. This might result in locally increased pressure on the floor exposed and cause structural damage. One of the possible solutions to solve the two issues (Uneven distribution of air and decrease the increased local pressure on the floor) is to construct a curved revolved structure as shown in Fig. 4. The advantages of having such structures.

1) Since it is revolved and curve shaped it can distribute the air in all directions
2) It increases the surface area so that local pressure on the floor is reduced

3) By this way, no human beings will stand directly under the air jet from the wind-catcher.

In 2nd design from Fig. 5 it can be incurred that though equal distribution in front and back of the wind-catcher was not achieved, a comparatively better and uniform distribution can be noticed.

Fig. 6 shows the velocity profile of range (0.2 m/s to 0.8 m/s) across the mid-section plane in the courtyard region for both the cases (left is for 1st design and right for 2nd design). It can be noticed from the velocity contour of 1st design (left) very low velocity (even below 0.2 m/s) on the front side of the wind-catcher in the courtyard. While in 2nd design there is a better velocity of air required for comfort than the 1st design but it is lower than the values on the rear side of the wind-catcher. It was also found that the mass flow rate from the top opening in this 3rd design (6.06 m^3/s) was higher than the traditional 2nd design (4.82 m^3/s).

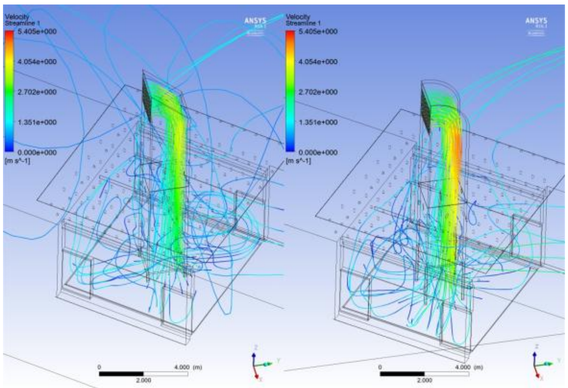

Figure 5. Comparison of streamlines from the wind-catcher entrance for both patterns

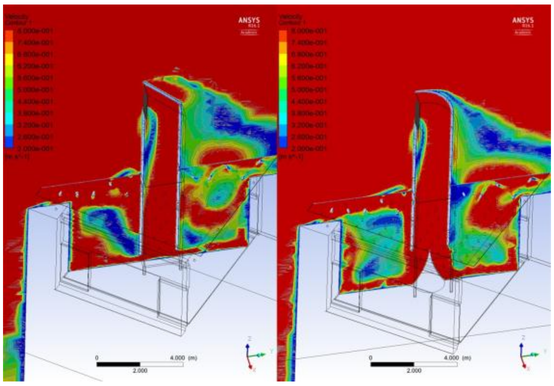

Figure 6. Comparison of velocity contour on the mid-section plane

B. *Comparison with Minimum Requirements Mentioned in ASHRAE Standard 62.1-2013*

Since the 2nd design was concluded to be better than the 1st design it is used for this comparison. The standard minimum requirement values corresponding to the courtyard were not included in the ASHRAE standard 62.1-2013 [27], hence nearest possible values were chosen and listed in the Table1. A maximum number of population density in the courtyard was chosen to be 10. Equations required to compute minimum ventilation rate by ASHRAE standard 62.1-2013 are given below.

$$V_{bz} = R_p P_z + R_a A_z$$

$$V_{oz} = V_{bz} / E_z$$

V_{bz}=breathing zone outdoor airflow (airflow required in the breathing zone of the occupied zones) (L/s)

V_{oz}=Zone outdoor airflow, outdoor airflow that must be provided to the zone by the supply air distribution (L/s)

R_p=people outdoor air rate (L/s.person)

R_a=Outdoor air rate (L/s.m^2)

A_z=zone floor area, the net occupiable floor area of the ventilation zone (m^2)

=(6.56*6.51)-(1.725*1.725)=39.78m2

P_z=zone population, the number of people in the ventilation zone during typical usage

= 10 (assumed maximum number of people)

Since the Rp and Ra values are not available for courtyard or atria in ASHRAE standard 62.1-2013, closest to the courtyard is considered.

TABLE II. COMPUTATION OF MINIMUM VENTILATION RATES FOR BETTER INDOOR AIR QUALITY

	R_p	R_a	#	A_Z	$R_pP_z+R_aA_z$	E_z	V_{oz} (L/s)
Breakrooms (office)	2.5	0.6	10	39.78	48.868	1.2	**40.72**
Dayroom	2.5	0.3	10	39.78	36.934	1.2	**30.78**
Breakrooms(general)	2.5	0.3	10	39.78	36.934	1.2	**30.78**
Coffee stations	2.5	0.3	10	39.78	36.934	1.2	**30.78**
Lobbies /prefunction	3.8	0.3	10	39.78	49.934	1.2	**41.62**
Libraries	2.5	0.6	10	39.78	48.868	1.2	**40.72**
Lobbies	2.5	0.3	10	39.78	36.934	1.2	**30.78**
Mall common areas	3.8	0.3	10	39.78	49.934	1.2	**41.62**
Restaurant dining rooms	3.8	0.9	10	39.78	73.802	1.2	**61.5**

From CFD analysis volume flow rate supplied by wind-catcher is **6.0565 m^3/s = 6056 L/s** (greater than minimum requirements).

In addition, it is also necessary to compare the Air Change Per Hour (ACH)

$$ACH = Q * 3600/Volume$$

=6.0565*3600/(6.56*6.51*4.7)

=108.62

Minimum ACH required in general is 4 and maximum ACH required is in clubs and the value is 30.

VIII. CONCLUSION AND FUTURE WORKS

The work in this article includes preliminary analyses on the design of wind-catcher for a courtyard on the 2nd floor of the engineering block in SQU. Two patterns of wind-catcher were designed to analyze the air flow distribution inside the courtyard. Cross-section dimension of the wind-catcher shaft was selected based on the previous studies and height was determined in random to abide by the laws. From the CFD analysis, the 2nd design provides adequate air flow in both front and rear side of the courtyard.

In this study, only predominant wind speed and direction was considered, but in reality, velocity varies with a vast range and also direction which should be taken into account for future analyses. Also the height of the wind-catcher has to be varied in future to see the performance, this might considerably reduce the cost. In this work, only CFD analyses were conducted but it is also necessary to perform structural analysis of the windcatcher which can be done using fluid-structural interaction (FSI) analysis.

The current size of the wind-catcher is ¼ of the size of the courtyard. In the most previous analyses, wind-catchers were attached to the roof-top but in this study, it was propagated to the floor. This design covers a large area and reduces the space for the occupants. Also on comparing with ASHRAE standard 62.1-2013, ventilation rate is minimum 100% times better than the required rate. Hence in future, the size of the cross-section of the shaft can be reduced. Though our work has a long way to proceed, we have designed the shape of the wind-catcher that can be used for semi-enclosed thin roof courtyard and also on the better distribution of air and avoid human beings to stand directly on the air jet.

REFERENCES

[1] M. Santamouris and D. Asimakopoulos, *Passive Cooling of Buildings*, Earthscan, 1996..

[2] T. Ibn-Mohammed, T. R. Greenough, S. Taylor, L. Ozawa-Meida, and A. Acquaye, "Integrating economic considerations with operational and embodied emissions into a decision support system for the optimal ranking of building retrofit options," *Build Environ*, vol. 72, pp. 82-101, 2014.

[3] C. H. Lim, O. Saadatian, K. Sopian, M. Y. Sulaiman, S. Mat, E. Salleh, and K. C. Ng, "Design configurations analysis of wind-induced natural ventilation tower in hot humid climate using computational fluid dynamics," *International Journal of Low-Carbon Technologies*, vol. 10, no. 4, pp. 332-346, 2015.

[4] H. F. Nouanégué, L. R. Alandji, and E. Bilgen, "Numerical study of solar-wind tower systems for ventilation of dwellings," *Renewable Energy*. vol. 33, no. 3, pp. 434-43, 2008.

[5] O. Saadatian, L. C. Haw, K. Sopian, and M. Y. Sulaiman, "Review of windcatcher technologies," *Renew Sustain Energy Rev*, vol. 16, pp. 1477-95, 2012.

[6] B. M. Jones and R. Kirby. "Quantifying the performance of a top–down natural ventilation Windcatcher™." *Building and Environment*, vol. 44.9, pp. 1925-1934, 2009.

[7] I. Chand, V. K. Sharma, and N. L. V. Krishak. "Studies on the design and performance of wind catchers," *Architectural Science Review*, Vol. 33.4, pp. 93-96, 1990.

[8] A. A. Elmualim, "Effect of damper and heat source on wind catcher natural ventilation performance," *Energy and Buildings*. vol. 38, no. 8, pp. 939-48, Aug 31 2006.

[9] A. A. Elmualim, "Dynamic modelling of a wind catcher/tower turret for natural ventilation," *Building Services Engineering Research and Technology*, vol. 27, no. 3, pp. 165-182, 2006.

[10] L. Li and C. M. Mak, "The assessment of the performance of a windcatcher system using computational fluid dynamics," *Building and Environment*, vol. 42, no. 3, pp. 1135-1141, 2007.

[11] Y. Su, S. B. Riffat, Y. L. Lin, and N. Khan, "Experimental and CFD study of ventilation flow rate of a Monodraught™ windcatcher," *Energy and Buildings*, vol. 40, no. 6, pp. 1110-1116, 2008.

[12] H. Montazeri, F. Montazeri, R. Azizian, and S. Mostafavi, "Two-sided wind catcher performance evaluation using experimental, numerical and analytical modeling," *Renewable Energy*, vol 35, no. 7, pp. 1424-1435, 2010.

[13] B. R. Hughes and M. Cheuk-Ming, "A study of wind and buoyancy driven flows through commercial wind towers," *Energy and Buildings*, vol. 43, no. 7, pp. 1784-1791, 2011.

[14] Y. Bouchahm, F. Bourbia, and A. Belhamri, "Performance analysis and improvement of the use of wind tower in hot dry climate," *Renewable Energy*, vol. 36, no. 3, pp. 898-906, 2011.

[15] H. Ahmadikia, A. Moradi, and M. Hojjati, «Performance analysis of a wind-catcher with water spray," *International Journal of Green Energy*, vol. 9, no. 2, pp. 160-173, 2012.

[16] S. M. Hosseinnia, H. Saffari, and M. A. Abdous, "Effects of different internal designs of traditional wind towers on their thermal behavior," *Energy and Buildings*, vol. 62, pp. 51-58, 2013.

[17] M. H. Ghadiri, N. L. N. Ibrahim, and M. F. Mohamed, "Performance evaluation of four-sided square wind catchers with different geometries by numerical method," *Engineering Journal*, vol. 17, no. 4, pp. 9-18, 2013.

[18] M. H. Ghadiri, N. Lukman, N. Ibrahim, and M. F. Mohamed, "Computational analysis of wind-driven natural ventilation in a two sided rectangular wind catcher," *International Journal of Ventilation*, vol. 12, no. 1, pp. 51-62, 2013.

[19] J. K. Calautit and B. R. Hughes, "Measurement and prediction of the indoor airflow in a room ventilated with a commercial wind tower," *Energy and Buildings*, vol. 84, pp. 367-377, 2014.

[20] J. K. Calautit, B. R. Hughes, and S. S. Shahzad, "CFD and wind tunnel study of the performance of a uni-directional wind catcher with heat transfer devices," *Renewable Energy*, vol. 83, pp. 85-99, 2015.

[21] M. Afshin, A. Sohankar, M. D. Manshadi, and M. K. Esfeh, "An experimental study on the evaluation of natural ventilation performance of a two-sided wind-catcher for various wind angles," *Renewable Energy*, vol. 85, pp. 1068-1078, 2016.

[22] T. Burton, D. Sharpe, N. Jenkins, and E. Bossanyi, *Wind Energy Handbook*, John Wiley & Sons, 2001.

[23] A. Y. Sultan, Y. Charabi, A. Gastli, and S. Al-Alawi, "Assessment of wind energy potential locations in Oman using data from existing weather stations," *Renewable and Sustainable Energy Reviews*, vol. 14, no. 5, pp. 1428-1436, 2010.

[24] P. J. Richards and R. P. Hoxey, "Appropriate boundary conditions for computational wind engineering models using the k-ϵ turbulence model," *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 46, pp. 145-153, 1993.

[25] B. Blocken, T. Stathopoulos, and J. Carmeliet, "CFD simulation of the atmospheric boundary layer: wall function problems" *Atmospheric environment*, vol. 41, no. 2, pp. 238-252, 2007.

[26] D. M. Hargreaves and N. G. Wright, "On the use of the k–ε model in commercial CFD software to model the neutral atmospheric boundary layer," *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 95, no. 5, pp. 355-369, 2007.

[27] ASHRAE, *ANSI/ASHRAE Standard 62.1-2013: Ventilation for Acceptable* Indoor *Air Quality*, Atlanta, ASHRAE, 2013.

Dr. Benkari is Architect and Urban planner. She holds a Ph.D. in urban planning, M.Sc. Architecture, B. Sc. Architecture. Her experience in teaching and practicing architecture and urban planning spreads over several years. Dr. Naima has published on topics such as Architecture education and curriculum Design, Sustainability in architecture and Urban Design curricula, built heritage preservation, architectural history, theory & criticism and the religious Architecture in the Arab and Islamic regions. She is a member of the ICOMOS and as a consultant for the Ministry of Heritage and Culture.