Investigate the Performance of the Windcatcher in Multi-story Buildings in Hot and Arid Climate by Using Computational Fluid Dynamics Simulation

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Abstract

In today's world, the importance of carbon and energy conservation is a common issue. Passive systems can be a promising alternative to reduce energy consumption and improve indoor air quality. One of the most common passive traditional strategy used in Egypt is windcatcher, which was used in single or double story buildings in the past to ventilate and cool the building in hot months. In this paper, the potentials of windcatchers as a strategy for passive cooling and natural ventilation during the summer months for multi-story building in Egypt is investigated, using computational fluid dynamics (CFD) technique. 3D CFD analysis is performed using Design Builder simulation software to compare the airflow pattern in three different cases; the first case is without a windcatcher, the second case is with a windcatcher on the windward side, and the last case is with two windcatchers one on the windward side and the other on the leeward side. The windcatcher model is incorporated into a 5m x 4m x 3m test room model. Thermal comfort analysis is evaluated based on ASHRAE standard 55. The result shows that the use of more than one windcatcher as an inlet and outlet can improve the thermal comfort and ventilation in the space.

Keywords: Windcatcher, natural ventilation, cooling, CFD, thermal comfort, passive cooling.

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التحقق من أداء مصائد الرياح في المباني متعددة الطوابق في المناخ الحار والجاف باستخدام محاكاة ديناميكيات السوائل الحسابية

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ملخص

في عالم اليوم، تعتبر أهمية الحفاظ على الكربون والطاقة قضية شائعة. يمكن أن تكون الأنظمة السلبية بديلاً واعدًا لتقليل استهلاك الطاقة وتحسين جودة الهواء الداخلي. واحدة من أكثر الإستراتيجيات التقليدية السلبية شيوعًا المستخدمة في مصر هي مصيدة الرياح، والتي كانت تستخدم في المباني من طابق واحد أو طابقين في الماضي لتهوية وتبريد المبنى في الأشهر الحارة. في هذه الورقة البحثية، تم التحقيق في إمكانات مصدات الرياح كاستراتيجية للتبريد السلبي والتهوية الطبيعية خلال أشهر الصيف للمباني متعددة الطوابق في مصر، باستخدام تقنية ديناميكيات السوائل الحسابية (CFD). يتم إجراء تحليل CFD ثلاثي الأبعاد باستخدام برنامج محاكاة DesignBuilder لمقارنة نمط تدفق الهواء في ثلاث حالات مختلفة؛ الحالة الأولى خالية من مصائد الرياح، والحالة الثانية بها مصدات الرياح على الجانب المواجه للريح، والحالة الأخيرة بها مصدات الرياح، أحدهما على الجانب المواجه للريح والآخر على الجانب المواجه للريح. تم دمج نموذج مصيدة الرياح في نموذج غرفة اختبار 5 م × 4 م × 3 م. يتم تقييم تحليل الراحة الحرارية على أساس معيار ASHRAE 55 . وتظهر النتيجة أن استخدام أكثر من مصاد الرياح كمدخل ومخرج يمكن أن يحسن الراحة الحرارية والتهوية في الفضاء.

الكلمات المفتاحية: مصدات الرياح، التهوية الطبيعية، التبريد، الراحة الحرارية، التبريد السلبي.

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1. Introduction

The energy demand worldwide is increasing at a rapid pace, as it is expected to increase by up to 50% from 2018 until 2050 (Mattoni et al., 2018). Buildings account for about 40% of the total energy consumption (Alrwashdeh, 2018a; Wang et al., 2014) and contribute to about 40% of the total world greenhouse gas emissions (Aflaki et al., 2015; Alrwashdeh, 2018b; Calautit & Hughes, 2014; Ibn-Mohammed et al., 2014; Lu & Lai, 2020). Generally, space heating, ventilation, and air conditioning (HVAC) systems consume almost two-thirds of the total building energy consumption (Chen et al., 2019; Chenari et al., 2016; Manzano-Agugliaro et al., 2015; Moosavi et al., 2014), which are mostly supplied by fossil resources (Hanif et al., 2014). Therefore, many researchers are looking to implement natural ventilation and passive cooling strategies as an energy-efficient alternative to reduce the building's energy demand. An example of a passive ventilation system is a windcatcher (Afshin et al., 2016; Hedayat et al., 2015). It is an eco-friendly and sustainable system which aims to combat the energy crisis, improve the thermal comfort inside the buildings and provide a good indoor air quality (IAQ) (Faggianelli et al., 2019). Other benefits of windcatcher are low maintenance cost due to the lack of moving parts (Bansal et al., 1986), and reducing greenhouse gases (GHGs) and air pollution (Gage & Graham, 2000).

Windcatcher has been employed in the traditional single and double story buildings in the Middle East and Egypt for many centuries to cool and ventilate buildings and improve the indoor thermal comfort (Ahmed Kabir et al., 2017; Chenari et al., 2016; Ionescu et al, 1996; Mehdi, 2014). Malqaf is the Egyptian word for wind catchers. The Egyptians used it in the construction of Tal Al-Amarna and the Pharaoh residences of the Nineteenth Dynasty in Neb-Amun (1300 B.C.). Nonetheless, Egyptian design has neglected the malqaf for the past 50 years, or more accurately, has been unable to incorporate this passive system into the modern city, resulting in more than half of the urban energy consumption in Egyptian cities being used to meet air conditioning demands (Eghtedari & Mahravan, 2021).

It provides natural ventilation due to two main effects: the wind effect and the stack effect.

The key driving force is the wind effect which is due to the difference in pressure on the windward and leeward sides of the windcatcher. The wind enters from the windward side of the windcatcher and through convective and evaporative heat transfer, removes the heat from the occupants and therefore results in cooling.

The significance of wind pressure increases with increasing wind speed. In the absence of wind, the driving force in the tower is the stack effect, which results from the differences in indoor and outdoor air temperature, as the hot and dense air moves upward, and cold and high dense air moves downward (Jones & Kirby, 2009; Nouanégué et al., 2008; Saadatian et al., 2012).

Many research studies have investigated the effects of various windcatcher configurations and components design on its performance using numerical, experimental, and theoretical methods (Alrwashdeh et al., 2018a; Alrwashdeh et al., 2016; Dehghan et al.,2013; Hughes & Ghani, 2011; Hughes & Ghani, 2010; Zendehboudi et al., 2014). The experimental studies of windcatcher systems are limited, as they are costly and time-consuming (Jones & Whittle, 1992). However, the simulation method is nowadays considering a promising tool (Al-Falahat et al., 2019a; Al-Falahat et al., 2019b), a numerical method using computational fluid dynamics (CFD) has recently been widely used to study airflow in and around buildings (Chow, 1996; Jones & Whittle, 1992; Li & Mak, 2007; Niu & van der Kooi, 1992), since it can provide detailed airflow velocity distribution and thermal conditions (Li & Mak, 2007). Moreover, it has been approved that CFD is a reliable tool for natural ventilation behavior analysis in buildings (Li & Mak, 2007).

In few research, DesignBuilder simulation software was used to conduct CFD analysis to study the effect of the windcatcher on improving the natural ventilation and thermal comfort (Eghtedari & Mahravan, 2021; Saif et al., 2021). For example; they used Designbuilder simulation software to assess that the wind catcher could Improve the indoor thermal comfort in educational buildings in Kuwait (Saif et al., 2021).

Bouchahm investigated the thermal performance of a one-sided windcatchersystem integrated into a bioclimatic housing located in a hot and arid region. Performance monitoring and site measurement provided data which assisted the numerical model validation. The analytical model was validated against the experimental measurements and a good agreement between the results was observed. Bouchahm’s research concluded that windcatcherscan provide fresh air and enhance the indoor thermal comfort regardless of the extreme external conditions. The work demonstrated the significance of windcatchers and their potential to reduce the energy demand, and they confirm the advantage of the application of this passive cooling strategy in hot dry climate (Bouchahm et al., 2011).

Hughes and Cheuk-Ming used CFD modelling to investigate the relation between the two driving forces, the wind pressure and buoyancy-driven flow through a four-sided windcatcher. The CFD results demonstrated that the main driving force is the external driving wind, providing 76% more indoor ventilation than buoyancy-driven flow (Hughes & Cheuk-Ming, 2011).

Montazeri et al. used analytical and CFD modelling to evaluate the effect of the windcatcher on the ventilation performance and the reliability of the experimental results. The work demonstrated the potential of multi-directional windcatcher for improving the indoor ventilation in the residential buildings. Furthermore, a good agreement between the experiment and CFD analysis was observed (Montazeri et al., 2010).

In this research, the potential of windcatchers as a passive cooling system during the summer season for multi-story building in the hot and arid climate has been investigated using Computational Fluid Dynamics (CFD) analysis.

1. Methodology

The study has been carried out in three parts. The first part aims to identify the thermal comfort band in a free-running building for Egypt's climate using an adaptive thermal comfort equation which will be described in the next section. The second part included an analysis of the existing windcatcher design in Egypt, to determine the main design parameters of the proposed windcatcher. The last part is to build a test model using the design-builder software for a single room in a multi-story residential building and analyzing the Computational fluid dynamics (CFD) simulation results to compare the airflow pattern and the cooling effect in three different cases: without a windcatcher, with one windcatcher, with two windcatchers.

Adaptive Thermal Comfort Temperature for Egypt Climate

The main purpose of using a windcatcher is to remove heat from the building by natural ventilation, which led to a decrease in the temperature and moves it towards the comfort zone. Figure , shows the comfort zone has been estimated by using the adaptive thermal comfort equation for free-running buildings which is developed by De Dear and Brager incorporated with ASHRAE (American Society of Heating & Air-Conditioning, 1997).

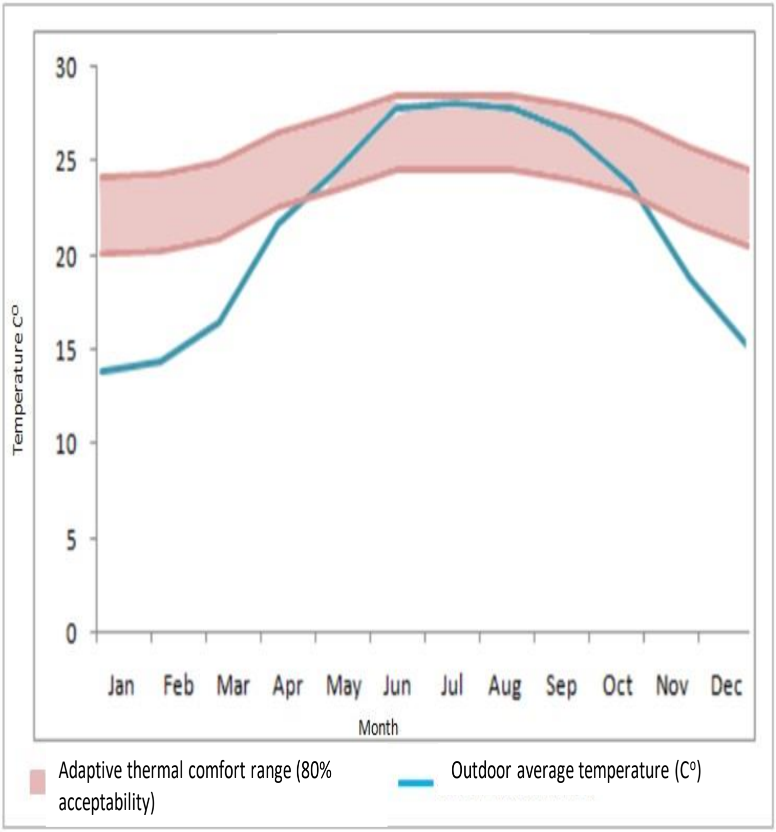


Figure (1) Adaptive thermal comfort zone and outdoor average temperature in Egypt, Cairo (Eid et al., 2019).

Windcatcher Design Parameters

Different factors affect the windcatcher design parameters such as wind speed and direction in the region, building dimensions and material, the activity inside the building, etc. (Hughes et al., 2012). Some of these parameters are position and orientation of the windcatcher, inlet cross-section and shape, shaft cross-section and height, outlet opening (Asfour & Gadi, 2006; Hughes et al., 2012), which are going to be discussed in this section.

Orientation

The typical orientation of the windcatcher opening is facing the prevailing winds to allow maximum airspeed and cross ventilation (American Society of Heating & Air-Conditioning, 1997); therefore, it is important to analysis the wind speed and direction on site. As illustrated in figure 2, the average wind speed in Cairo is around 4 m/s, and the prevailing wind blows from the north direction and only two months in winter the wind blows from the south direction(Attia & Herde, 2009; Dehghani-sanij, Soltani, & Raahemifar, 2015). Thus, in most cases in Egypt, the windcatchers are oriented towards the north (Attia & Herde, 2009).

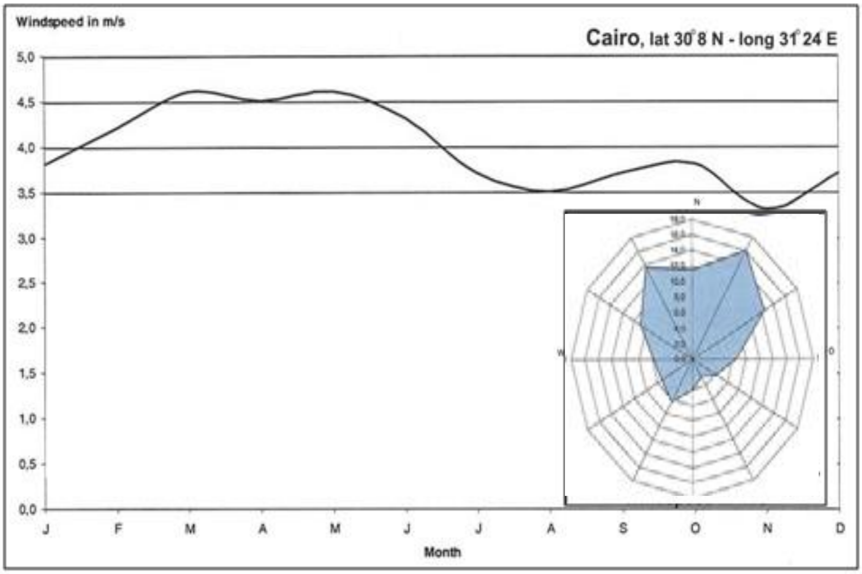


Figure 1: Average annual wind speed and direction in percentage (Attia & Herde, 2009).

Inlet Cross Section and Shape

In traditional buildings in Egypt, the top of the windcatcher is designed to be inclined from 30° to 45°, also it is found that the area of the inlet cross-section is at least equal to the shaft cross-section area (Dehghani-sanij et al., 2015).

Shaft Cross Section and Height

The shaft height and area are other factors affecting the windcatcher efficiency where performances of octagonal windcatchers are weaker than square and rectangular ones (Chan et al., 2010). In most traditional buildings in Egypt, it is found that the shaft form is square or rectangular, and its cross-sectional area is around 3% of the ventilated space floor area. Moreover, the windcatcher relative height must be at least one story above roof height (Dehghani-sanij et al., 2015; Elmualim & Awbi, 2002).

Test Model

A simple reference test model, representing an individual single-space in a multi-story residential building in Egypt was modelled using DesignBuilder software. The model was designed to be three-story, each story contains a test room with dimensions of 5m x 4m and 3m height, each room has two openings in the middle of the north and south walls and considered the existence of obstruction buildings surrounded the building, as the building is located within the urban context. Then, based on the reference test model, three different cases were tested to investigate the effect of the windcatchers for cooling and ventilation through analyzing the computational fluid dynamics simulation results and determine the ideal case in the context for achieving thermal comfort.

The studied cases as presented in both Figure and Figure as:

- Case 1 represents the current situation of the residential building in Egypt without using a windcatcher.
- Case 2 investigated the effect of placing one windcatcher in facing the prevailing wind.
- Case 3, two windcatchers in different directions, one on the windward and the other in leeward.

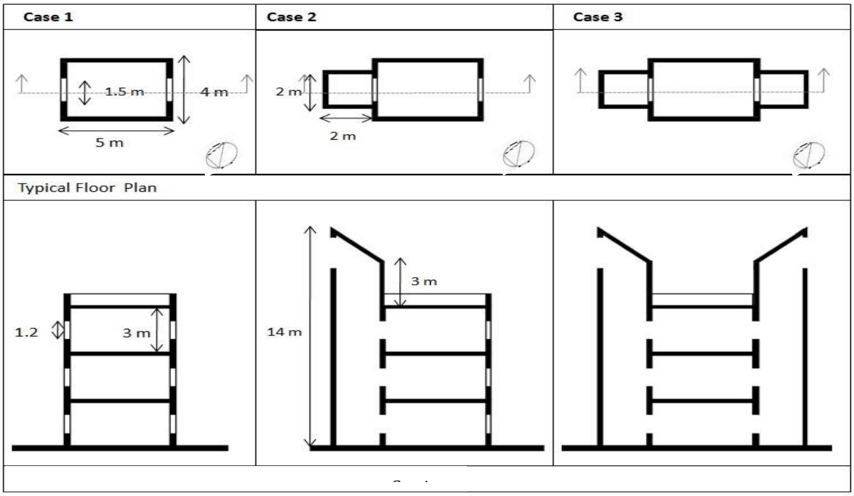


Figure (3) Plans and sections for the proposed cases.

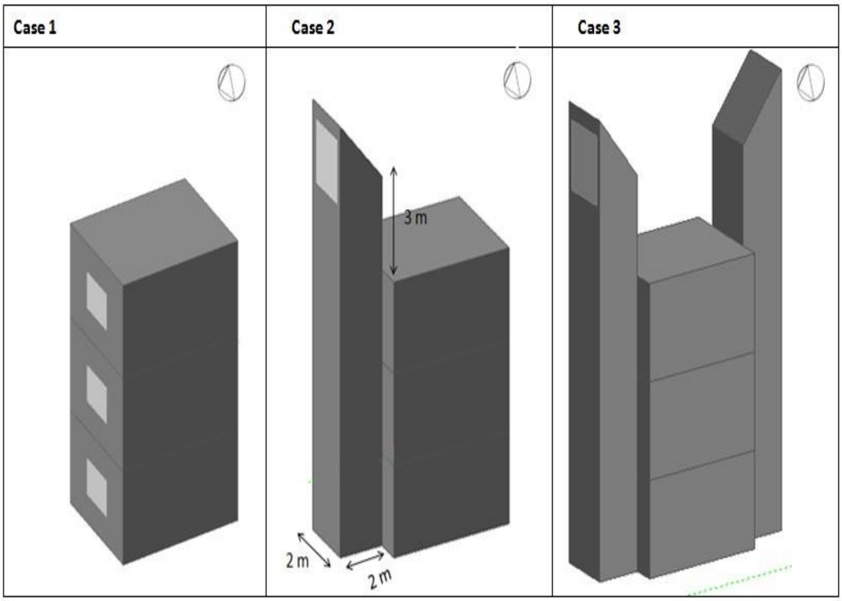


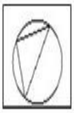
Figure (4) the perspective view for the proposed cases

Results and Discussion:

In the first case where no windcatcheris used the air blows from the north direction, then enters from the north openings and passes through the space and exits from south windows as shown in Figure 5.

The simulation results show that the operative temperature in 15 of the July range from 32 C^{O} in the ground floor to 32.6 C^{O} in the second floor, which is the equal or higher than the outdoor temperature at the same time.

First case (reference case)



simulation time :15 July 12:00 pm

Prevailing wind direction : North

Prevailing wind Speed : 3.5 m/s

Outdoor dry temperature :32 C^{O}

	Airflow In (m^3/s) (north openings)	Wind speed (m/s)	Operative temperature (C^{O})
Wind catcher	-	-	-
Ground floor	0.57	0.77	32.0
First floor	0.50	0.88	32.4
Second floor	0.40	0.97	32.6

Velocity	0.00	0.09	0.18	0.26	0.35	0.44	0.53	0.61	0.70	0.79	0.88	0.97	(m/s)
Temperature	30.06	30.24	30.42	30.60	30.79	30.97	31.15	31.33	31.51	31.70	31.88	32.06	(C)

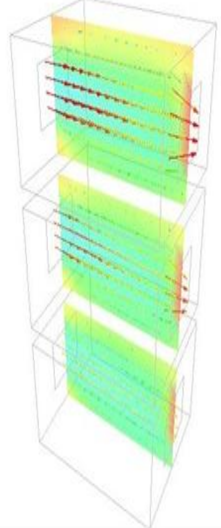


Figure (5) CFD simulation results for the first case

In the second case where the windcatcher is placed on one side and faces the north direction, the air enters the shaft, then it is directed down, due to the pressure difference between the inlet and outlet, next it enters the space and exit through the south openings. The airflow to the ground floor is higher than the other floors this is due to the higher difference in the pressure, Which led to decrease the temperature in the ground floor more than the upper floor, with about 0.4 CO and 0.2 CO, respectively less than in the reference case (no windcatcher), see Figure 6. The windcatcher help to improve the indoor comfort, however, the operative temperature still out of the adaptive comfort zone.

Second case

simulation time :15 July 12:00 pm

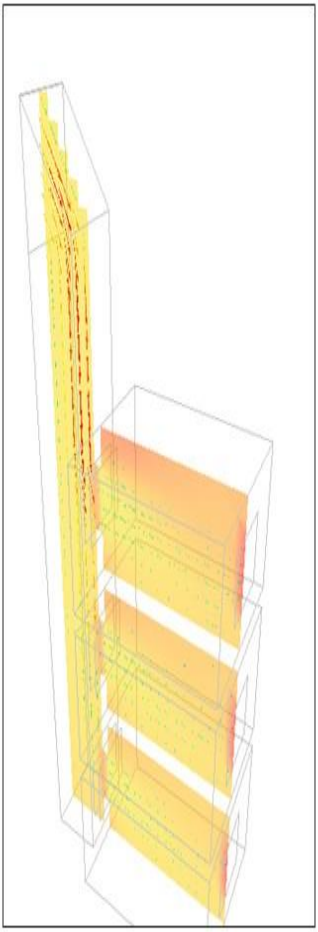
Prevailing wind direction : North

Prevailing wind Speed : 3.5 m/s

Outdoor dry temperature :32 C^O

	Airflow In (m^3/s) (north openings)	Wind speed (m/s)	Operative temperature (C^O)
Wind catcher	0.52 -0.1	0.79	
Ground floor	0.16	0.35	31.6
First floor	0.14	0.55	32.1
Second floor	0.12	0.69	32.4

Velocity	0.00	0.07	0.14	0.21	0.28	0.35	0.41	0.48	0.55	0.62	0.69	0.76 (m/s)
Temperature	26.81	27.30	27.80	28.29	28.78	29.27	29.77	30.26	30.75	31.25	31.74	32.23 (C)

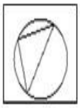


Figure(6) CFD simulation results for the second case.

In the last case, two windcatchers are installed: one on the windward side and the other on the leeward side. As observed in Figure 7, the airflow passed through the windcatcher, and then enter the space through the pressure difference, after entering the space the wind decelerates, and accelerated again at the end of space, and direct it up due to the stack effect to exit through the leeward windcatcher.

The operative temprture decrease 0.6-0.8 C^{o} in comparison to the Reference case. Moreover, this case is the most effective case among the proposed cases. The temperature decreased more than when one catcher used this due to both wind effect and stuck effect, which improve the air movement in the space, accordingly improve the indoor comfort.

Third case (reference case)



simulation time :15 July 12:00 pm
Prevailing wind direction : North
Prevailing wind Speed : 3.5 m/s
Outdoor dry temperature :32 C^{O}

	Airflow In (m^3/s) (north openings)	Wind speed in north space openings (m/s)	Operative temperature (C^{O})
North Wind catcher	0.4 -0.1	0.8	
South Wind catcher	0.1 -0.4		
Ground floor	0.1	0.44	31.2
First floor	0.097	0.51	31.7
Second floor	0.09	0.66	32.0

Velocity	0.00	0.04	0.08	0.12	0.16	0.20	0.24	0.28	0.31	0.35	0.39	0.43	(m/s)
Temperature	29.90	30.35	30.81	31.26	31.72	32.17	32.63	33.08	33.54	33.99	34.44	34.90	(C)

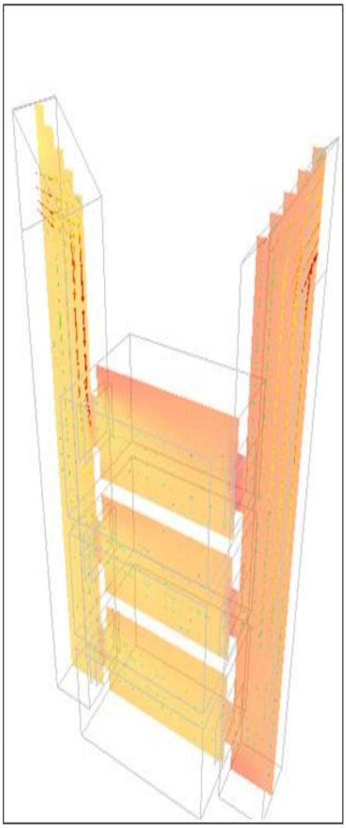


Figure (7) CFD simulation results in the third case

The results confirm that the best way among the previous cases to decrease the indoor temperature and enhances the ventilation in the space is through using more the one windcatcher. As illustrated in Figure 8, the indoor temperature is exceeding the comfort temperature. However, the results confirm that the indoor temperature in case 3 is lower than case 1 by about 1-2 C^o in the summer months.

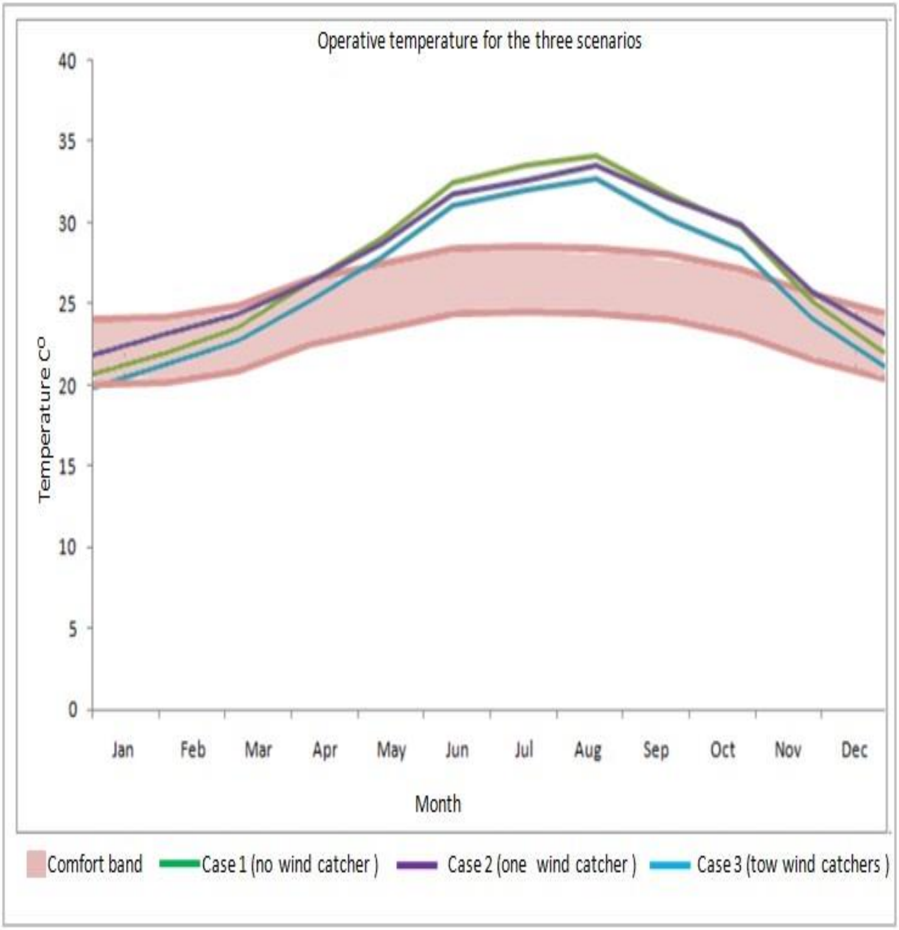


Figure (8) Adaptive thermal comfort temperature and the operative temperature for the studied cases

Conclusions and Recommendations:

This paper has investigated the ability of the windcatcher to decrease the temperature in summer months in multi-story residential building, and it proofed that the windcatcher can be integrated into the multi-story buildings to improve the indoor comfort, also it shows that both wind and stack effects in the windcatcher are important to improve indoor comfort. However, this study was conducted in a single space. Therefore, in future works, it is recommended to see the effect of integrating windcatcher in more than one space with different parameters. Another recommendation for future study is to study the effect of integrating windcatcher with other strategies such as evaporative cooling, thermal mass, solar chimney to improve the thermal and ventilation performance.

References:

Aflaki, A., Mahyuddin, N., Al-Cheikh Mahmoud, Z., & Baharum, M. R. (2015). A review on natural ventilation applications through building façade components and ventilation openings in tropical climates. ENB Energy & Buildings, 101, 153-162.

Afshin, M., Sohankar, A., Manshadi, M. D., & Esfeh, M. K. (2016). An experimental study on the evaluation of natural ventilation performance of a two-sided wind-catcher for various wind angles. Renewable energy., 85, 1068-1078.

Ahmed Kabir, I. F. S., Kanagalingam, S., Safiyullah, F., st Joint Conference on World Engineers Summit - Applied Energy, S., Forum: Low Carbon, C., & Urban Energy, W.-C. (2017). Performance evaluation of air flow and thermal comfort in the room with Wind-Catcher using different CFD techniques under neutral Atmospheric Boundary Layer. Energy Procedia Energy Procedia, 143, 199-203.

Al-Falahat, A. M., Kardjilov, N., Khanh, T. V., Markötter, H., Boin, M., Woracek, R., . . . Manke, I. (2019). Energy-selective neutron imaging by exploiting wavelength gradients of double crystal monochromatorsSimulations and experiments. NIMA Nuclear Inst. and Methods in Physics Research, A, 943, 2019-2011.

Al-Falahat, A. M., Kupsch, A., Hentschel, M. P., Lange, A., Kardjilov, N., Markötter, H., & Manke, I. (2019). Correction approach of detector backlighting in radiography. The Review of scientific instruments, 90(12).

Alrwashdeh, S. S. (2018a). Assessment of photovoltaic energy production at different locations in Jordan. International Journal of Renewable Energy Research, 8(2), 797-804.

Alrwashdeh, S. S. (2018b). Modelling of operating conditions of conduction heat transfer mode using energy 2D simulation. International Journal of Online Engineering, 14(9), 200-207. doi:10.3991/ijoe.v14i09.9116

Alrwashdeh, S. S., Alsaraireh, F. M., Saraireh, M. A., Markötter, H., Kardjilov, N., Klages, M., . . . Manke, I. (2018). In-situ investigation of water distribution in polymer electrolyte membrane fuel cells using high-resolution neutron tomography with 6.5 µm pixel size. AIMS Energy, 6(4), 607-614. doi:10.3934/energy.2018.4.607

Alrwashdeh, S. S., Markötter, H., Haußmann, J., Scholta, J., Hilger, A., & Manke, I. (2016). X-ray tomographic investigation of water distribution in polymer electrolyte membrane fuel cells with different gas diffusion media. Paper presented at the ECS Transactions.

American Society of Heating, R., & Air-Conditioning, E. (1997). 1997 ASHRAE handbook : Fundamentals. Atlanta, GA: ASHRAE.

Asfour, O. S., & Gadi, M. B. (2006). Effect of Integrating Wind Catchers with Curved Roofs on Natural Ventilation Performance in Buildings. Architectural Engineering and Design Management, 2(4), 289-304. doi:10.1080/17452007.2006.9684623

Attia, S., & Herde, A. (2009). Designing the Malqaf for Summer Cooling in Low-Rise Housing, an Experimental Study.

Bansal, N. K., Mathur, R., & Bhandari, M. S. (1994). A study of solar chimney assisted wind tower system for natural ventilation in buildings. Building and Environment, 29(4), 495-500. doi:https://doi.org/10.1016/0360-1323(94)90008-6

Bouchahm, Y., Bourbia, F., & Belhamri, A. (2011). Performance analysis and improvement of the use of wind tower in hot dry climate. Renewable Energy, 36(3), 898-906. doi:10.1016/j.renene.2010.08.030

Calautit, J. K., & Hughes, B. R. (2014). Wind tunnel and CFD study of the natural ventilation performance ofa commercial multi-directional wind tower. Build. Environ. Building and Environment, 80, 71-83.

Chan, H.-Y., Riffat, S. B., & Zhu, J. (2010). Review of passive solar heating and cooling technologies. Renewable and Sustainable Energy Reviews, 14(2), 781-789. doi:https://doi.org/10.1016/j.rser.2009.10.030

Chen, Y., Tong, Z., Wu, W., Samuelson, H., Malkawi, A., & Norford, L. (2019). Achieving natural ventilation potential in practice: Control schemes and levels of automation. APEN Applied Energy, 235, 1141-1152.

Chenari, B., Dias Carrilho, J., & Gameiro da Silva, M. (2016). Towards sustainable, energy-efficient and healthy ventilation strategies in buildings: A review. Renewable & sustainable energy reviews, 59, 1426-1447.

Chow, W. K. (1996). Application of Computational Fluid Dynamics in building services engineering. Building and Environment, 31(5), 425-436. doi:https://doi.org/10.1016/0360-1323(96)00012-1

Dehghan, A. A., Esfeh, M. K., & Manshadi, M. D. (2013). Natural ventilation characteristics of one-sided wind catchers: experimental and analytical evaluation. Energy and Buildings, 61, 366-377. doi:https://doi.org/10.1016/j.enbuild.2013.02.048

Dehghani-sanij, A. R., Soltani, M., & Raahemifar, K. (2015). A new design of wind tower for passive ventilation in buildings to reduce energy consumption in windy regions. Renewable and Sustainable Energy Reviews, 42, 182-195. doi:https://doi.org/10.1016/j.rser.2014.10.018

Eghtedari, M., & Mahravan, A. (2021). Evaluation a Hybrid Passive Cooling System for a Building Using Experimental and Commercial Software (Design Builder).

Eid, M., Gad, E., & Abdel Basset, H. (2019). Temperature Analysis over Egypt. Al-Azhar Bulletin of Science, 30(2), 13-30. doi:10.21608/absb.2019.86755

Elmualim, A., & Awbi, H. B. (2002). Wind Tunnel and CFD Investigation of the Performance of “Windcatcher” Ventilation Systems. International Journal of Ventilation, 1, 53-64. doi:10.1080/14733315.2002.11683622

Faggianelli, G. A., Brun, A., Wurtz, E., & Muselli, M. (2014). Natural cross ventilation in buildings on Mediterranean coastal zones. ENB Energy & Buildings, 77, 206-218.

Gage, & Graham. (2000). Static split duct roof ventilators. Building Research and Information, 28(4), 234-244.

Hanif, M., Mahlia, T. M. I., Zare, A., Saksahdan, T. J., & Metselaar, H. S. C. (2014). Potential energy savings by radiative cooling system for a building in tropical climate. Renewable Sustainable Energy Rev Renewable and Sustainable Energy Reviews, 32, 642-650.

Hedayat, Z., Belmans, B., Hossein Ayatollahi, M., Wouters, I., & Descamps, F. (2015). Performance Assessment of Ancient Wind Catchers - an Experimental and Analytical Study. Energy Procedia, 78, 2578-2583. doi:https://doi.org/10.1016/j.egypro.2015.11.292

Hughes, B. R., Calautit, J. K., & Ghani, S. A. (2012). The development of commercial wind towers for natural ventilation: A review. Applied Energy, 92, 606-627. doi:https://doi.org/10.1016/j.apenergy.2011.11.066

Hughes, B. R., & Cheuk-Ming, M. (2011). A study of wind and buoyancy driven flows through commercial wind towers. Energy and Buildings, 43(7), 1784-1791. doi:10.1016/j.enbuild.2011.03.022

Hughes, B. R., & Ghani, S. A. (2011). A numerical investigation into the feasibility of a passive-assisted natural ventilation stack device. International Journal of Sustainable Energy, 30(4), 193-211.

Hughes, B. R., & Ghani, S. A. A. A. (2010). A numerical investigation into the effect of Windvent louvre external angle on passive stack ventilation performance. Building and Environment, 45(4), 1025-1036. doi:https://doi.org/10.1016/j.buildenv.2009.10.010

Ibn-Mohammed, T., Greenough, R., Taylor, S., Ozawa-Meida, L., & Acquaye, A. (2014). Integrating economic considerations with operational and embodied emissions into a decision support system for the optimal ranking of building retrofit options. Building and Environment Building and Environment, 72, 82-101.

Ionescu, C., Baracu, T., Vlad, G.-E., Necula, H., & Badea, A. (2015). The historical evolution of the energy efficient buildings. Renewable and Sustainable Energy Reviews, 49, 243-253. doi:https://doi.org/10.1016/j.rser.2015.04.062

Jones, B. M., & Kirby, R. (2009). Quantifying the performance of a top-down natural ventilation Windcatcher. BAE Building and Environment, 44(9), 1925-1934.

Jones, P. J., & Whittle, G. E. (1992). Computational fluid dynamics for building air flow prediction—current status and capabilities. Building and Environment, 27(3), 321-338. doi:https://doi.org/10.1016/0360-1323(92)90033-L

Li, L., & Mak, C. M. (2007). The assessment of the performance of a windcatcher system using computational fluid dynamics. Building and Environment Building and Environment, 42(3), 1135-1141.

Lu, M., & Lai, J. (2020). Review on carbon emissions of commercial buildings. RSER Renewable and Sustainable Energy Reviews, 119.

Mahyari, A. (1996). The wind catcher : a passive cooling device for hot arid climate. Available from http://worldcat.org /z-wcorg/ database.

Manzano-Agugliaro, F., Montoya, F. G., Sabio-Ortega, A., & García-Cruz, A. (2015). Review of bioclimatic architecture strategies for achieving thermal comfort. Renewable and Sustainable Energy Reviews Renewable and Sustainable Energy Reviews, 49, 736-755.

Mattoni, B., Guattari, C., Evangelisti, L., Bisegna, F., Gori, P., & Asdrubali, F. (2018). Critical review and methodological approach to evaluate the differences among international green building rating tools. RSER Renewable and Sustainable Energy Reviews, 82, 950-960.

Mehdi, N. B. (2014). Wind Towers : Architecture.

Montazeri, H., Montazeri, F., Azizian, R., & Mostafavi, S. (2010). Two-sided wind catcher performance evaluation using experimental, numerical and analytical modeling. Renewable Energy, 35(7), 1424-1435. doi:https://doi.org/10.1016/j.renene.2009.12.003

Moosavi, L., Mahyuddin, N., Ab Ghafar, N., & Azzam Ismail, M. (2014). Thermal performance of atria: An overview of natural ventilation effective designs. RSER Renewable and Sustainable Energy Reviews, 34, 654-670.

Niu, J., & van der Kooi, J. (1992). Two-dimensional simulation of airflow and thermal comfort in a room with open-window and indoor cooling systems. Energy and Buildings, 18(1), 65-75. doi:https://doi.org/10.1016/0378-7788(92)90053-J

Nouanégué, H. F., Alandji, L. R., & Bilgen, E. (2008). Numerical study of solar-wind tower systems for ventilation of dwellings. Renewable Energy Renewable Energy, 33(3), 434-443.

Pan, W., Liu, S., Li, S., Cheng, X., Zhang, H., Long, Z., . . . Chen, Q. (2019). A model for calculating single-sided natural ventilation rate in an urban residential apartment. Building and environment., 147, 372-381.

Saadatian, O., Haw, L. C., Sopian, K., & Sulaiman, M. Y. (2012). Review of windcatcher technologies. RSER Renewable and Sustainable Energy Reviews, 16(3), 1477-1495.

Saif, J., Wright, A., Khattak, S., & Elfadli, K. (2021). Keeping Cool in the Desert: Using Wind Catchers for Improved Thermal Comfort and Indoor Air Quality at Half the Energy. Buildings, 11(3). doi:10.3390/buildings11030100

Wang, T., Foliente, G., Song, X., Xue, J., & Fang, D. (2014). Implications and future direction of greenhouse gas emission mitigation policies in the building sector of China. Renewable & sustainable energy reviews, 31, 520-530.

Zendehboudi, A., Zendehboudi, A., Hashemi, R., & Zendehboudi, A. (2014). An investigate on the performance of one-sided and four-sided windcatchers in the southwest of IRAN. Int. J. u e Serv. Sci. Technol. International Journal of u- and e- Service, Science and Technology, 7(4), 73-84.