# Simulation of the effect of windcatchers on air quality inside courtyards

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**Abstract.** The courtyard is an essential traditional building element for sustainable construction in hot arid areas. However, there are some limitations in using it for future sustainable buildings. One of these is air quality, where previous research indicates that the courtyard provides thermal comfort to its residents by generating a microclimate that isolates the courtyard from external air, but this can reduce the building's ventilation potential. Traditional houses in the Middle East use windcatchers as a solution to this problem. This paper shows the results of a numerical simulation of a courtyard with windcatchers in traditional houses. The results indicate that windcatchers can provide enough fresh air for ventilation. It can also reduce the outdoor air temperature by using the thermal mass of the windcatcher wall and earth cooling, but will not provide low enough temperatures to maintain the microclimate, which suggests the need for more research in this field.

**Keywords**. Windcatcher, CFD, Traditional houses.
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## 1. Background

The courtyard house is the traditional form of housing in the Middle East and has been subject to much research in thermal comfort and building energy. Much of this research concludes that a house with a deep courtyard will have a microclimate with a better thermal environment than outdoors for the house's residents [1–3]. However, the work of Hall et al [1] shows that a deep courtyard will have the highest concentration of pollution, as shown through practical measurement in a wind tunnel. Furthermore, traditional houses in the Middle East are usually built-in dense cities and are next to a narrow alleyway where air quality is unsatisfactory. In addition, the house's windows overlooking the outside are few or non-existent [4, 5]. Also, the courtyard is usually covered to reduce the solar irradiation on the courtyard as shown in the book of Reynolds [6] which further isolates the courtyard.

Thus, we need to increase the outdoor airflow toward the courtyard by using a windcatcher. The windcatcher (also called a wind tower, badgeers or malkafs) can be defined as a "*structure built onto the roofs of buildings with open vents at their head facing in the direction of the cooler prevailing wind. Air caught in the vent is channelled down through a shaft in the building into the room below which are cooled ventilated*" [7]. A windcatcher's function is inducing airflow and cooling the air passing through the windcatcher by passive means such as thermal mass and earth cooling (geothermal cooling). The shape of a windcatcher is shown in Figure (1) where the windcatchers in Baghdad (Iraq) are usually short and have a lower external surface area to reduce exposure to solar radiation. The dimensions of a windcatcher as given in references are shown in Table (1) where the height of a wind catcher is around the height of the external parapet with dimensions (L x D) as shown in Figure (1) for section equal to (1 x 0.4 m) and has a section with a rectangular shape, which is common in Baghdad [8]. The windcatchers in Figure (1) have only one opening directed towards the predominant wind [9].

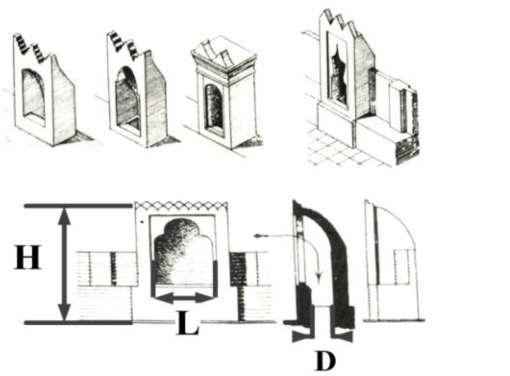



**Fig 1**- Various windcatcher designs from [4], the notation for dimensions is from Table (1)

**Tab 1-** Review for the dimensions of a windcatcher

| Reference | Height (over the roof) (m) | Depth (D)(m) | Length(L) (m) |
|---|---|---|---|
| [9] | 1.5 ~ 2.5 | | |
| [10] | | 0.2 | 1 |
| [4] | To the highest point of an external parapet | 0.15~0.2 | 0.5 |
| [8] | 2 | 0.3~0.4 | 1 |

Furthermore, to take advantage of earth cooling (geothermal cooling), the windcatcher guides the air from the top of the tower to the basement, so it is cooled by geothermal cooling and is then expelled into the courtyard. In this case, the ground is used as a heat sink, and it must have a sufficient difference in temperature between the earth and the ambient air above it.

This paper will focus on the windcatcher's role in enhancing the air quality inside the courtyard house and its effect on its thermal condition. We used Computational Fluid Dynamics (CFD) for the numerical simulation because it is less expensive than a full-scale model and gives satisfactory results and high-resolution details compared with other numerical models.

## 2. Methodology

In this paper, we simulated the pollutants through calculating the concentration of gas carbon dioxide ($CO_2$). The concentration of $CO_2$ gas was used as an indicator for the air quality because it is a by-product of the house residents' respiration. Furthermore, $CO_2$ gas cannot be filtered or absorbed (like an odour or emissions), and it will affect human health if its concentration exceeds a specific limit. The accepted limits for $CO_2$ in indoor air ranges are 3500-5000 ppm [11], also in the book of Awbi [12] explains that for cases that include an extended stay (i.e. several hours), a concentration less than 1000 ppm is preferable to avoid discomfort and headaches.

The concentration of $CO_2$ inside the courtyard was predicted using CFD software STAR CCM+. It models the flow in and around the courtyard, and the airflow was modelled as turbulent flow using Renolds Averaged Navier Stokes (RANS) model, with a two-layer realizable $k$-$\varepsilon$ model. The radiation effect is included to show the impact of solar radiation. The air is treated as a non-participating medium in radiation transfer due to the air's low emissivity in dry weather. CFD is used to calculate the flow by dividing the domain into cells and solving the Navier-Stokes equations (conservation of momentum), the continuity equation (conservation of mass), the energy equation (conservation of energy); the initial and boundary conditions are listed in Table (2). Extra transport equations need to be solved for simulations that examine the air quality by finding the concentration of $CO_2$. Air quality was represented through the concentration of $CO_2$. It is emitted during the process of respiration. A source point is used to release gas in the same quantity as a human, with a density of occupants in the courtyard equal to 1 person /$m^2$ [13]. The software measures the $CO_2$ released during the simulation, not the ambient $CO_2$ (whose concentration depends on the area's pollution levels). All the drawings show the concentration of $CO_2$ release only. The computational model is set according the recommendations from guide book of Franke et al [14] and as shown in Figure (2). The geothermal cooling effect on the windcatcher was simulated by setting the soil temperature using the following equation from [15]

$$T(z,t) = T_{avg} + T_{amp}\exp(-z * G_c) * \cos(\frac{2\pi t}{365} - z\, G_c - 1.02\pi)$$

here $z$ (m) is the depth below the surface, and $t$ is time in days beginning from 1st Jan; $T_{avg}$ is the average soil temperature (25 °C), $T_{amp}$ is the annual amplitude of surface soil temperature (22 °C) and $G_c$ is a coefficient that depends on the thermal diffusivity for the sand and the time cycle (0.83 (1/m). This equation will be used to determine the temperature in the soil which is in contact with the windcatcher. The computational domain is extended by only 1 m. This limited thickness was chosen because the heatwave inside soil tends to be stored in the ground surface rather than penetrating it. The simulations were done on three houses with different courtyard ratios between height to width (Aspect Ratio); the ratios used are AR4, AR2, AR 1.

The mesh used is an unstructured, polyhedral mesh with a prism layer and local refinements for a specific region. The number of grids reaches over a million. The accuracy of the solution was compared with published works of other researchers, as shown in Figure (3) where the model has well predicted the velocity distribution within the courtyard.

**Table 2-**The boundaries and parameters of the simulation.

| | |
|---|---|
| Walls, roof, floor | Brick with thermal conductivity = 0.69 W $K^{-1}m^{-1}$, specific heat = 840 J $kg^{-1}$ $K^{-1}$, density= 1600 kg m-3, thickness =0.2 m, emissivity = 0.8 and reflectivity =0.2. All the external surfaces are insulated by extruded polystyrene with thermal conductivity = 0.032 W $K^{-1}m^{-1}$ and reflectivity =1.0 |
| Initial conditions | Room air temperature =300 K, outside air temperature =313 K, Walls's temperature = 300 K |
| Boundary conditions | Wind speed at 10m from ground = 5 m $s^{-1}$ , the air velocity, turbulent dissipation and kinetic energy for the boundaries of CFD domain. Velocity inlet and pressure outlet, are set using equation from [16] |
| Time step and total time | 3 seconds and continues for 3600 s |
| Date and time | Summer solstice day 21 Jun 2012, 12 PM |
| Place of the simulation | Baghdad city, Latitude 33.3° and longitude 44.3° |
| Soil | $\rho = 1470(\text{kg m}^{-2})$ , $k = 1.7(\text{W m}^{-1}\text{K}^{-1})$and $Cp = 1000(J\ kg^{-1}K^{-1})$ [17] |

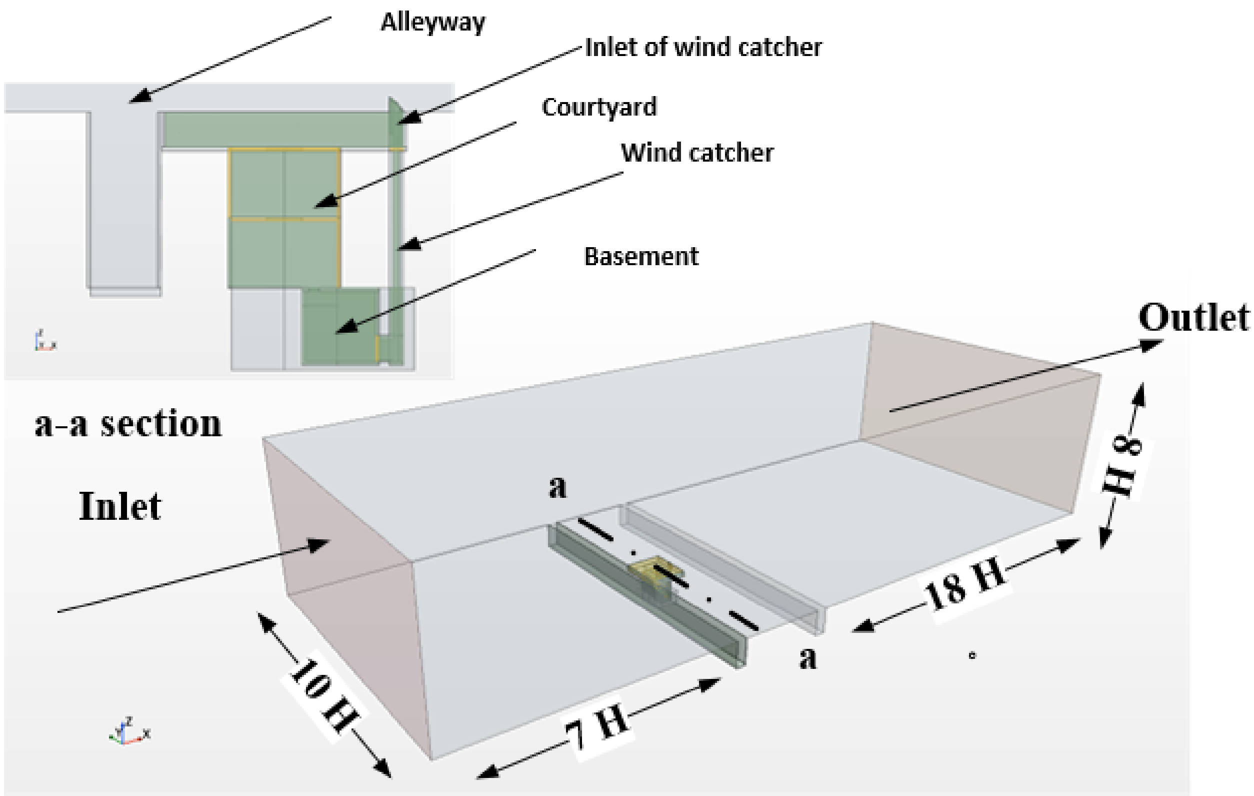
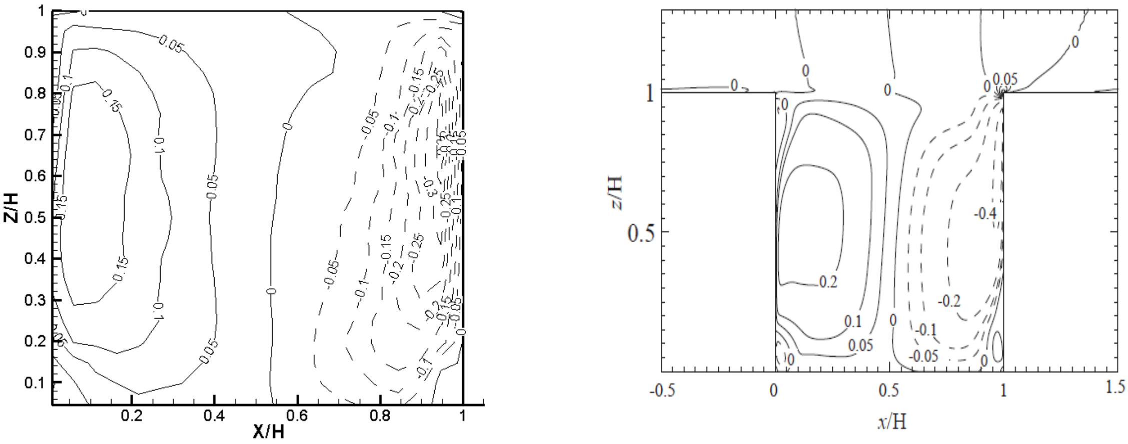



**Fig 2-**The computational model.




Courtyard with AR=1.0

**Fig 3-** The comparison for the results of spatial contours of the dimensionless mean streamwise velocity w/Uat 10 metres between the current research (left) and the results from work by **[18]** right (note dashed line is negative pressure).

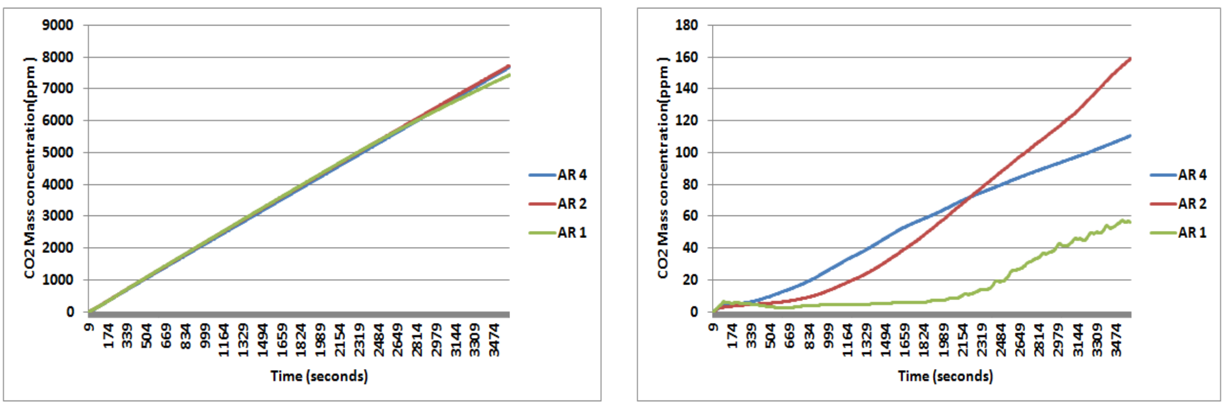
## 3. Results

The results show the effect of courtyard isolation on the air quality, and simulations were done with $CO_2$ gas emitted to represent outputs of the process of respiration from several persons. The case chosen is for a courtyard without any opening and which is covered from the top.

Figure (4) shows how the average volume of $CO_2$ concentration in the ground level is escalated through time to be seven times above the acceptable limit (1000 ppm). The $CO_2$ concentrations in the first level are much lower than those in the ground level, suggesting that convection between the ground and first level is limited. The local concentration for $CO_2$ in two of the courtyards is shown in Figure (5). The concentration near the ground can reach even higher levels, especially with a narrow courtyard (*AR*4). This indicates that a number of people cannot inhabit the courtyard for a long time without an extra means of ventilation, especially given the arrangement of the windows.

The building is attached to other houses from three directions and overlooks a narrow alleyway, and this restricts the windows to only overlook the courtyard. Windcatcher can represent a short path from outdoor air at the top of the house to the courtyard, through the basement (Figure (6)).

A windcatcher provides fresh air to the courtyard and increases the connection between the courtyard levels. Figure (7), shows an increase in the level of $CO_2$ in the first level in comparison with cases without windcatcher and this is due to the moving of air with $CO_2$ from the ground to the first level. Where the windcatcher is capable of delivering fresh air through the basement with a flow rate equal to 1 $m^3/s$ (for wind speed equal to 5 m/s) and the concentration of $CO_2$ in the basement is similar to the ambient air. The figure also shows that the levels of $CO_2$ are within acceptable limits and that they are stable.




Ground Level

First Level

**Figure 4-** The local concentration for $CO_2$ inside the courtyard.

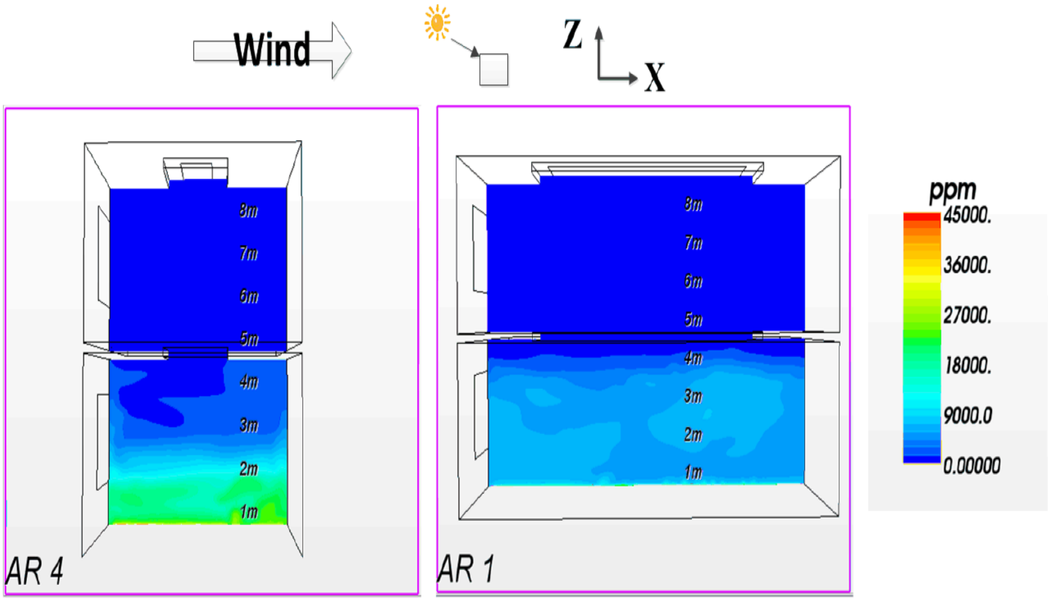



**Figure 5-** The local concentration for $CO_2$ inside the courtyard.

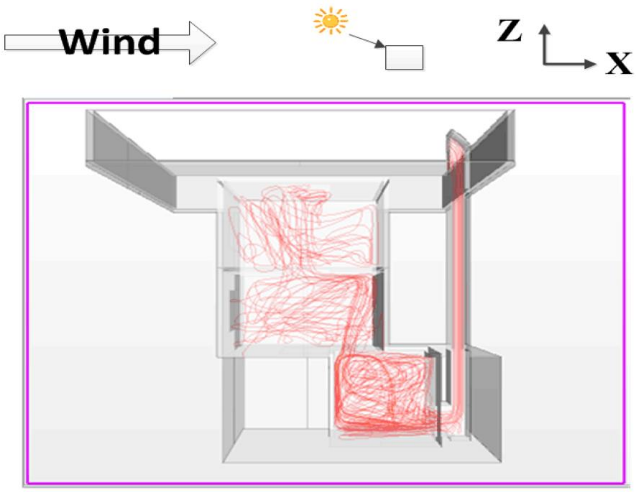
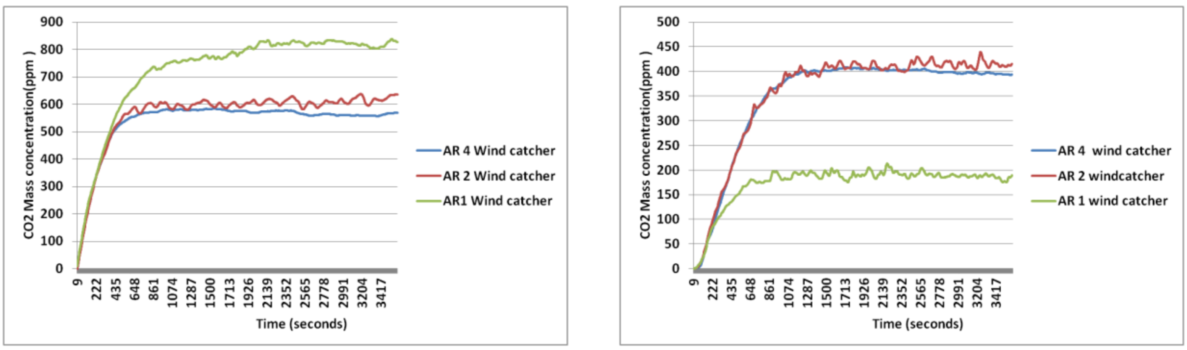



**Figure 6-** The airstream for a house with a windcatcher and a basement.




Ground Level First Level

**Figure 7-** Volume average with time for $CO_2$ inside the courtyard with a windcatcher.

Though there is clear enhancement in air quality, the windcatcher would reduce the thermal comfort by introducing the outdoor warm air to the courtyard, where the air temperature increases by two degrees in the case of using a windcatcher for an hour between 12 PM to 1 PM. However, the temperature in the courtyard, without a windcatcher, only increases by less than half-degree, as shown in Figure (8). This increase in courtyard temperature was even with air which had been cooled down by three to four degrees in the basement by earth cooling and with a thermal mass of the windcatcher, and this can explain why in traditional houses the windcatcher is usually closed in the afternoon and courtyard usage becomes less at that time, according to [19]. Other researchers such as [20] suggest using evaporative cooling to increase the windcatcher's cooling potential. However, using evaporative cooling in hot arid areas becomes limited due to water scarcity. More research is needed to use other passive cooling alternatives, such as a windcatcher with phase change materials to store the heat during the day and release it at night. However, we can achieve an acceptable indoor air quality by opening the access between the courtyard and basement (which is connected with the windcatcher). The access opening is happing when the concentration of $CO_2$ reaches a limit (800 pp,) and closes at 500 ppm. This process was controlled using Java code and the result for a number of hours during the afternoon is shown in Figure (9). The figure shows that opening the windcatcher for a few minutes is enough to reduce the $CO_2$ concentration in the basement, and this can also temporarily increase the air temperature by more than two degrees; however, it will subsequently return to the average temperature.

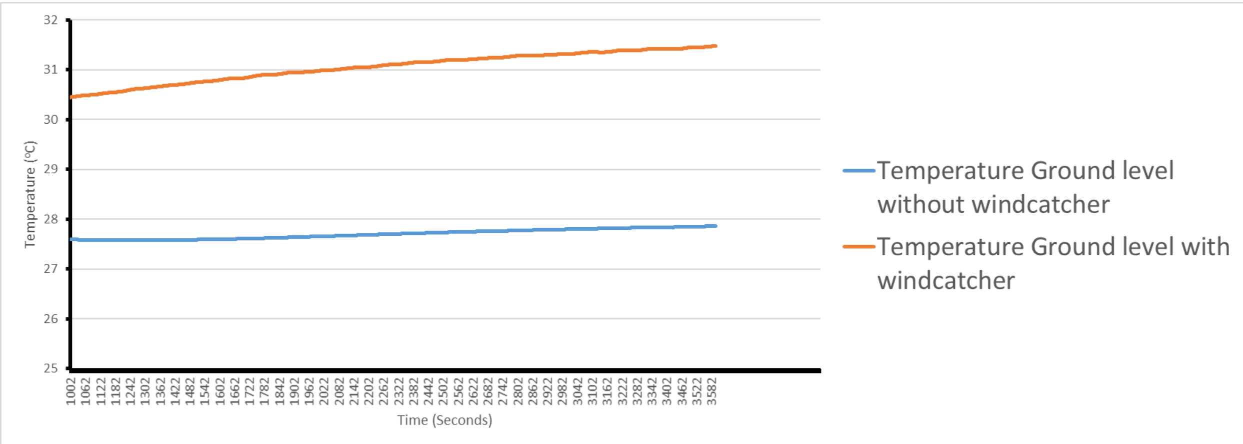



**Figure 8-**The increase in air temperature at ground level for cases with and without a windcatcher.

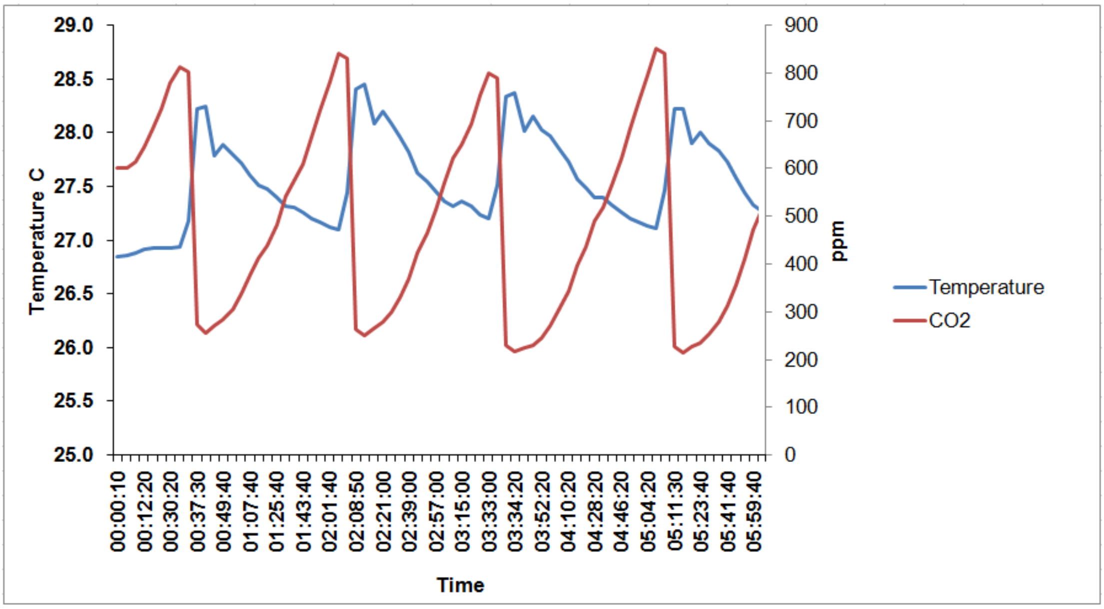



**Figure 9-** the air temperature with $CO_2$ concentration represented by ppm for a basement with attached wind catcher (the data are from a house with *AR2*)

## 4. Conclusion

This paper has discussed the use of CFD for numerical simulations of windcatchers attached to the courtyards of traditional houses. The courtyard is usually not well-ventilated. The simulations show that pollutions represented by $CO_2$ gas can reach many times the acceptable limit within a short period (one hour). It concentrates mainly on ground levels, where they will be away from the courtyard's opening and with weak convection between the levels. This is more apparent in cases with narrow and deep courtyards.

The traditional builder has found a solution for this problem using a windcatcher; a shaft connecting an air scoop at the roof to the basement and delivering fresh air from the roof levels to the ground levels. CFD simulates this building element, and we found it achieves an acceptable level of air quality but with some effect on the courtyard’s microclimate. The thermal mass of the windcatcher and the earth cooling was used to reduce the temperature, but they were not enough to cool down the outdoor air to the level of thermal comfort. It requires more research to find alternatives to achieve enough pre-cooling for air to maintain thermal comfort in the house.

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### *Data Statement*

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.