STUDY OF AIR QUALITY AND NIGHT VENTILATION INSIDE THE COURTYARD HOUSE

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Abstract

Many authors suggest the use of night time ventilation as a passive cooling technique for hot dry areas. This technique depends on using ventilation only during the night to cool the thermal mass of the building and keeping the openings closed during the daytime when the outside temperature is relatively high. However, closing the openings for many hours during the daytime can cause bad air quality (i.e. a high percentage of CO2 gas). The solution for such a problem can be found by studying the traditional designs of courtyard houses. These houses have existed for thousands of years and maintain a sufficient air quality with acceptable thermal comfort. This paper studies the daytime temperature and air quality inside a typical courtyard house by using Computational Fluid Dynamics (CFD). The simulation considers the effect of solar radiation and geothermal cooling and also shows the effect of using low energy equipment like a ceiling fan. It was found that if the house was protected from intensive solar radiation by shading, the temperature was kept within the thermal comfort limit by using night ventilation. The air quality in the house was kept within the accepted limit by opening and closing the windows and by using a wind catcher which introduced fresh air first to the basement and then through the courtyard to other rooms, the outdoor air being cooled by using the thermal mass of the earth. The use of a ceiling fan increased the effectiveness of night cooling and kept the air more homogenous in the room which reduced the risk of a locally high concentration of CO2 near occupants. This paper recommends the courtyard house as an alternative for modern house designs. There is a need for further research to show the effect of using modern methods, such as phase change materials, on the performance of traditional house designs.

Keywords: CFD, Courtyard, Night Ventilation

1 Introduction

Attention has increased in the last few decades in passive cooling techniques as a low-energy alternative to mechanical cooling systems that are used in buildings, due to global warming. Night cooling is one of the techniques which is used in traditional buildings (courtyard houses) in areas with hot dry climates. Night cooling can be defined according to Givoni (1998), as “the case when a high mass building is ventilated only during the evening and night hours and the openings are closed during the day time. In the way the structure mass of the building is cooled by convection during the night and is able to absorb the heat penetration into the building during the day”. The technique is simple and does not need maintenance work or water consumption and it depends on the range of diurnal temperature, which is enough in hot arid areas (around15-20k), which occurs in such areas. More researches on night ventilation have been done in the field and on full scale buildings, like the work of Al-Hemiddi and Megren Al-Saud (2001), where they tested the effect of night ventilation in cooling a courtyard house and they found that ventilation during the night only, with closing the windows and covering the courtyard could provide the lowest indoor temperature. However, this work and others were done in empty buildings and without considering the effect of the presence of residents for many hours on the air quality. Therefore this paper aims to simulate a traditional courtyard house that is pre-cooled by night ventilation in hot arid areas under different scenarios, for the houses, such as leaving the windows open, closing all the windows, etc and shows their role in indoor air quality by using the concentration of CO2 as an indicator for the quality of air.
The house

Baghdad city (latitude 33.3° N and longitude 44.3°E) is the geographic location for the simulation and it chosen because it is in a hot dry area and the courtyard house is the traditional form of housing. According to a survey done by Raed (1988) on traditional houses in Baghdad, the typical dimension for a courtyard is 5 m long, 4 m width and 8 m height (above ground). There is also a corridor next to the courtyard with a 1.5 m width. The houses are usually on two levels with one level underground (basement) which is used during the afternoon to benefit from geothermal cooling. The rooms have a limited depth equal to 4 m (Al-Haidary (2008) and Akbar (1980)). The other dimensions of the rooms are 4 m length and 4 m width. The roof is flat according to Manioğlu and Yılmaz (2008), with a high parapet on the external edge of the roof of up to 2 m (John and Ihsan (1982). Furthermore in courtyard houses there is also a wind catcher and the job of a wind catcher is not only inducing air but also cooling the air passing through the wind catcher by passive means, such as thermal mass. The shape of a wind catcher is shown in Figure 1, where the figure shows that the wind catcher takes fresh air to the basement and usually from there the air goes to the courtyard. The wind catchers in Iraq are usually short and have a lower external surface area to reduce the exposure to solar radiation (the height is around the parapet height). The dimensions of the wind catcher, from Al-Haidary (2008), are 1 m long and 0.4 m width.

Figure 1. Structure of a wind catcher from John and Ihsan (1982).

Figure 2a. The air stream through the house

Figure 2b. Side view of the house model

The solar radiation in a hot arid area is intensive to a degree that makes the thermal comfort dependent mainly on the shading. The N-S orientation in the courtyard has the highest amount of shading (Berkovic et al. (2012)) and this results in the residents of the houses staying in the parts of the house that face north and south where these parts receive less solar radiation than other parts, with the rooms in other parts being used for either stores or services. Also, the life is more dynamic in traditional houses than modern houses, as the residents change places many times during the day. In
the early morning they stay on the ground level. Then they spend the afternoon in the basement so they benefit from geothermal cooling, and in the night time they sleep on the roof as shown in Akbar (1980), Al-Haidary (2008) and John and Ihsan (1982). Therefore the simulation needs to show this behaviour of the residents, especially during the morning and afternoon when they actually are in the house. The house model is shown in Figure 2b where the simulation is for one room in the north part on the ground level and underneath the basement. The air flow from wind catcher to courtyard and then to room is shown in figure 2a.

The rooms are designed to have the dimensions as mentioned before and its external and internal design is shown in Figure 3, where according to the time of day is will include two persons in a sitting position.

![Diagram of room and wind catcher](image)

*Figure 3. The design of the room and the design of the wind catcher on the right*

### 3 Methodology

The paper aims to show the effect of applying of different scenarios for the windows, wind catcher, etc. on the prediction of daytime temperature and air quality. The air quality is represented by using CO2 percentage, and the CO2 is produced from the respiration process of residents in the room. The simulation will focus on finding the values of the temperature of the air and the percentage of CO2 and will use CFD for finding their values.

This paper will use CFD rather than a simpler modelling technique because we wish to investigate the distribution of temperature and air quality within the spaces, not just the average values for each space. CFD divides the domain of the problem into a number of cells and solves a discretized version of the energy and momentum conservation equations for each of them. A second-order discretization was used with pressure–velocity coupling by applying a SIMPLE algorithm. Turbulent flow is expected to be found in ventilation problems, and this can be simulated by using one of Reynolds-Averaged Navier–Stokes equations (RANS) which is realizable k-ε models by Shih et al. (1995). The variations in air density due to natural convection were solved by using the ideal gas (law) model. The simulation was done using STAR CCM+ Ver. 7.04 software and by using a non-uniform unstructured polyhedral mesh with prism layers at the surfaces. An overset mesh was also used for cases that include a ceiling fan and fan interface for the exhaust fan.

The size of grid was decided according to the mesh sensitivity analysis with a higher density in and around the house and courtyard. The domain was designed to have dimensions according to the recommendations of the benchmark by Franke et al. (2011). The velocity, turbulent kinetic energy and turbulent dissipation rate at the inlet are defined by a user defined function based on the equations that
were suggested by Richards and Hoxey (1993) to simulate the atmospheric boundary layer, and furthermore the inlet conditions (velocity, etc.) were changed from time to time by using Java Code. The outlet was set as a pressure outlet and the other sides of the domain as a slip wall except for the ground and building surfaces, which are defined as no-slip walls. The software used has a solar load model which can be used to impose solar radiation on the building surfaces. The intensity of solar radiation was decided according to time, date and location as shown in Table 1. A grey body thermal radiation model was used to make radiation properties fixed and constant with regard to the wave length. The radiation exchange between the house and the environment (i.e. two surfaces) can be calculated by the application of a surface to surface transfer model (S2S).

Table 1. The boundaries and the parameters of the simulation

| Walls, roof, floor | Brick with thermal conductivity = 0.69 W K⁻¹m⁻¹, specific heat = 840 J kg⁻¹K⁻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⁻¹m⁻¹, specific heat = 1.21 J kg⁻¹K⁻¹, density= 33.5 kg m⁻³, thickness =0.05 m and reflectivity =1.0 |
| Fenestration (for cases with window closed) | Clear with glass thickness = 0.006 m, thermal conductivity = 0.78 W K⁻¹m⁻¹, emissivity =0.07, transmissivity = 0.77 |
| Initial conditions | Day-time: room air temperature =298 K, outside air temperature =303 K, Wall temperature = 298 K (temperature was chosen to be higher than minimum ambient temperature for night and under the maximum during daytime) |
| Boundary conditions | Wind speed at 10m from ground and air temperature are from weather data Sky temperature = 0.0552 (T_outside)¹.5 Swinbank (1963) |
| Time step | 1800 seconds |
| Date and time | day 1 Jun 2012, began from 6 am to 6 pm |
| Metabolic rate (M) | 60 W/m² ( for seated quietly) (this was set as heat flux) |
| Human body surface area (A) | 2.1 m² |
| CO2 Production | G = 4*10⁻³ * M*A (L/s) |
| Exhaust fan | 0.1 m diameter with performance according to fan curve and simulated by using (fan interface) where it models the pressure rise through an axial fan as a function of local flow rates or velocity. |
| Ceiling fan | 160 RPM with downward air flow |
| Courtyard cover | Transmissivity = 0.3, emissivity =0.1 , reflectivity=0.6 |
| Soil temperature | set according to equation of Williams and Gold (1976): \[ T(Z,t) = T_{average} + A \exp(-Z \sqrt{\frac{\pi}{\alpha t}}) \cos \left( \frac{2\pi t}{t_o} - Z \sqrt{\frac{\pi}{\alpha t}} - \beta \right) \] where \( T_{average} \) is the average soil temperature, A the annual amplitude of surface soil temperature, Z depth, \( \alpha \) thermal diffusivity, \( \beta \) is the phase shift, \( t \) time in day and \( t_o \) is the time for one complete cycle (364 days). The entire values were taken for local sand. |

The simulation includes six cases as:

- Open; all the windows were kept open with an uncovered courtyard and opened wind catcher.
• Closed; all the windows were kept closed with a covered courtyard and closed wind catcher.
• Case one; where the windows should open only in the first half of each hour and in the second half they would be closed also in second half the wind catcher was opened by removing the cover from the courtyard.
• Case two; all windows were kept open with a covered courtyard and closed wind catcher.
• Case three; all windows were kept open with an uncovered courtyard and closed wind catcher.
• Fan; in this case there is a ceiling fan working with an exhaust fan which provides extracts air to the room for one minute when CO2 inside the room reaches a specific level, with other conditions as ‘Closed’.

The simulation has two stages; the first stage (morning) is from 6 am to 1 pm which includes all the cases. The second stage (afternoon) is from 1 pm to 6 pm which includes only the first three cases.

4 Results

The CO2 percentage in the room during the morning is shown in Figure 4 as the volume average for CO2 inside the room, furthermore the CO2 for the breathing level is shown in Figure 6. The closed case increases the level of CO2 inside the room to over 5000 ppm but the accepted level is less than 1000 ppm (Awbi, 2003).

A question may arise about the air infiltration, which usually decreases the level of CO2 in similar cases. However, courtyard houses are usually built in blocks where each house is surrounded by other houses on three sides and a narrow alley on the fourth side, and this leaves the courtyard as the only source of fresh air. However, the ventilation inside the courtyard in normal conditions is not efficient according to Halls (2000) and with covering the courtyard, the inefficiency will be increased as shown in Figure 5, where it shows that there is a nearly a complete reduction of the free stream velocity through the courtyard in the Closed case.

By returning to Figure (4), the lowest level is for the Fan then the Open and Case three. For Case one and Case two, the levels of CO2 are lower than (Close) but relatively higher than other cases, however it is still at an acceptable level. From a comparison of Open and Case three, the difference in CO2 levels due to the wind catcher is clear (especially with low wind speed as in the time

![Figure 4. The CO2 level inside the room during the morning](image1)

![Figure 5. The percentage of air velocity to an external air velocity through the courtyard](image2)
below 11.30), which suggests the importance of the wind catcher for places with low wind speeds. Figure 6 shows the CO2 levels from the breathing level (the level of CO2 emission from the mouth). The effect of the ceiling fan in mixing the air and reducing the local concentration is clear in the figure where the rest of the cases are nearly the same, except the Closed case.

![Figure 6. The CO2 levels in breathing level with trend line](image)

The average temperature for the room during the morning is given in Figure 7. In this case, the worst scenario is in Case three, where the windows are open, but without the cooling from the wind catcher and the basement and without the additional shading from the courtyard cover. The case with best performance is again the Fan and this due to it generating a higher indoor air velocity and consequently a higher convective heat transfer from walls with a relatively low temperature. Furthermore the Closed case provides a good performance (especially without any consumption for energy from fans) and covering the courtyard is shown a to give a good performance, as in Case one, Fan and Closed.

![Figure 7. Average room temperature during the morning](image)

However, covering the courtyard without opening the wind catcher can cause a relatively high temperature (but still below the ambient temperature) inside the courtyard, as shown in Figure 8, because the cover should allow for a significant portion of solar radiation to penetrate inside the courtyard to be used as a daylight source for the rooms and this radiation will heat the walls. Therefore, it will be better to use the wind catcher when the courtyard plays a role in everyday life.
During the afternoon, the residents usually spend their time in the basement. The temperature record for that period is shown in Figure 9 where the Open case has a temperature higher than other cases due to leaving the wind catcher fully open during the morning which made it unusable. The Closed case shows a lower temperature but still has the problem of a high concentration of CO2 as shown in Figure 10 where the levels of CO2 for (Open) and (Case one) is even lower than the morning because the wind catcher is able to provide a more fresh air flow than the windows.

Therefore, the best scenario is a mix of Open and Closed as in Case one, where both the temperature and CO2 concentration are relatively better than other the cases expect the Fan case.

5 Conclusion

The paper gives an example of how CFD can be used to give information, which helps in the decision stage of house design. Six scenarios were simulated and their effect on both the temperature and CO2 concentration was monitored. The work includes simulation for traditional house from the Middle East and the effect of two of its residents on air temperature and quality, who are usually settled in the ground level during the morning then in the basement; the house has been cooled by using night ventilation. Furthermore, the simulation included the effect of solar radiation and extended from 6 am to 6 pm. The results indicate that one shouldn’t keep all the windows open or closed all the time, as this can produce either bad air quality (a high concentration for CO2) or high
air temperature and the best case is to use a combination of opening and closing. The use of a wind 
catcher and covering the courtyard can enhance the conditions inside the house and courtyard. The use 
of fans (ceiling and exhaust fan) can further enhance conditions.

Further work needs to show the effect of other elements like the roof shape, the room depth, 
and using modern building techniques like using phase change materials in the building, also other 
scenarios need to be considered and with simulations over a longer time (several days).

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