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THERMAL COMFORT ANALYSIS OF A TRADITIONAL IRANIAN COURTYARD FOR THE DESIGN OF SUSTAINABLE RESIDENTIAL BUILDINGS

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ABSTRACT

This paper presents the results of simulation modeling analysis of natural ventilaiton systmes in a traditional courtyard residence in a hot and dry climate. The purpose of this research was to analyze and evaluate passive energy systems and their elements to provide implications for the design of sustainable residential buildings. An existing traditional courtyard in the city of Kashan, Iran, was used as a case study to analyze the indoor thermal comfort conditions and to develop a simulation model. The EnergyPlus simulation program was used to calculate the thermal loads of the building and to analyze the effectiveness of the natural ventilation systems along with other native design strategies in terms of thermal comfort.

INTRODUCTION

With the growth of global warming and energy consumption, courtyard buildings have been considered as an alternative of energy efficient building typology due to the large temperature difference between internal and external areas within buildings. Courtyard is one of the Iranian traditional architecture elements, which all of the spaces in a building are located around this open and rectangular area. This spatial structure has both social and environmental function, which provides private space, while acting as a source of light, fresh air and heat. Another characteristic of Iranian architecture is using the relatively constant ground temperature by digging the courtyard and constructing the building under the ground. The ground temperature is warmer than outside temperature in cold weather season and cooler in hot weather season. This feature appears to have significant potential to maintain comfortable thermal condition in indoor spaces.

LITRTURE REVIEW

Several studies have been done about thermal performance of the courtyard form, specifically in hot and arid climate to address the thermal, shading, daylight, and airflow characteristics (Safarzadeh, 2005; Saint, 1980; Mostafa and Costa, 1983; Moore, 1983; Khammar, 2011).

Giovini (1998) reported results from the experimental passive cooling study. He proposed a model based on the parameters of ventilation rate, thermal mass, openings, and outdoor temperature. Aldawoud (2007) claimed that courtyard integration is energy-efficient in all climates, specifically in hot-dry and hot-humid condition with evaluating the energy performance of a courtyard in various situations. Muhaisen et al. (2006) examined the effect of various irradiations due to different parameters of courtyard such as height to reduce heating and cooling loads in Rome climate. Al-Hemiddi et al. (2001) examined the effect of ventilation in thermal performance of a courtyard house in Saudi Arabia using sensors instruments. Sharples et al. (2001) examined the airflow through courtyard in an urban environment by wind tunnel experiment. Malekzadeh and Loveday (2008) integrated two programs (TRNSYS (Klein, 2010) and ENVI-met3.1 (Bruse, 2009)) for the analysis of indoor spaces and adjacent outdoor spaces in Iranian houses to estimate heating and cooling loads. Talaghani et al. (2012) analyzed thermal comfort and energy consumption of dwellings with transitional spaces in three different climates in Netherland using the DesignBuilder program (Tindale, 2009). They focused on heating and cooling energy consumption of courtyard, atrium and sun spaces of buildings.

Berkovic et al. (2012) evaluated the thermal comfort during summer in hot and dry condition for three different courtyards. They used CFD model to evaluate the thermal comfort and ENVI-met 3.1 (Bruse, 2009) to calculate the temperature of microclimatic courtyard. They investigated about which parameter has the most impact to improve comfort, shade contribution or wind contribution.

Taking into account of all these studies, courtyard has been known as one of the passively energy efficient building forms. Thermal performance of this spatial building has been investigated by many researchers; however, it is still not sufficient of evaluating courtyard’s thermal performance in detail along with its microclimate impact and cross ventilation with simulation tools. This study goes further to examine the behavior of a courtyard house as a case study against different parameters, specifically, certain materials and natural ventilation system to show in what extent the natural ventilation, as a result of changing relative parameters, can reduce the thermal energy requirement in hot and dry climate of Iran.

SOCIAL AND ENVIRONMENTAL IMPACT OF COURTYARD

The typology of traditional courtyard buildings is introverted. The courtyard is the heart of the house and all the spaces are located around it, which has the best view and access to the other areas and shape the link between different spaces (Arjmandi, 2010). It also can mitigate noises from surrounding buildings or from the adjacent street (Tlaghani, 2012).

Using optimized spatial forms of courtyard with natural elements such as water and plant helps make appropriate strategy for passive cooling design. Natural ventilation and shading are the most significant effects in passive cooling design and remedy of the indoor temperature increase.

Natural ventilation function

Applying the wind energy for ventilation was considered as one of the main methods of traditional architecture to provide thermal comfort for occupants in buildings especially in hot and dry climates. This strategy is utilized not only to conserve energy, but also to provide proper thermal comfort for inhabitants in indoor spaces (All-hemidi, 2001; Behbood, 2010). Wind energy has two functions in courtyard buildings. One of them is circulating the air between outdoor and inside the courtyard. The other effect is ventilating indoor air of the courtyard. In hot and dry condition, during the night, warm air rises in front the courtyard and exits while the cooler air replaces it. Then, during the day, cool air is circulated through the indoor spaces. (Al-Hemidi, 2001).

Considering energy consumption increase and health concerns of occupants in buildings, the interest of using natural ventilation in buildings and other natural elements has been increased over time (Sharpless, 2001). In order to present solutions for applying natural energy and dispense it to reduce the loads of mechanical systems, comprehensive and scientific studies on vernacular cooling systems in courtyard buildings and an in-depth analysis in terms of energy conservation and human comfort are presented as follows.

CASE STUDY

It has been previously shown from several studies about why the temperature of the inside spaces of courtyard building is considerably lower than the outdoor temperature (Meir, 1995; Muhaisen, 2005; Al- Hemiddi, 2001; Taleghani, 2012, Berkovic, 2012; Al_Masri, 2012). The passive design strategies in a traditional house, known as Brojerdi-ha house in hot dry climate of Kashan, Iran, were examined in this study. The construction of this building was finished in 1892 with more than 150 marble stones with other materials such as stucco in its construction. Figure 1 shows the geometry of the courtyard building, which indicates some design strategies about location, orientation and minimum relationship with outdoor conditions. It has the linear form, which is divided in four distinction volumes in different directions. The openings of these building are looked inwards. Most of the apertures are open toward courtyard, and the exterior walls have the minimum apertures, which increased the safety and security of buildings (Taleghani, 2012).

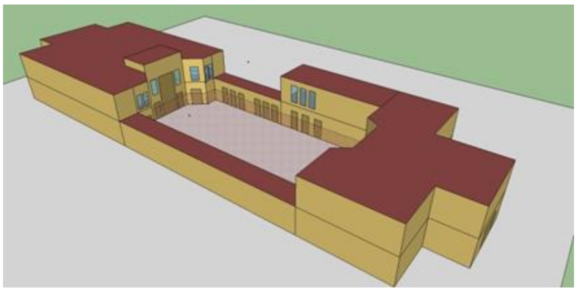

Figure1 Geometry model of the case study courtyard for the EnergyPlus simulation

Simulation modeling program

In this study, the EnergyPlus (DOE, 2010) program was used to evaluate the impact of multi parameters on the energy consumption of the courtyard buildings. EnergyPlus has been validated through multiple processes such as empirical validation, comparative analysis, and analytical verification.

EnergyPlus is a new generation of simulation tool which developed by integrating two main building simulation programs, DOE-2 and BLAST (Building Loads Analysis and System Thermodynamics, 1992) with support from U.S. department of Energy. It uses a modular program structure, which is easy to maintain, update, and extend. All the input and output data files related with EnergyPlus are in simple formats and can be easily used by other programs and databases. This program gives detailed simulations of the building such as building loads, heat gain, daylight, solar analysis and airflow, and the energy applied or extracted by mechanical systems (Talaghani, 2012; Al-Masri, 1989). The simulation parameters implemented in the EnergyPlus program are as follows.

Building geometry and climate data

To examine the energy performance of courtyards, the geometry model was developed using the Google SketchUp7 (Google, 2012) program with the OpenStudio program plugged in to it (Ellis, 2009) developed by National Renewable Energy Laboratory (NREL). OpenStudio is a graphic user interface for EnergyPlus running in SketchUp. The model was simplified to have only the central courtyard and nine adjacent thermal zones. Design requirements, including schedules for residential buildings, people, light, equipment, construction of the building with earthen vernacular materials, and natural ventilation system, were considered for the simulation process. The main focus of the simulation process was to evaluate the thermal energy requirement in the form of cooling loads for the courtyard model.

The city of Kashan is located in the center of Iran in the province of Isfahan. The climate of central region of Iran is relatively similar to desert condition. The weather characteristic of this area is hot and dry condition with a high range of temperature between day and night (Behbood, 2010). Readily available weather data in the form of EPW available from the US DOE website was used for the simulation.

Material

In traditional house of Iran, the effect of the thermal mass, such as clay and thatch with more thickness, reduces the amount of heating and cooling loads of the building considerably. For the comprehensive study of the role of these materials in energy conscious design, the cooling loads of Brojerdi-ha house were calculated with traditional materials for controlling the thermal comfort of inside the building. In the simulation, the construction of wall, roof, and floor was defined based on traditional house, which consists of the following materials.

- The external walls consist of five layers; i.e., Plaster (1.5 cm), thatch as thermal insulation layer (2.5 cm), fired clay (32 cm), thatch (2.5 cm), and plaster (1.5 cm), layered from outside to inside. The total U-value of this wall is 0.76 W/m^{2}K. Figure 2 shows the layers of the external wall.

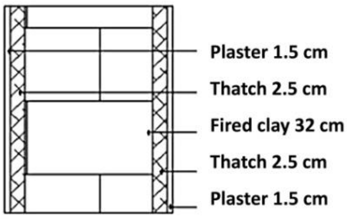

Figure 2 Layers of external wall

- The internal walls are the same with the configuration of the external wall without the insulation layer.
- The roofs are also have five layers, from outside to inside with the U-value of 0.42W/m^2 K
- The U-value of floor is 0.66 W/m^2 K
- The type of window is double-glazing with 2 layer of 3mm clear float glass and 13mm of air within those (U-value of 2.7 W/m^2 K).

The U-values of these materials were manually calculated and used in the EnergyPlus simulation.

Table 1
U-values of building materials

	Thickness (m)	R-value m^2 K/W	U-value W/m^2 K
Wall	0.40	1.31	0.76
Roof	0.35	2.30	0.42
Floor	0.25	1.51	0.66
Window	0.019	0.37	2.70

With and without thermostat Settings

In this study, there were total of four scenarios developed. The first two cases are based on the thermostat settings to calculate the thermal loads of the building. The thermostats were set to 25.5 ^{o}C for cooling and 20 ^{o}C for heating. This is for loads calculation, so the “Ideal Loads Air System” option was used in EnergyPlus. No mechanical systems need to be defined. In another case, however, the natural ventilation function was used as a separate case in EnergyPlus to see the impact of it and compare to the case without natural ventilation.

There were also two other cases without the thermostat control. Consequently, no thermal loads were calculated, rather observed were the hours where the zone temperature and humidity conditions are fall in to the ASHRAE thermal comfort zone. These hours were compared between the cases with and without the natural ventilation controls.

Air flow network

This section provides parameters to see how air movement, either from the outside or between rooms in conjunction with environmental systems, is considered and treated. The AirFlowNetwork model is utilized to simulate the performance of the airflow in multizones considering outdoor wind and the pressure of air through HVAC system operation. This model gives the ability to simulate thermal condition in different zone and air leakage through the surfaces with the constant volume of air distribution. The input objects for the simulation integrates five main objects; i.e., 1) air flow Network simulation object which presents the basic run factors for the model like model control, 2) the airflow Network: Multizone data objects which utilized for calculation airflows of multizones (Each object consists of building zones, exterior of building as nodes and building surfaces as linkage), 3) the airflow Network: Distribution: Node object utilized to simulate air distribution, 4) Airflow Network component data which indicate the relationship between air pressure and air flow, and 5) Airflow Network linkage data objects which represent the connection between two AirflowNetwork: Distribution: Node objects and AirflowNetwork component.

The AirflowNetwork model calculate three steps in order: Pressure difference and airflow system, Node temperature and humidity, sensible and latent load of cooling and heating.

By calculating the pressure and airflow at each node and determining the airflow through each linkage, the model can determine the node temperature and humidity ratio. Based on these calculations, the sensible and latent loads for each zone can be defined. According to these information considering HVAC system load, the final zone air temperature, humidity ratio and pressure are attained to evaluate thermal condition of each zone and total cooling load.

This simulation specifies the basic parameters for airflow simulation and wind pressure. It determines the air mass flow based on the amount of airflow through crack in surfaces, windows and doors in closed and open conditions. The detail inputs are the characteristics of opening and crack in surfaces, assigned specific coefficient value for air mass flow, and wind pressure concerned with cracks and openings in building's surfaces. By providing these input objects, it was able to measure the thermal condition of each zone and evaluate the effect of air flow system.

ASHRAE comfort zone

Thermal comfort has been defined by American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) as "the condition of the mind in which satisfaction is expressed with the thermal environment" (Atwater, 1971). Thermal comfort depends on different parameters. There are two main factors which determine human thermal comfort; i.e., "personal factors" such as occupant activity, clothing level, age, and sex, and "environmental factors" such as dry-bulb temperature, mean radiant temperature, which refers to surrounding objects temperature, humidity, and air velocity" (Asfour, 2008).

One of the methods for defining thermal comfort is evaluating effective temperature, which is calculated by humidity ratio and the indoor temperature (Frier, 2007). The thermal comfort zone can be identified in psychometric chart adopted by ASHRAE as shown in Figure 3.

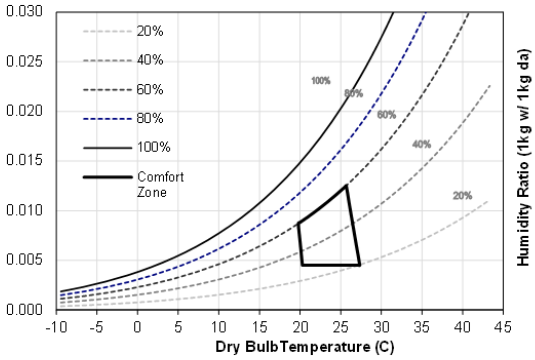

Figure 3 Comfort zone in Psychometric chart

RESULTS AND ANALYSIS

Figure 4 and 5 show the floor plans of the first and the second floor. The first floor has 5 zones. All four directions have each zone, and Zone 5 is inside the courtyard connecting the two levels, first floor and second floor. In the second floor, there are three zones in east, west and north directions. By monitoring the simulation results of the four cases described earlier, it can be identified which zone has better or worse thermal conditions compared to the other zones.

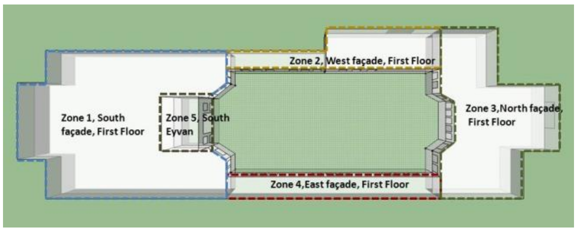

Figure4 First Floor plan

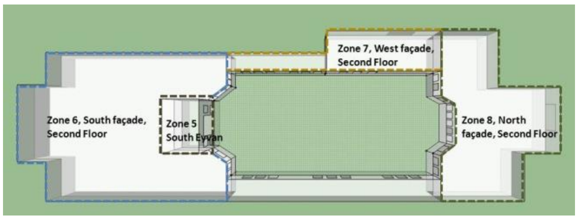

Figure5 Second Floor Plan

Without thermostat control

Figures 6 through 13 show and compare the thermal condition of each zone between the cases both with and without natural ventilation in which no thermostat is assigned. The red colour indicates outdoor condition, while the yellow for the case with natural ventilation and the blue for the case without natural ventilation. The effect of the natural ventilation is clearly indicated in the graphs by the temperature shift. For example, due to the natural ventilation effect, the maximum temperature of Zone-1 changed from 32.1°C to 29.8 °C (i.e., 2.3 °C lower with natural ventilation).

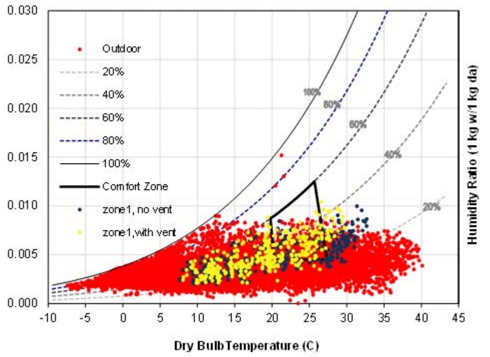

Figure 6 Zone-1, south façade, first floor, no thermostat set point, with /without ventilation

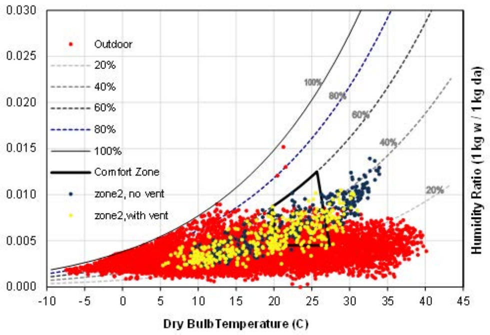

Figure 7 Zone-2, west façade, first floor, no thermostat set point, with /without ventilation

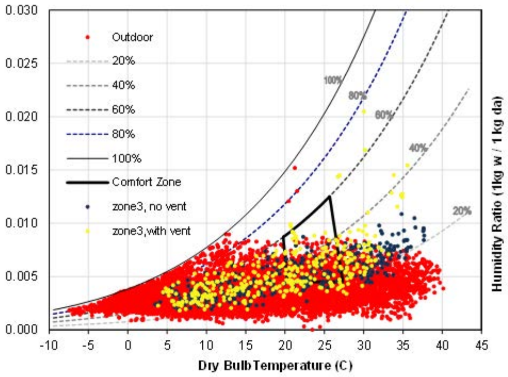

Figure 8 Zone 3, north façade, first floor, no thermostat set point, with /without ventilation

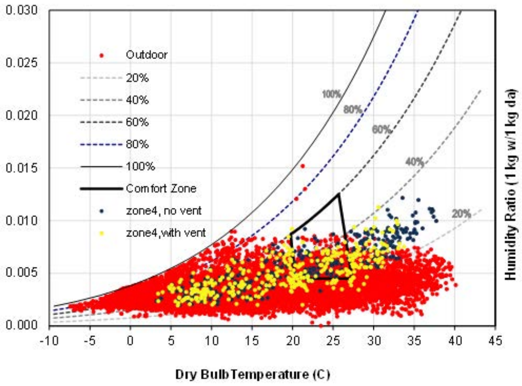

Figure 9 Zone 4, east façade, first floor, no thermostat set point, with /without ventilation

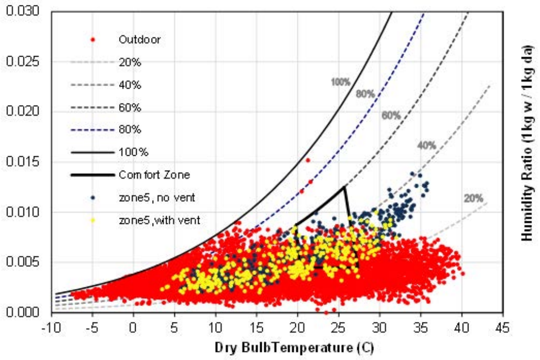

Figure 10 Zone- 5, south Eyvan no thermostat set point, with /without ventilation

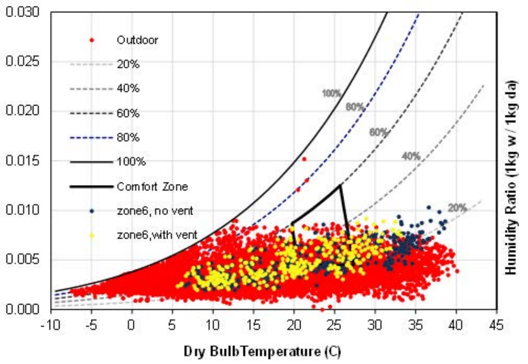

Figure 11 Zone-6, south façade, second floor no thermostat set point, with /without ventilation

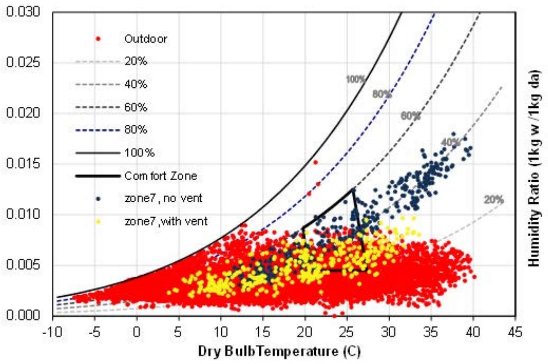

Figure 12 Zone- 7, west façade, second floor no thermostat set point, with /without ventilation

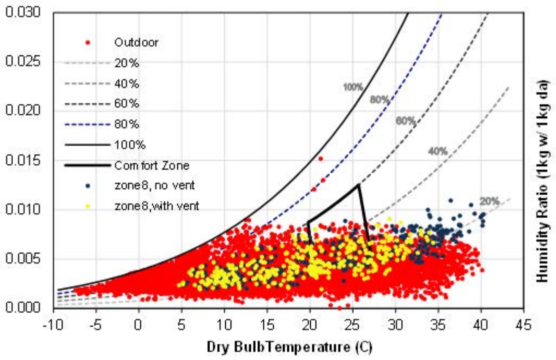

Figure 13 Zone- 8, north façade, second floor no thermostat set point, with /without ventilation

Table 2 summarizes the individual zones' maximum temperatures. Zone-7 (2nd floor west) shows the largest temperature difference, 5.6 °C. Also, Zone-8 (2nd floor north) and Zone-6 (2nd floor south) made a significant temperature reductions from the natural ventilation. However, Zone-3 (1st floor north), Zone-2 (1st floor west), and Zone-1 (1st floor south) showed the least effect with about 2 °C differences.

Table2
Comparison of maximum temperatures

Zone	**Max. Temp. (°C)**		**Temperature Difference (°C)**
	W/ Nat. Ventilation	**W/O Nat. Ventilation**	
Zone-1	29.8	32.1	2.3
Zone-2	31.0	33.5	2.5
Zone-3	35.5	37.5	2.0
Zone-4	33.7	37.7	4.0
Zone-5	32.0	35.3	3.3
Zone-6	33.1	38.2	5.1
Zone-7	33.5	39.1	5.6
Zone-8	34.7	40.1	5.4

Likewise, the total number of days that fall in to the ASHRAE comfort zone is shown in the similar fashion. Table 3 compares the number of days of comfort condition between with and without natural ventilation.

Table 3
Number of days in a year in thermal comfort condition in two cases with and without airflow

Zone	# of Days in Comfort Zone		Difference (Days)
	w/ Nat. Vent.	w/o Nat. Vent.	
Zone-1	116	81	35
Zone-2	95	74	21
Zone-3	95	73	22
Zone-4	93	72	21
Zone-5	103	75	28
Zone-6	104	67	37
Zone-7	105	68	37
Zone-8	101	66	35

The results are about the same with the maximum temperature comparisons in Table 1. Zones 6 to 8 show the largest impact from the natural ventilation. One exception in this comparison is that Zone-1 (1st floor south) made a considerable improvement in the number of days even though the maximum temperature difference was not significant.

With thermostat control

To analyse and compare the thermal loads between the two cases, with and without natural ventilation, the thermostat was set to 20 ºC for heating and 25.5 ºC for cooling. Figures 14 through 21 show the thermal conditions of the individual zones in Psychrometric charts. As expected, all the zones are satisfied in terms of the thermal conditions, meeting the ASHRAE's comfort conditions. The humidity was not controlled, so that there are a number of data points outside of the comfort zone in terms of humidity level. Again, the red is for outdoor condition, the yellow for the case of natural ventilation, and the blue for the case of no natural ventilation.

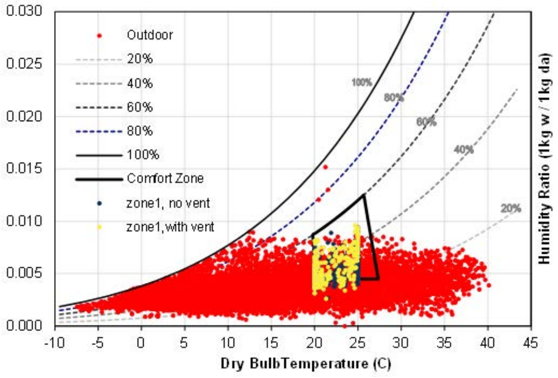

Figure 14 Zone- 1, south façade, first floor, with thermostat set point with /without ventilation

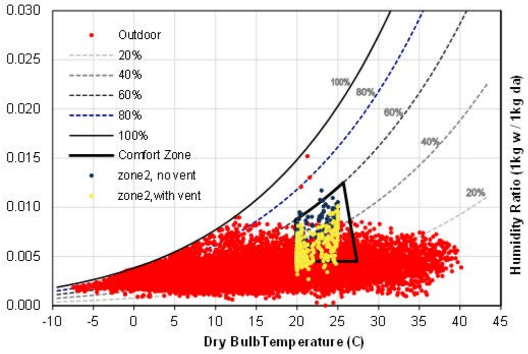

Figure 15 Zone- 2, west façade, first floor, with thermostat set point, with /without ventilation

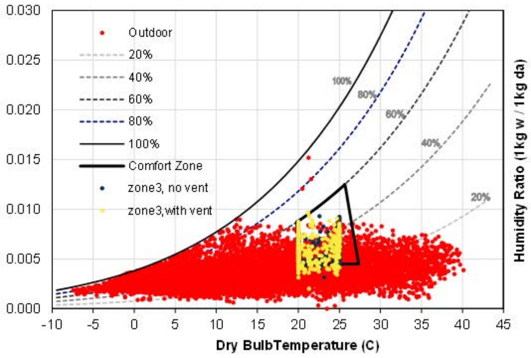

Figure 16 Zone-3, north façade, first floor, with thermostat set point, with /without ventilation

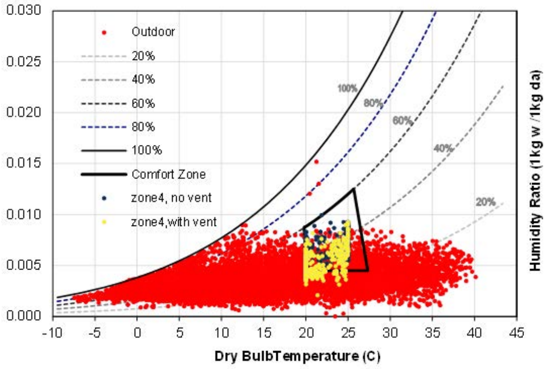

Figure 17 Zone-4, east façade, first floor with thermostat set point with /without ventilation

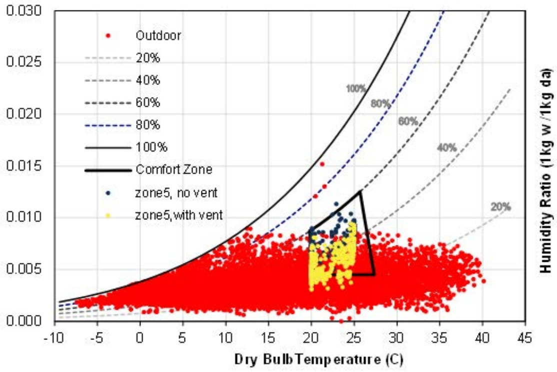

Figure 18 Zone-5, south Eyvan with thermostat set point with /without ventilation

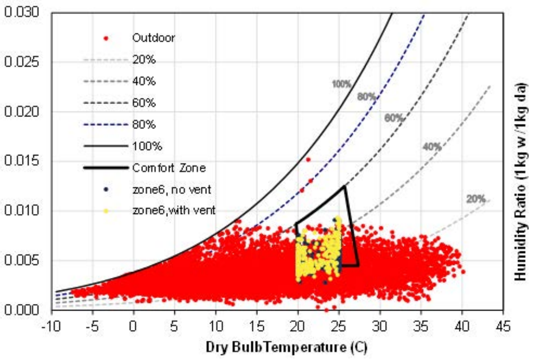

Figure 19 Zone-6, south façade, second floor with thermostat set point with /without ventilation

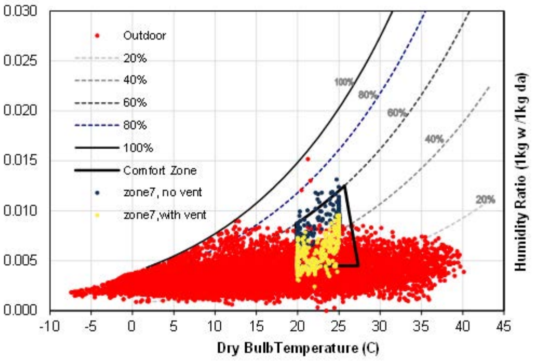

Figure 20 Zone-7, west façade, second floor, with thermostat set point with /without ventilation

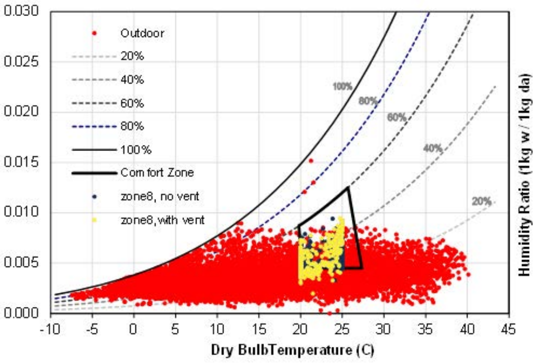

Figure 21 Zone-8, north façade, second floor, with thermostat set point with /without ventilation

Figure 22 shows the Energy Use Intensities (EUIs) of the individual zones' cooling energy. The gray columns are the cases of natural ventilation. The red columns include the results without natural ventilation system.

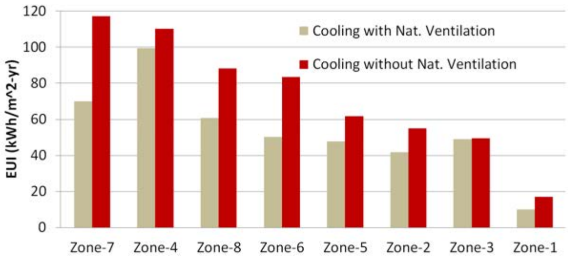

Figure 22 Cooling loads comparison

Table 3 summarizes the EUIs. As shown, Zone-7 (2nd floor west) required the most cooling energy than any other zones without natural ventilation. This zone along with Zone-6 and Zone-8 achieved the largest effect from the natural ventilation technology. In the other hand, Zone-1 (1st floor south) required the least cooling energy. It depends on the direction of façade and its opening percentage.

Table 3
Comparison of total cooling loads

Zone	**Cooling EUI (kWh/m^2-yr)**		**EUI Difference**
	W/ Nat. Ventilation	**W/O Nat. Ventilation**	
Zone-1	10.0	16.9	6.9
Zone-2	41.8	54.9	13.1
Zone-3	48.9	49.5	0.6
Zone-4	99.5	110.2	10.7
Zone-5	47.6	61.8	14.2
Zone-6	50.3	83.4	33.1
Zone-7	70.0	117.3	47.3
Zone-8	60.6	88.1	27.5

As shown earlier, using the thermal mass characteristic in external wall has the significant factor in conduction heat percentage and reducing the cooling loads during the day.

Note that the comparison of energy consumption with the natural ventilation system is limited to the cooling loads, and it excludes heating systems, lighting, and appliances, all of which were constant in all cases.

CONCLUSION

Courtyard has significant advantages on thermal performance of indoor spaces, specially the areas adjacent to the courtyard in hot and dry climates.

EnergyPlus includes the integrated network model which can calculate the amount of airflow through openings and surfaces and represent its impact on cooling energy loads. This impact can be modeled with the consideration of other important factors such as thermostat set points, occupancy schedules, and space configurations. The results from simulation analysis indicated that the influence of the internal courtyard on the thermal condition has a strong reliance on the envelope openings due to the airflow system. This study comes up that sufficient and efficient openings in appropriate direction are suitably incorporated in passive cooling design. This approach helps predict the average indoor air temperature of a high-mass building, under given climatic conditions, which are not universally applicable though. Input values based on the adjustments should be checked or changed for the analysis of the effects of other designs and climatic conditions. Results also showed that how much energy can be saved by applying airflow system throughout the courtyard buildings.

This research considered the function of courtyard system associated with outdoor temperature. Future research will involve a correlation analysis between the indoor conditions and the microclimatic characteristics of the inner area of the courtyard.

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