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The wind towers of Bastakiya: assessing the role of the towers in the whole house ventilation system using dynamic thermal modelling

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A thermal model of the complex wind environments in and around a traditional wind tower house in Bastakiya, Dubai, was constructed using Virtual Environment Software. The original house with its three wind towers was simulated and the potential to increase comfort in it using adaptive comfort criteria was explored with varying iterations of the wind tower design. The height of one tower was increased and reduced by 33%, and the cross-sectional area of a tower increased and reduced by 50%. This article presents the results of these simulations and the three key methodological conclusions reached. Firstly, that only by using the adaptive comfort model was it possible to understand how the buildings actually operated in terms of the comfort they provide for tradition populations in this historic building. Secondly, that the whole house behaves as a self-regulating thermal system in which the internal ventilation system operates around on modal shifts in each of the three towers from updraft to downdraft airflows. Thirdly that these modal shifts occur around thermal thresholds that are a direct result of the cross-sectional area and height of the towers and that by changing the dimensions of the towers these thresholds can be raised or lowered. Thus, the geometry of the towers themselves provides some control over the temperatures experienced in the home and its indoor comfort environment.

Keywords: Adaptive comfort; middle eastern culture; natural ventilation; thermal modelling; wind towers

Introduction

Wind towers have been used in the Middle East since at least 1300 BC, as depicted on tomb walls of the Egyptian 19th dynasty (Roaf 1989). In 1272, Marco Polo visited the Iranian port of Hormuz and commented on the wind towers in some detail: ‘the heat is tremendous, and on that account their houses are built with ventilators to catch the wind. These ventilators are placed on the side from which the wind comes, and they bring the wind down into the house to cool it. But for this the heat would be unbearable’ (Coles and Jackson 2007). It was not until the mid-19th century that the greatest flourishing of wind towers occurred in the trading cities of the Iranian Plateau stimulated not only by the suitable climate but also by the booming silk industries and opium trade (Roaf 2008).

In the late 19th century, an emigration of merchant families from the southern Iranian towns such as Bastak and Lingeh to the Arab side of the Gulf was associated with the spread of wind towers to Bastakia, Kuwait and Bahrain. In Dubai, the ruling Makhtoum family gave these Sunni immigrants a particular welcome and offered them attractive trading opportunities. These merchants brought with them Persian house forms and wind towers (Coles and Jackson 2007).

The aim of this study was to investigate what indoor ‘comfort’ conditions were provided by the wind tower houses in Bastakiya and whether these conditions could be enhanced by increasing or decreasing their heights and cross-sectional areas of their towers (Figure 1).

Previous studies on wind tower house performance

Bahadori (1985) pioneered the development of numerical performance scenarios for Iranian windcatchers and proposed that raising the towers could improve airflow rates and temperatures could be lowered by involving evaporative cooling (Bahadori 1994). Karakatsanis *et al.* (1986) concluded that the most influential factors effecting airflow in the wind tower was the presence of the courtyard and the incident angle at tower openings. Khan *et al.* (2008) proposed that a one-sided wind tower facing in the optimum direction of the prevailing winds will perform better than a multi-directional one in certain wind conditions. Badran (2003) modelled wind towers for various weather conditions in Amman, Jordan. A number of studies explored the ventilation performance of multi-directional wind towers and the harmful phenomenon of air short-circuiting between the internal vents of the multi-directional wind towers

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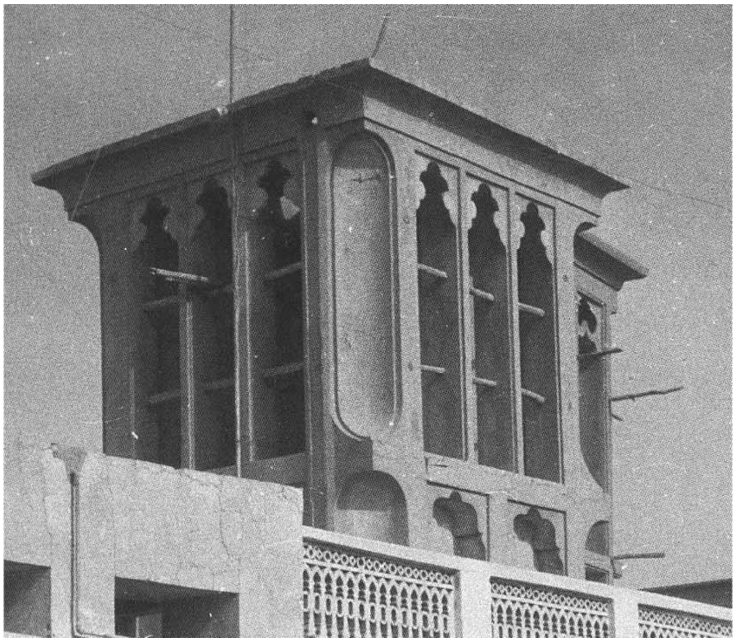

Figure 1. Windcatcher in the Bukhash house. Note the 'Sar-e Turq' or Turk's head vent head details and the angled cornice designed to channel winds down into the vents below.
Source: Coles and Jackson (2007).

(e.g. Montazeri and Azizian 2008). A more recent study (Kalantar 2009) attempted to analyse the cooling performance of a wind tower in a hot arid region using a computer program with language C++. This study focused on the computer language solving the continuity, momentum and energy equations and dealt with parameters such as tower height, vaporised cooling, wind velocity and input/output air temperatures. He concluded that very large reductions in air temperatures down these towers of 10–12°C could be achieved, a finding at odds with the more modest reductions recorded in the field by Roaf in the 1970s in Yazd, Iran (Roaf 1989).

Methodology of the present study

The study house is now demolished and belonged to Mohammed Sharif Bukhash, a trader from the town of Bastakiya on Dubai creek. The house had three wind towers including one smaller tower and two larger, identical, towers. One of the larger towers faced north and the other south. The house was recorded in detail by Coles and Jackson (2007) and their drawing used as the basis for the current model.

The thermal model of a wind tower house in Dubai was constructed using the Virtual Environment (VE) software toolkit developed by Integrated Environmental Solutions (IES) using ApacheSim, a dynamic thermal simulation tool incorporated in the VE toolkit and one that is based on first-principles mathematical modelling of the heat transfer processes occurring in and around a building (IES 2009a). ApacheSim was linked to other dynamic calculation tools including macroflo bulk airflow simulation and suncast solar analysis. Heat transfer by conduction, convection and radiation for each building element was individually calculated giving more accurate localised results for the wind towers and adjoining bedrooms. The importance of using typical 'real life' weather was emphasised (A. Coles, personal communication, 4 February 2009) and as ApacheSim uses real weather data, it has a major benefit over other thermal software tools for this study. Climate data for Dubai were obtained from the meteorological services at Dubai International Airport. A series of simulations were run for a 1-month period, August, typically the warmest month. For each simulation the three-dimensional (3D) models were similar, until the final runs in which changes were made to the tower height and cross-sectional area. Air exchange, in air changes per hour to and from the tower openings, was analysed using the Vista application within the IESVE toolkit after the simulation had been completed. The adaptive thermal comfort temperatures were derived from the methodology set out in BS EN 15251:2007 using the running mean outdoor temperature for Dubai and the indoor operative temperature, formerly known as the dry resultant temperature.

Wind speed and direction were based on an annual data set from the Dubai MTN.fwt simulation weather file, updated using the latest data provided by Dubai International Airport (including recorded weather data from 1974 to 2007) using the ASHRAE methodology that allows for different wind boundary profiles according to terrain type. The 2 months of recorded data used for Bastakiya (1 July–31 August 2005) were provided by Dr Anne Coles (Figure 2).

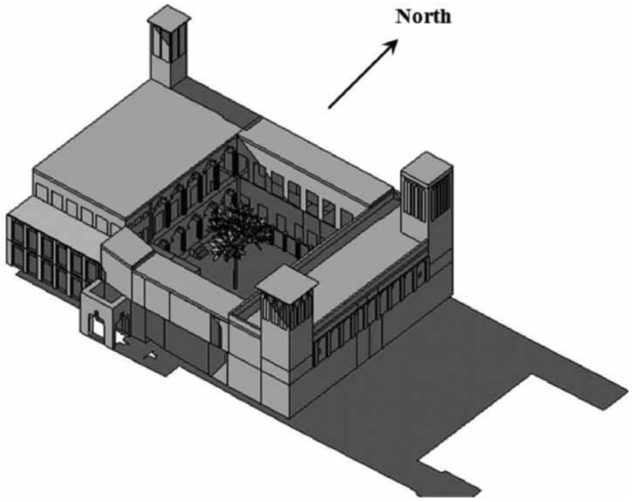

Figure 2. A solar shading image of the Bukhash house model for the 13th of August at 16:00 hours.
Source: IES (VE) Suncast.

For bulk airflow network analysis, and crackage/leakage data $ls^{-1}m^{-1}Pa^{-0.6}$ were calculated in concordance with Orme *et al*. (1998).

Problems with modelling such complex naturally ventilated buildings

Difficulties arose when attempting to replicate the intricate yet important features of the Bukhash house with its large openings and screens (Figure 3). VE, like many thermal software packages, rarely requires the need for modelling external openings as architects increasingly specify fixed-window buildings. Openings had to be modelled as doors within VE as macroflo openings with the same physical dimensions. In macroflo a new opening type needed to be created to replicate a hole opening. This new opening type then needed to be assigned to its particular location. Internal holes are automatically assigned the same opening-type properties as that of a door always 100% open (IES 2009b).

During the modelling, the downdraft performance was marginalised due to the limitations of the IES VE software in dealing with complex wind-driven ventilation patterns and impacts for which the use of computational fluid dynamics (CFD) model are more appropriate. Downdraft air velocities were manually calculated over the free area of the openings using average velocities for the large tower of 4 m/s. But to explore the complex internal flows within the tower complex CFD modelling would be required.

One modification from the original building was made to this model for the base case simulation in that the leeward wind tower openings were closed off completely in line with the findings of Bahadori (1985), Karakatsanis *et al*. (1986) and Montazeri and Azizian (2008) who concluded that the performance of wind towers increased by eliminating the risk of short circuiting of air. This also made the system easier to model.

Context of the study

Context: climate of Dubai

Figure 4 shows a Nicol Graph of the climate in Dubai where the hottest month is usually August with average maximum temperatures over 41°C and an average minimum temperature of 30°C (Coles and Jackson 2007).

Sea breezes are important locally, driven by thermal updrafts over the land as it warms after sunrise. By late afternoon the winds are strongest and can reach average wind speeds of up to 12 knots (6m/s) (Coles and Jackson 2007). By late summer, the average daily maximum humidity exceeds 70% and can rise to 80% in September. Diurnal temperatures range between 9 and 13°C providing a high potential for night time cooling of buildings with strong natural airflows. Locals are sensitive to small local variations in climate: 'People were irritable if the dry, hot desert air persisted an hour or so later than normal, delaying the onset of the fresher afternoon sea breeze' (Coles and Jackson 2007).

Context: the Bukhash house

The historic Bastakiya houses are of heavy mud construction (Jackson and Coles 1975). They incorporate a rich vocabulary of decorative and climatic design

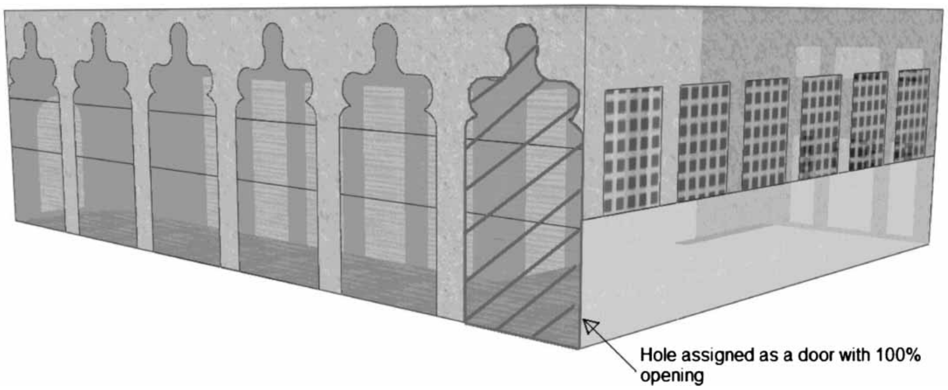

Figure 3. The geometrical sizing of openings in macroflo for the model.

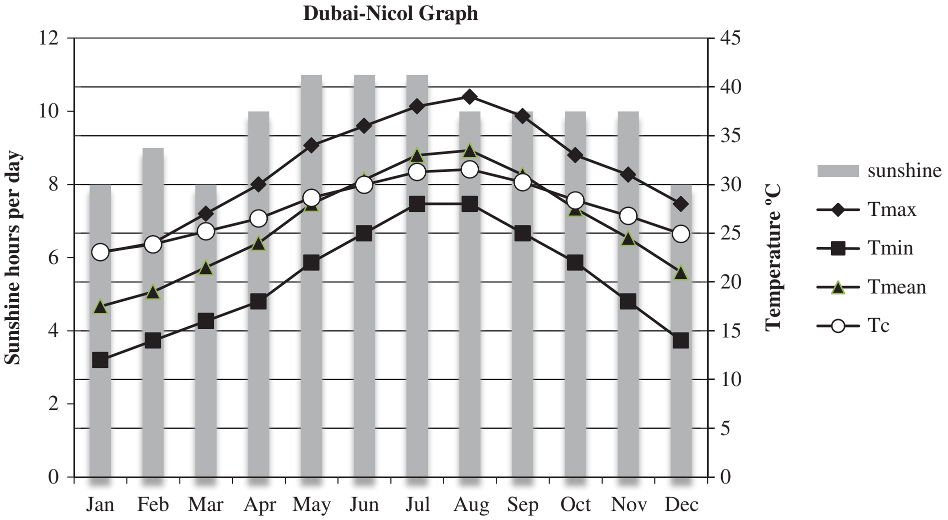

Figure 4. Nicol graph for Dubai.
Source: Reference data obtained from Dubai International Airport.

Table 1. Dimensions and details for the three towers.

Wind tower	Cross-section area (m^2)	Height above roof (m)	Vents per face	Vent decoration
North west	4.58	6.3	3	
North east	9.87	7.5	6	Turk's head
South east	9.87	6.3	3	Turk's head

elements including the wind tower, courtyard, surround shaded narrow alleys and *aiwans* (verandas). Courtyards were an integral part of the overall dwelling design with their own individual rhythms of diurnal heating and cooling in conjunction with the surrounding elaborate design elements helping to absorb and emit heat at different times of day and year.

The Bukhash house consists of two floors built around a central courtyard. The ground floor plan has a floor area of 630m^2 with the stores and living rooms buffered from the hot overhead sun by the similarly planned 320m^2 first floor. The house has three wind towers in the north west, north east and south east corners. The smaller north west wind tower has a cross-sectional area of 4.58m^2 while both the north east and the south east wind towers are larger at 9.87m^2, each of a different shape, size and height above the roof parapet (Table 1). The hottest corner of the house, south west, has none and the largest tower is on the coolest corner (receiving less sun) in the north east.

The wind towers are positioned diagonally to the prevailing north west strong afternoon sea breeze, typical of the wind tower houses of Bastakiya. The wind tower bedroom to the North West, with its four openable window shutters took particular advantage of the sea breezes from the creek. Other distinctive characteristics of the house were the winter and summer living rooms, kitchen and bathroom wing to the south and the staggered main lobby which provided privacy of the family (Figure 5).

Context: people and behaviours

Traditionally many local inhabitants would have migrated to cooler places such as Jumeirah or Shindagha in the Emirates in summer to escape the worst of the heat and humidity in the towns (Coles and Jackson 2007). In Bastakiya, families would move around their own homes, on a well-worn path, in search of warm or cool spots to eat, sleep, work or play at different times of day and seasons of the year. Intra-mural migration was a key part of the complex and interactive comfort system of adaptive behaviours that involved location, activity, clothing, eating, drinking and attitude.

Early mornings were cool and most of the house was usable then, even in summer. As temperatures began to peak after lunch, the family would gather in the wind tower room to eat and sleep taking benefit from the onshore breezes. These rooms had high ceilings so that by stratification warm air accumulated at high level so distancing occupants below from the radiant heat from the roof slab above. At night the roof was the most comfortable place for sleeping, away from the radiant heat of the mud walls below and beneath quilts to conserve body warmth from the radiant cold of the deep space above beyond the night sky. High parapet heights were crucial for security, privacy and in some Gulf homes these walls were perforated by angled slots to keep out prying eyes but still allow air to flow over the lying or sitting behind the

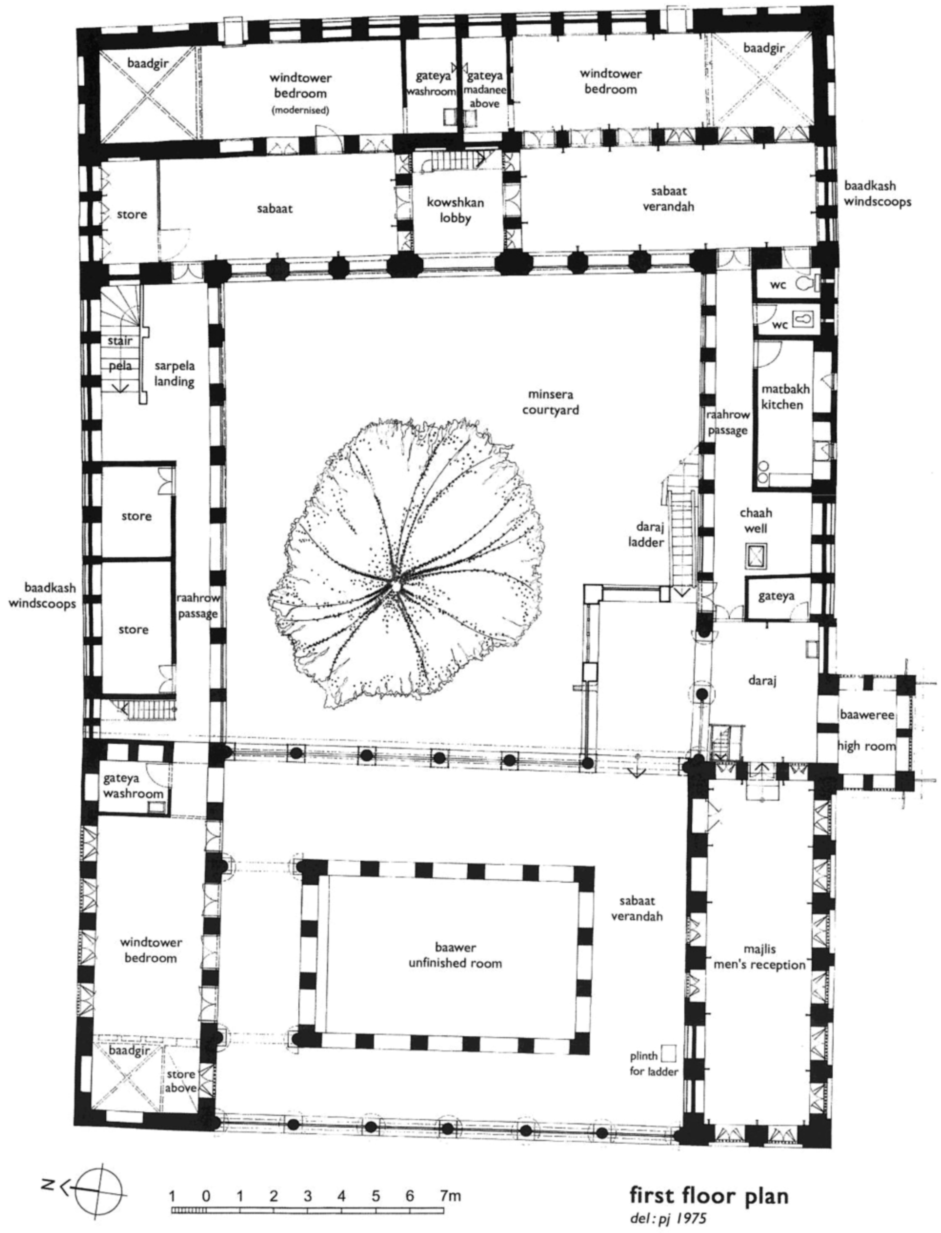

Figure 5. Plan of the Bukhash house, the grey rooms are studied here.
Source: Coles and Jackson (2007).

parapets. Basements were not an option in Bastakiya and many other Gulf settlements due to the high local water tables.

Traditional Arab clothing is designed to provide as much comfort as possible being light and free flowing enabling the pumping action of air around the body to enhance both evaporative and convective heat loss from the skin. White cotton robes are worn by men. Black, worn typically by women, absorbs significantly more solar radiation and studies show that temperatures beneath a black robe can be 6°C hotter than wearing a similar white robe (Shkolnik *et al*. 1980, Nicol *et al*. 2012). The mandatory wearing of black outdoor clothing must provide a temptation for women to stay in the cooler house in their lighter cotton house clothes rather than venture out into hot sunny streets in their black full-length veils.

Predicting the local comfort temperature

Humphreys Adaptive Algorithm (CIBSE 2006; CEN standard 15251: 2007 was used to predict local comfort temperature, based on the adaptive principle that people adapt to those conditions that they normally occupy or they adapt the conditions to improve their own comfort (Nicol *et al*. 2012). Bastakiya has a hostile climate, yet a review of the literature suggests that the wind tower houses generally provided liveable, more or less comfortable, conditions over the year. This comfort experience can certainly not be explained by European and US-centric heat balance calculation methods. When comparing the adaptively predicted comfort temperature against the indoor operative temperature (50%$_{mrt}$ 50%$_{tai}$) was calculated for each time step by the IESVE model.

Validation of the model

The model was validated using results of a previous similar study carried out by VIPAC engineering in 2005 who continuously recorded the temperatures of two similar wind tower houses during July and August of that year (Coles and Jackson 2007). Early validation model runs revealed a good correlation between the outputs of the two modelling exercises. Both found that air temperatures in the wind tower rooms appeared to lag behind the outdoor temperature by approximately 1 hour. The VIPAC concluded, however, that this lag extended to 2 hours but, possibly because of the limited simulation period in this study, a lag of this magnitude was not shown. Temperatures recorded in the wind tower rooms during the day where 1–3°C less than the outdoor temperature, mirroring the results of both the VIPAC and the current model's results. Average temperatures for the wind tower rooms in the VIPAC model were stable at around 35°C with the air from the north-west wind tower presenting as warmer for most of the afternoon, as should be expected being on the afternoon hot side of the house to the west.

Simulation results

The key variables for this research project were identified as the indoor operative temperatures and the air exchange rate of the three wind tower rooms from the external and/or internal environment all of which were obtained from the IESVE software. During the simulation period indoor operative temperatures for the three wind tower rooms ranged from 27.5 to 43°C. Typically the coolest period in the wind tower rooms was between 6:00 and 7:00 hour when the courtyard would typically be at its coolest. The warmest periods were in mid-afternoon. The average indoor operative temperatures for the south-east, north-west and north-east wind tower rooms are 35.3, 35.4 and 35.5°C, respectively. Despite the three wind towers being different in terms of location, height, cross-sectional area and architectural features, the temperatures in the rooms below them fluctuate daily in a similar pattern. This pattern was reviewed for 31 days in August. Particular attention was paid to the day when the peak outdoor temperature occurred to see how the system works in more extreme conditions, that is 10 August at 13:00 hours (Table 2).

In this complex building in summer the coolest space can be taken as a proxy for an occupied space. In the morning the south-east tower room is between 0.5 and 1°C cooler than the other two wind tower rooms as it is more shaded from the sun. The calculated running mean temperatures for the month of august were found to range from 35.7 to 36.9°C. Upper limits for acceptable indoor temperatures using the adaptive methodology, as outlined in BS EN 15251:2007 only extend to a running mean of 30°C. However, the author Roaf recorded people in such houses in Iran being comfortable in temperatures up to 38°C. Note that such conditions are occupied only temporarily over the course of a day (Figure 6).

In contrast, it was found that the total calculated airflow rates entering the room from the external environment are however very different between the three wind towers of the Bukhash house. In the prevailing higher temperatures and modest ambient windspeeds of the study the towers predominantly behaved like chimneys with the dominant flow of air being from the room up to the top of the wind tower. In different climates and conditions the down draft mode may dominate as envisaged in the conventional idea of how wind towers work funnelling cooler air downwards. A parallel predominance of the updraft mode was found earlier with models done by Karakatsanis *et al.* (1986). The airflow rate up into each wind tower room was analysed at the instant when the peak external temperature occurred on

Table 2. Table of outdoor and indoor conditions on 10 August at 13.00 hours.

	Minimum value	Maximum value	Mean value
Wind speed (m/s)	0.5	5.7	3.4
Wind direction	N	NE	NW
Outside dry bulb temperature (°C)	28	46.1	36.3875
Outside wet bulb temperature (°C)	18.06	24.3	22.07
Operative temperature (SE tower Rm)	30.52	43.23	36.66
Operative temperature (NW tower Rm)	31.38	42.41	36.87
Operative temperature (NE tower Rm)	31.11	43.09	36.86
Mean radiant temperature (SE tower Rm)	31.56	41.98	36.83
Mean radiant temperature (NW tower Rm)	32.31	41.08	36.82
Mean radiant temperature (NE tower Rm)	32.01	41.9	37.04
Comfort temperature (°C)	33.4		

NE, north east; NW, north west; SE, south east.

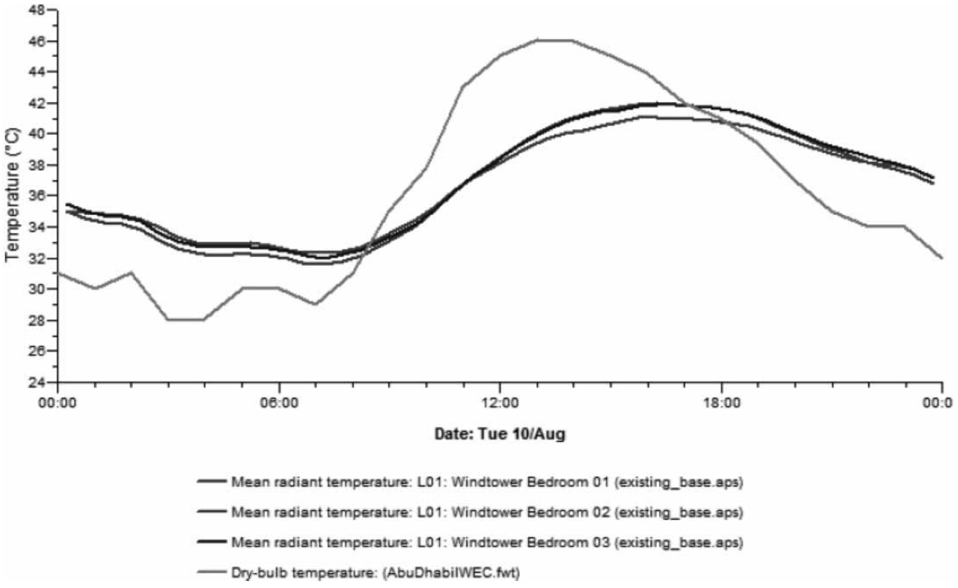

Figure 6. Calculated running mean temperatures for August.
Source: IESVE Vista Application.

10 August at around 13:00 hours. A consistent pattern of air supply was discovered. Airflow to the wind tower rooms in the morning was largely provided from the openings facing the courtyard and not from the wind tower itself. In the morning the courtyard in particular provided a cooler environment than the ambient air above the roof. The warmer north-west wind tower, heating quickly in the morning sun, mainly acted as an exhaust for this air as the cooler air travelled from the courtyard through the shaded aiwans with their shuttered and doors which were assumed to be open for the purpose of this research study. IESVE interprets this air as external ventilation as it comes directly from the courtyard micro-climate. This provision of external ventilation is typically present from dawn to 13:00 hours. As the onshore breeze picked up and the afternoon progressed to early evening the airflow provision is mainly from the wind tower itself, working as a downdraft ventilator. IESVE interprets this air as internal ventilation, as although it comes from outside, it is provided to the wind tower bedroom via an adjacent space, that is the wind tower itself. The air in the courtyard remains cool until mid-day, with some shading from its four walls, but by noon the overhead sun shines makes the court too hot to occupy.

How the house and towers operate

On the basis of the study period of the month of August, a clear finding was that despite large ranges of temperatures in the wind tower rooms at different times of day, the mean operative temperature for air in all three towers was around 35.44 ± 0.1°C with each tower being hotter or cooler at different times of day as the sun moves around the building. At the peak outdoor temperature the mean indoor operative temperatures of all three wind tower rooms shifted to 36.8 ± 0.14°C. These simulation results do indicate the importance of intra-mural migration as each wind tower provided better comfort conditions at different periods of the day. The south-east wind tower provided cooler temperatures to the adjacent rooms in the morning and the north-west in the late afternoon and early evening with migration between rooms during the day potentially significantly improving comfort. Note that in the cool mornings and evenings the family may also have occupied different parts of the courtyard, each with different shade, airflow and mean radiant and air temperatures.

In the moderately still conditions modelled as the sun moves around the building during the course of the day, each tower heats the air within it according to its exposed surfaces (cross-sectional area and height) to shaft volume, so driving stack flows of different speeds within the towers. The house operates as a self-regulating system resulting from the configuration of the towers and the living areas of the house they serve. In still conditions, when temperatures rise above the thermal threshold where the tower air is warmer than the courtyard the tower reverts to updraft mode drawing the cooler air across the living areas. When the internal air in the tower is below the courtyard temperature, it reverts to the downdraft mode.

The temperature in the tower is determined in part by the actual configuration of the tower itself and so the following studies were undertaken to investigate the extent to which this thermal threshold or mode change triggers could be manipulated by the height and cross-sectional area of the tower, thus lowering or raising the trigger temperatures in the self-regulating, natural ventilation system of the whole complex.

Table 3. Percentage change in thermal-operating characteristics of the Bukhash house ventilation system with 33% increase in wind tower height.

	Minimum value	Percentage difference	Maximum value	Percentage difference	Mean value	Percentage difference
Wind speed (m/s)	0.5	N/A	5.7	N/A	3.4	N/A
Wind direction	N	N/A	NE	N/A	NW	N/A
Outside dry bulb temperature (°C)	28	N/A	46.1	N/A	36.3875	N/A
Outside wet bulb temperature (°C)	18.06	N/A	24.3	N/A	22.07	N/A
Operative temperature (SE)	30.41	−0.4	43.12	−0.3	36.56	−0.3
Operative temperature (NW)	31.29	−0.3	42.12	−0.7	36.81	−0.2
Operative temperature (NE)	30.84	−0.9	42.94	−0.3	36.69	−0.5
Mean radiant temperature (SE)	31.47	−0.3	41.89	−0.2	36.75	−0.2
Mean radiant temperature (NW)	32.28	−0.1	41.03	−0.1	36.78	−0.1
Mean radiant temperature (NE)	31.83	−0.6	41.79	−0.3	36.91	−0.4
Adaptive comfort temperature (°C)	30.4					

NE, north east; NW, north west; SE, south east.

Table 4. Percentage increase in air change rates as a result of increasing the tower height by 33% compared to the base model.

	SE tower	Percentage increase	NW tower	Percentage increase	NE tower	Percentage increase
Airflow from courtyard (air changes/hour)	85.1	17.4	42.5	6.3	43	26.5
Airflow from wind tower (air changes/hour)	76	8.1	80.51	10.3	76	2.7

Impact of the height on the wind tower performance

The 3D model of the wind tower house was modified in four ways to explore ways of maximising the ventilation effectiveness of the systems and to reduce internal temperatures and enhance comfort. The characteristics of the tower and openings remained the same as in the initial simulation and in each of the following scenarios, using the same climate data, with attention focused on the hottest day in the dataset on 10 August at 13:00 hours.

Increasing tower heights by 33% did not provide temperatures that would be considered comfortable under the adaptive comfort standard in the rooms, however airflow speeds into the wind towers were increased providing enhanced opportunities for evaporative cooling of occupants seated in the adjacent spaces (Table 3). Airflow rates were measured in two directions, entering from the external environment to the wind tower rooms from the courtyard and entering from the air above the building, down and in from the wind tower. These results concurred with earlier studies by Bahadori (1985) and Karakatsanis *et al.* (1986) who emphasised the benefits of increased wind tower height with the negative quadrants closed off (Table 4).

The north-west wind tower room, is the first to be reached by the prevailing north-west wind that in practice both catches that wind and splits it to create a wind shadow effect to its lee. The resultant vortex consequently reduces the pressure on the windward face of the two other towers. This explains why the majority of the increase in airflow comes in from the north-west tower and not from the courtyard as with the other two towers. This wind-shadow effect was monitored by Roaf (1989) in a number of towers in Yazd. The height increase resulted in both an increase in air change rates up the south-east and north-east wind towers and across the rooms beneath them. Lower vent level air pressure in these towers resulting from the wind shadow will lead to an enhanced stack effect in these towers less fettered by down drafts, as in the case in the north-west tower (Figure 7).

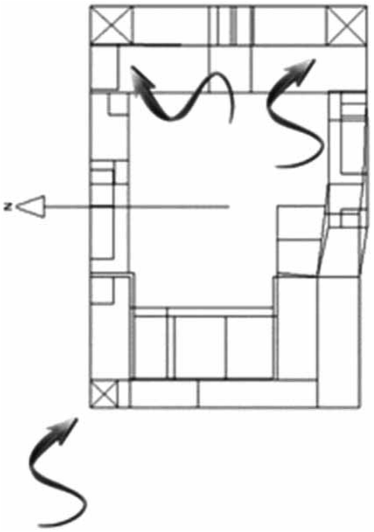

Figure 7. Arrows showing the direction of the main ventilation flow down the north-west tower and up the north- and south-east towers.
Source: IESVE – Suncast application, site orientation.

Table 5. Percentage change in thermal-operating characteristics of the Bukhash house ventilation system with 33% reduction in wind tower height.

	Minimum value	Percentage difference	Maximum value	Percentage difference	Mean value	Percentage difference
Wind speed (m/s)	0.5	N/A	5.7	N/A	3.4	N/A
Wind direction	N	N/A	NE	N/A	NW	N/A
Outside dry bulb temperature (°C)	28	N/A	46.1	N/A	36.3875	N/A
Outside wet bulb temperature (°C)	18.06	N/A	24.3	N/A	22.07	N/A
Operative temperature (SE tower Rm)	30.55	0.1	43.4	0.4	36.75	0.2
Operative temperature (NW tower Rm)	31.45	0.2	42.56	0.4	36.94	0.2
Operative temperature (NE tower Rm)	31.16	0.2	43.31	0.5	36.99	0.4
Mean radiant temperature (SE tower Rm)	31.51	−0.2	42.22	0.6	36.9	0.2
Mean radiant temperature (NW tower Rm)	32.25	−40.2	41.22	0.3	36.86	0.1
Mean radiant temperature (NE tower Rm)	32.01	0.0	42.16	0.6	37.16	0.3
Comfort temperature (°C)	30.4					

NE, north east; NW, north west; SE, south east.

Table 6. Air change rate changes from reducing the tower heights by 33%.

	SE tower	Percentage increase	NW tower	Percentage increase	NE tower	Percentage increase
Airflow from courtyard (air changes/hour)	61.5	−15.2	37.1	−7.3	27.97	−17.7
Airflow from wind tower (air changes/hour)	66.1	−6.0	65.26	−10.6	64.88	−12.3

Decreasing the tower heights by 33% led to a slight increase in operative temperatures and a slight decrease in mean radiant temperatures (Table 5).

The air change rate in the wind tower dropped significantly as a result of the height decrease. Maximum decreases in air change rates with decreased height occurred in the same locations where the largest increase had occurred as a result of the height increases both from the courtyard or from the wind tower itself (Table 6).

Performance of the towers with increased cross-sectional area

When the cross-sectional areas of the three wind towers were increased by 50% limited temperature decreases in the rooms were recorded corresponding approximately to the changes found when the towers were increased in height by 33%. In all cases the decrease in mean operative temperature was less than 0.2°C.

Table 7 demonstrates that an increase in the cross-sectional area actually reduced the airflow rate ventilation performance in the rooms by −8.2% (north east) to 61.1% (north west). The wind tower rooms which benefited most from an increased stack effect from higher towers suffered the most from doubling the cross-sectional areas as the shaft wall to volume was reduced lowering internal air temperatures in the towers. Common to both the south-east and north-east towers is the fact that air drawn from the courtyard is most affected as a result of the decelerated stack effect. The interaction between pressure-driven and

Table 7. Percentage change in thermal-operating characteristics of the Bukhash house ventilation system with a 50% increase in tower cross-sectional area.

	Minimum value	Percentage	Maximum value	Percentage	Mean value	Percentage
Wind speed (m/s)	0.5	N/A	5.7	N/A	3.4	N/A
Wind direction	N	N/A	NE	N/A	NW	N/A
Outside dry bulb temperature (°C)	28	N/A	46.1	N/A	36.3875	N/A
Outside wet bulb temperature (°C)	18.06	N/A	24.3	N/A	22.07	N/A
Operative temperature (SE tower Rm)	30.27	−0.8	43.41	0.4	36.57	−0.2
Operative temperature (NW tower Rm)	30.97	−1.3	42.76	0.8	36.61	−0.7
Operative temperature (NE tower Rm)	30.83	−0.9	43.35	0.6	36.81	−0.1
Mean radiant temperature (SE Room)	31.37	−0.6	41.95	−0.1	36	−2.3
Mean radiant temperature (NW Room)	31.75	−1.7	41.2	0.3	36.59	−0.6
Mean radiant temperature (NE tower Rm)	31.84	−0.5	41.92	0.0	36.9	−0.4
Comfort temperature (°C)	30.4					

NE, north east; NW, north west; SE, south east.

Table 8. Air change rate resulting from increasing tower heights by 50%.

	SE tower	Percentage increase	NW tower	Percentage increase	NE tower	Percentage increase
Airflow from courtyard (air changes/hour)	45.9	−36.7	18.7	−53.3	18.7	−45.0
Airflow from wind tower (air changes/hour)	56.5	−19.6	28.4	−61.1	67.9	−8.2

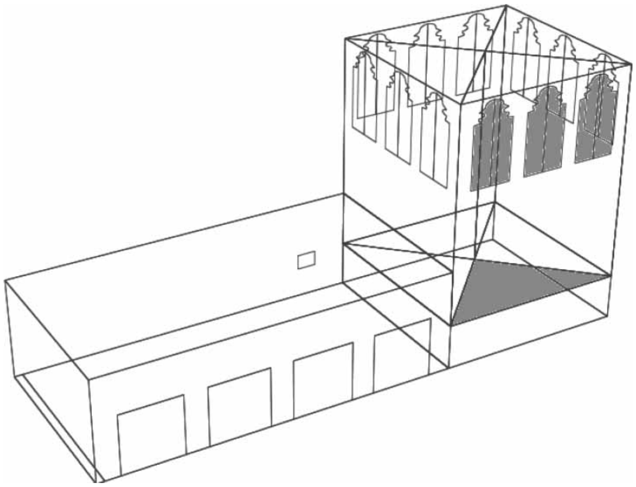

Figure 8. Figure showing the cross-sectional areas of the tower shaft and its related vents.
Source: IES (VE) model viewer.

buoyancy-driven air in the system can be clearly seen here in the north-west tower where the reduced stack effect in the towers combines with the larger volume of the shaft serving the same vent inlet area so also slowing airflow rates down the tower in combination by over 60% (Table 8).

Coles and Jackson (2007) explained that wind towers were said to work best if the open vent area is around twice the area of the cross-section in the triangular shaft below. Doubling the cross-section reduced the vent-to-shaft cross-sectional area ratio as show in Figure 8.

Performance of the towers with decreased cross-sectional area

When the cross-sectional areas of the three wind towers were decreased by 50% this proved to be the first case where a noticeable decrease in operative temperature was recorded. At peak outdoor temperature, that is 10 August at 13:00 hours, the operative temperatures in all three wind tower rooms are more than 1°C below body temperature, at temperatures in a range recorded as comfortable in the 1975 field studies of Roaf (1989). The Adaptive Comfort CEN standard for existing buildings suggests that $T_{\mathrm{comf}} \pm 4$ should be maintained for more than 95% of the time. This simulation has edged the average indoor operative temperature very close to the comfort envelope recommended by CEN (Table 9).

Table 10 shows that reducing the cross-sectional area of the wind tower led to an air change rate increase in the region of 60–100%. This has obviously been the most effect design stratagem to increase comfort within the natural ventilation systems of wind tower houses.

This simulation run using the narrower wind towers draws the majority of this increased air from the courtyard as opposed to from the wind tower itself indicating that the smaller the shaft in relation to the exposed heat walls the higher the internal temperature in the shaft, the stronger the stack effect and the more of the airflow through the house system is drawn from the shaded lower level in the environment, less exposed to solar gain that the upper reaches of the towers themselves. So a little redesign of the system to enhance its stack performance shifts the stack (south east and north east) and pressure-driven (north west)

Table 9. Percentage change in thermal-operating characteristics of the Bukhash house ventilation system with a 50% increase in tower cross-sectional area.

	Minimum value	Percentage	Maximum value	Percentage	Mean value	Percentage
Wind speed (m/s)	0.5	N/A	5.7	N/A	3.4	N/A
Wind direction	N	N/A	NE	N/A	NW	N/A
Outside dry bulb temperature (°C)	28	N/A	46.1	N/A	36.3875	N/A
Outside wet bulb temperature (°C)	18.06	N/A	24.3	N/A	22.07	N/A
Operative temperature (SE tower Rm)	30.02	−1.6	42.33	−2.1	35.93	−2.0
Operative temperature (NW tower Rm)	30.36	−3.3	41.12	−3.0	35.72	−3.1
Operative temperature (NE tower Rm)	30.31	−2.6	41.99	−2.6	35.88	−2.7
Mean radiant temperature (SE tower Rm)	30.55	−3.2	40.46	−3.6	35.55	−3.5
Mean radiant temperature (NW tower Rm)	30.82	−4.6	38.98	−5.1	35	−4.9
Mean radiant temperature (NE tower Rm)	30.72	−4.0	40.1	−4.3	35.47	−4.2
Comfort temperature (°C)	30.4					

NE, north east; NW, north west; SE, south east.

Table 10. Air change rate resulting from decreasing tower heights by 50%.

	SE tower	Percentage increase	NW tower	Percentage increase	NE tower	Percentage increase
Airflow from courtyard (air changes/hour)	117.12	61.5	80	100.0	54.2	59.4
Airflow from wind tower (air changes/hour)	73.51	4.6	93.2	27.7	73.1	−1.2

Table 11. Air velocities calculated for the the tower reduced by reduce cross-sectional area.

	SE tower (m/s)	NW tower (m/s)	NE tower (m/s)
Airflow from courtyard	1.6	1.4	1.8
Airflow from wind tower	3.2	2.9	1.9

NE, north east; NW, north west; SE, south east.

system into a largely stack-driven system in the three towers requiring the whole house systems to source its inflowing air from a different, lower level, cooler, air temperature reservoir centred around the courtyard and its adjacent air sources.

Thermal comfort, especially where it is mainly provided by means of air movement over the skin to enhance cooling by both convection and evaportion is best described in terms of velocity (m/s). As a whole, this dissertation has not examined air movement in terms of velocity as it is not provided by the IESVE software and CFD modelling was not used. However in this simulation study, where the reduced tower cross-sectional area appeared to improve the comfort temperatures provided by the towers, it seemed appropriate to manually calculate the air velocity flowing over the free area of the openings. Table 11 below shows the relevant air velocities that are compatible with the airflows recorded in the field by Roaf (1989) at 'breeze' speeds well able to enhance comfort at the temperatures in the house.

Conclusion

This study has a number of important findings.

Using the dynamic modelling tools IES VE 5.9.0.3 provided an adaptable and a useful tool in understanding key drivers of this complex thermal and ventilation system. Future modifications to enable wind speeds to be incorporated in its outputs would help to understand comfort potentials in hot climates where comfort is dominated by wind speed-dependent heat loss from the skin by convection and evaporation.

In terms of comfort it was found that even on extremely hot afternoons using historic temperature data that, after some modifications including increasing the height of the towers and decreasing their cross-sectional area, the wind tower houses could provide indoor conditions that are high, but very close to those required to provide comfort using the adaptive model of thermal comfort. Temperatures modelled are within comfort temperatures recorded in the wind tower houses of Yazd in the mid-1970s by Roaf (1989) but at the very high end that may explain why the women and children of many Gulf families were sent to summer residences higher inland where the general climate was cooler. This Dubai house was originally occupied by an Iranian merchant' family, and in an interview with its last owner were not described as providing an environment that was so uncomfortable as to be of note during conversations on its summer performance with the author (McCabe).

Behaviours within the buildings are key to the ability to tolerate high temperatures in these houses. Intra-mural migration of occupants around the house in search of the coolest areas in which to eat, rest, sleep, work and entertain is fundamental to their success. Optimised thermal pathways through the indoor activities, time and spaces were exploited to reduce heat discomfort. The results, and interviews, also suggest that the surface treatment of the courtyard, its vegetation, fountains and pools and the practice of wetting floors would also enhance cooling, potentially bringing temperatures near to the CEN 15251:2007 comfort zone; however, these additional cooling features could not be modelled with the performance toolkit provided by IESVE and its bundled accessory programmes.

The natural ventilation systems at play within the whole house are in effect a complex self-regulating climate system that is composed of a number of different elements that are bolted together in one building. Each of the towers works in at least six modes that provide more or less air in or out of the bases of the wind tower shafts and resulting directions and intensities of air movement across the wind tower rooms beneath them to provide:

(1) updraft flows due to stack-driven updrafts;
(2) updraft flows drawn by negative pressure from the leeward pull of a wind pressure-driven flow;
(3) combinations of stack- and pressure-driven updraft flows;
(4) downdraft flows driven from positive wind pressure;
(5) reverse stack downdraft flows resulting from temperature differentials down the tower;
(6) downdraft flows resulting from combinations of pressure and reverse stack effect.

The trigger temperature, in still conditions, at which the downdraft switches to updraft will depend on the cross-sectional area and height of the tower, local wind speeds and direction, the time of day and year and the solar incidence (cloud cover) driving temperatures in the towers. The temperatures within and below the tower, and the trigger temperatures at which the switch between the six modes occurs in each tower can be adjusted by changing the cross-sectional area and height of the towers.

Many of the most climatically effective historic buildings in the world incorporate advanced, complex natural ventilation systems with a number of subsystem features. This study suggests that that each element can effectively be modelled as a subsystem to explore its own internal thermal thresholds and modification potentials to make those potentials earier to access and adapt. The whole system model can be bolted together and tested as a whole system. The wind-tower house works as a whole system that is driven not only by its form and occupant behaviours, but also to a greater extent by the local wind speeds and directions that shape the aeoilian landscape around the whole building and tower confirgurations. The modelling of the Bagkhash house was time consuming and not easy to achieve and one can see why architects and engineers today take the easy way out by simply fixing windows shut and letting machines do the hard work of cooling. However, as afforablity and security of the energy to run those machines decreases and its impacts on the climate become less and less acceptable, the ability to create passive buildings, even in the hottest climates of the world, that create comfort indoors for all or part of the day or year, using the free natural energy of the wind, becomes vital. More work is needed to develop tools that make this task possible and affordable.

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