Assessing the Thermal Performance of Bedouin Tents in Hot Climates

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ABSTRACT HEADING

The aims of this study it to improve conditions inside Bedouin tents shelters and to develop tools to assess shelter quality and comfort. A prototype tent was tested in hot conditions with an internal vapor load. Temperature, humidity measurements and air speed were taken inside the shelter while the external temperature was maintained at 40°C (104°F). Building performance simulation was conducted to produce a simulation model. A model of a tent was constructed using the EnergyPlus simulation software and were calibrated with the test data. The shelter models were simulated in Wadi Rum, Jordan using real data from. The feasibility of heating the tent using only the casual gains from occupants and solar radiation was investigated, although it was found that a tent heated in this way would only be appropriate in spring and autumn. Design issues included coping with stratification of air temperature inside the tent, improving thermal comfort without compromising fabricating the materials cheaply and simply. The validity of the results is limited by the lack of measured data for rates of air infiltration.

INTRODUCTION

The Bedouin tent is an Arabian desert-dwelling for Bedouins or desert dwellers without any sort of heating and cooling devices used in the modernized world. The tent is called in Arabic 'Beit Sha'r' (Woollen House) and is in full contact with the exterior environment (Figure 1). It is a dynamic system with internal environmental characteristics that follow those of the outside, running in a free-mode (Yannas 1994). During the Bedouins migratory roam, the Bedouins need shelter should be both moveable and reliable in a variety of climatic conditions. On the plains and mountains of the Sinai and Wadi Rum, temperatures often rise above 49°C (120˚F). There is neither shade nor wind. However, the black Bedouin tent of coarsely woven goat hair provides a breathing membrane. The black surface creates a deep shade while the coarse weave diffuses the sunlight, creating an illuminated interior. As the sun heats the dark fabric, hot air rises above the tent and air from inside is drawn out, in effect creating a cooling breeze. When it rains and snows on the mountains the woven fibers swell, the tiny holes in the fabric close, and the structure becomes tight. The tent is lightweight and portable and can be easily repaired.

Although Bedouin tents are vernacular dwellings that had and still have a significant function throughout Arab civilization, very little studies evaluated the thermal performance of Bedouin Tents in hot climates. The Bedouin population across Arabia is estimated to exceed 4 million Bedouin (Losleben 2003). Therefore, this study aims to define thermal comfort adaptation measures adopted by Bedouins inside their tents. This work forms part of wider research that aims to assess the thermal performance of Bedouin tents in Arabia. The scope is to investigate the acclimatization strategies inside the tent and how that is influenced by social and cultural behavior. The first objective of the study is to assess the internal

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conditions of a Bedouin tent by taking daily measurements of three environmental parameters (air temperature, relative humidity and air speed) inside and outside the tent. The second part questions the occupants and makes general observations on how Bedouins have their own adaptation mechanisms, which assist them to achieve their thermal comfort. This paper describes a series of measurements and questionnaires to test the performance of a tent in hot climates.

Figure 1 The Bedouin tent in Wadi-Rum, Jordan where measurements were carried.

PREVIOUS STUDIES

The following literature review demonstrates a limited overview on Bedouin tents and thermal comfort in hot climates.

Existing work on Bedouin tents

In 1997, a study by the Bartlett School, University College London graduate was conducted to compare strategies and mechanisms used to achieve thermal comfort in tents in the Negev Desert (Schleisner 1997). The study is considered as the only study that focused on thermal comfort and provided real measurements and analysis for different tents. However, the study did not include any modeling work. One year later, the United Nations Relief and Works Agency (UNRWA) for Palestine and the Near East carried out a study of thermal comfort in low-cost, adobe refugee shelters in hot arid climates (Ajam 1998). Despite the significant information provided by the study, it only focused on adobe shelters which do not correspond to tent structures.

Assessment of thermal comfort in hot climates

Hassan Fathy said: “People living in the hot, climates, are faced with a different problem: amplified ultraviolet rays that hit our concrete structures and rebound onto us in hot and humid weather conditions” (Fathy 1986). In hot climates, it is always necessary to avoid sensible and latent heat gains in every possible way and to achieve thermal comfort conditions while minimizing energy consumption. Ideally, housing in the desert should be cool by day and warm by night. Heavy weight construction and small windows help to achieve this in stone or mud houses, but these are hardly suited to nomadic life (Hillel 1986). The great black traditional tents of the Bedouin do very well. They provide dense shade by day and release a little heat at night. However, in Arabia there are almost no current standards or models that define what those “comfortable” ranges or conditions that should be in residential buildings. At the same time, the available models worldwide are mainly focused on office buildings, partly because of the limited number of surveys in the area of residential buildings. Recent standards are based on Fanger’s PMV-model for sealed air-conditioned buildings and adaptive models for naturally ventilated buildings (Nicol 2004). The ASHRAE Standard 55-2004 (2005) and the EN 15251 (2007) refer both to Bragger and de Dear’s studies. Parsons (1995) finds that western world standards aren’t appropriate for many countries, especially hot climate countries, and an updated international standard for thermal comfort is required (Nicol et al. 1995, Nicol 2004). Therefore, the largest issue in this discussion remains the applicability of those standards and models of none air-conditioned buildings in hot climate residential buildings and in particular tent structure (Attia 2014).

Modelling of Tents

The main sources of uncertainty in modeling buildings in hot climates lies not only in simulating the hygrothermal physical properties of construction materials, casual gains and infiltration rates but also the impact of solar radiation (Attia 2012). For Bedouin tents the case is more uncertain because the building is open and the aerodynamic behavior outside and around the tent in relation to infiltration rates affects the operative temperature through a tent. Another important problem associated with tent modeling is that the data found in literature is scarce or unrepresentative (Crawford el al. 2005). There is insufficient data on thermal performance, infiltration rates and comfort requirements for Bedouin tents. For this study simplifying assumptions have been made regarding comfort criteria in relation to own measurements and literature review.

METHODOLOGY

The research methodology aims to assess the ways in which the Bedouins have adapted themselves (their lives and homes) to the desert environment and the way in which thermal comfort is achieved in their tents and structures in the extreme climatic conditions. The methodology has three fold approaches comprising a field measurement, structured interview and building performance modeling. The aim was to see the difference between outdoor and indoor temperatures and to define the adaptation measures taken by Bedouins to achieve thermal comfort. Four environmental parameters were measured mainly: ambient temperature (°C), indoors and outside the tent (with no effect of sun's radiation), relative humidity (%), wind speed (m/s) using several HOBO U12-12 data loggers and thermal conductivity (W/m·K) using thermo couples. Testo’s (635-2) thermocouples were arranged to give measurements across two vertical slices through the tent for U-values. Four days were spent in Wadi Rum for selecting a representative tent; taking measurements and finding a family that would agree to allow installing the measurement devices and conduct interviews. Two data loggers were positioned on the height of 0.9 m (2 feet) in *Al-Madiyaffa* and *Al-Mah’rim* to measure on the sitting level. One data logger was positioned outside the tent while being shaded. The data loggers took readings for 48 hours on the 3rd and 4th of April 2013. These measurements were measured inside the tents and outside, in the open. During the measurement, ventilation varied continually with the fluctuations in external wind direction and velocity. Due to the limited access to the tent during the day, measurements were carried at a 15 minutes interval using the loggers. The tent unlike a building is an open structure so that wind variations closely follow those of the outside and therefore inaccuracy could be considered to be very small. The qualitative structured interviews were conducted with 6 Bedouins (4 men and 2 women) ranging from 16 to 83 years old. The structured interviews were made based on appointments with the family living in the tent. The questionnaire focused on the lifestyle and occupancy patterns. The climatic adaptation strategies (clothes and activities) taken by the occupants for thermal comfort were questioned too. The interviews findings were summarized and integrated in the performance modeling process to set occupancy schedules and control strategies for the four seasons. The final step was to build a simulation model in EnergyPlus and calibrate the model input and results.

CASE STUDY

“Bedou” is the Arabic word for “inhabitant of the desert.” For centuries, the Bedouin tribes of Arabia migrated from oasis to oasis, wadi to wadi in the deserts of Arabia. They moved about in a land in which every element of survival—food, water, soil, energy—was devastatingly rare. And yet the culture that emerged from these extremities could hardly be called arid. Instead, from a deep understanding of the harsh realities of the land grew fierce protectiveness of territory, an agro-pastoral lifestyle and a rich tradition of vernacular tent dwellings. The roaming Bedouins need their dwellings to be movable and suitable for a travelling lifestyle, a home which could be constructed from materials in the vicinity, which the Bedouin owns or which are plentiful in their environment. Their dwellings need to be maintained in a free-running mode, with minimum expenses. They should be easily and quickly dismantled. These tasks have to be easily performed by the women of the family. Another very important requirement for Bedouin’s dwellings is that they should be suitable for the desert climatic conditions, mainly summer and winter variations as well as the wide daily fluctuations. The true Bedouin only means of transportation is the camel which is the best suited animal the desert conditions. The Bedouin also relies on the camel as a source for food (milk and meat) and energy (dry wooden sticks for fire). The Bedouin's food is very much subsistence, milk, butter, dried cheese made from goat's product, bread and rice (since 1920). During special occasions and feasts, a sheep/goat, is sacrificed and eaten. Goats following the Bedouins around provide valuable wool while transforming the botany of the desert into horn, skins, meat, milk, butter, and cheese. The goat hair gets woven into coarsely woven breathing membrane that is designed into black Bedouin tent. The black Bedouin tent is an ingenious design, locally relevant and culturally rich and makes the desert skyscraper.

Climate Analysis

The simulations were performed using TMY2 weather data for Wadi Rum, Jordan. Wadi Rum is part of the central highlands that comprise of mountainous and hilly regions that run through Jordan from north to south, with varying altitudes of 600 to 1600m (1968 to 5249 feet). Wadi Rum is a valley formed into sandstone and granite rock with monolithic rock spaces that rise from the hot desert ground, reaching up to 1750m in height. The highest elevation in Wadi Rum is Mount Um Dami at 1840m followed by Jabal Rum at 1734m (5688 feet). Wadi Rum has a dry landscape of barren desert. The climate of this region is characterized by hot summers and fairly cold winters. The high variation of daily temperature depends on the time of the year. Summertime temperatures range from 45°C (*113°F*) to 48°C (*118.4°F*), whereas nighttime temperatures can go down to 15°C. The hotter months bring a weather condition called *Khamasin*, which basically means dry, hot and dusty wind blowing from the Arabian Peninsula. Because the weather is dry and the area is sandy, sandstorms are frequent. During winter months, though there is no snow or ice, temperatures during the day can be at 20°C (68*°F*) and night time temperatures can get down to 5°C (41*°F*). Rain is also frequent during this time, though it tends to occur more toward winter months. Wadi Rum experiences at least 12 hours of sunlight every month and the annual precipitation is low where it can be between 50 to 100mm.

Tent Characteristics

The Bedouin tent should be located to favor the climatic conditions (Figure 2). In general the front of the tent should be oriented towards the east in the winter or towards Mecca (Muslims' prayer direction). During the summer the tent front is be oriented towards the prevailing wind direction and the tent might be moved in the mountain shade. The privacy zone of each tent forms a rectangle. The rectangle dimension area 40 yard from the east, west and south and 60 yard from the north. Bedouins call their tent's sections by names of their function and use. The tent is divided into two parts. One part covers the males' section but is left open all day long and the second part covers the females' section and is semi-covered during the day due to the tradition of privacy. The tent size depends on the wealth of the owner thus could comprise from 2 to 7 divisions or *Bawahir*. The front of the tent is called the *Al-Madiyaffa* or *Al-Shiq* for male guests, the back side is called *Al-Mah'rim* for women. Also each pole, carrying the tent, is made from a tree branch and has a name (Figure 2). The traditional tent is woven from goat hair wool so that it stretches well over the poles without the need for much wood. In the traditional tent, the roof is made of long strips of wool sown together which the women weave and are called *Shiqaq*. The back cloth (west) is called Al-Ruaq and is connected to the roof so it can be flexible enough to be pulled up when needed. When winds are too strong, or dust is blown, the cloth can be tightly adjusted and connected to the ground. The side cloths are continuous to the roof cloth. The cloth on the southern side (near the men's section) and on the northern side (near the women's section) is called *Al-Rifraf* and slopes at an angle from the roof. The cloth on the front is known as *Al-Ghidfa* and descends almost vertically down from the roof to the ground during night, rain, cold or strong wind. There are two reasons for this difference in shape. The first is so that strangers coming would be able to recognize the men's part and avoid women's privacy violation. The second reason is that the extended sloping section in the women's room provides extra space for storage of cooking material and water as most of the household activity takes place at the women's section of the tent. The tent has not toilet and Bedouins answer the call of nature in the open field.

The selected tent for this study is a typical unit with five divisions representing the tents found in Wadi Rum (Figure 1). The tent layout is rectangular with a total area of 90 m^2 (968 f^2) with 8 family members (Figure 2). The basic tent roof construction is from goat hair fiber interwoven with sheep hair to repel rainwater. The tent side cloth (*Rifraf* and *Ruaq*) are made from a woolen fiber made from sheep and camel hair. Table 1, lists the general description of the sample tent and some physical properties for the tent construction material used.

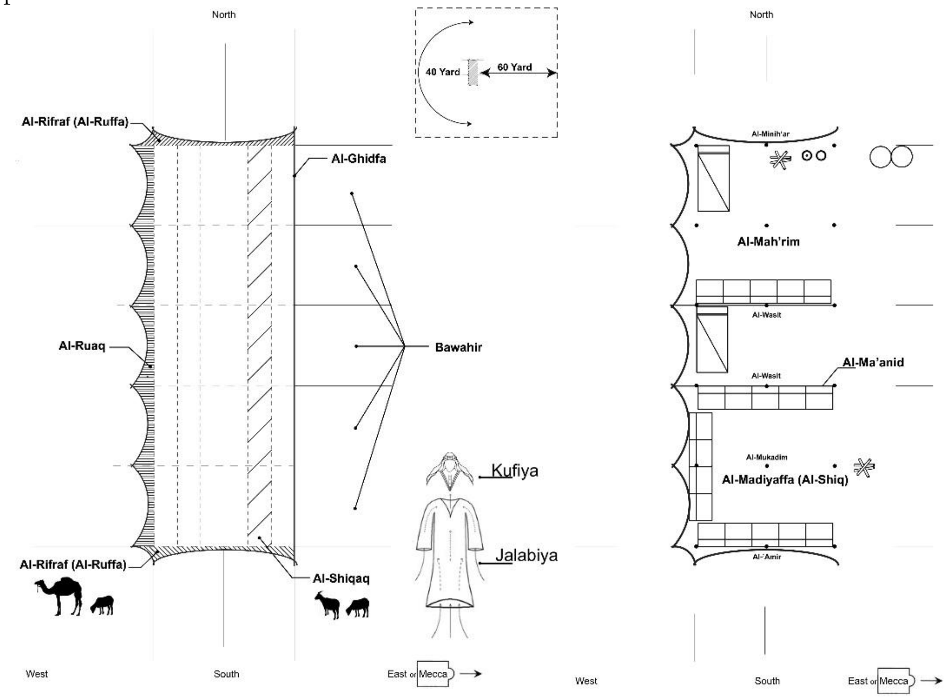

Figure 2 The tent layout and plan description

Model construction

To model the tent, one thermal zone was modeled. The tent model was constructed from surfaces with the appropriate material attributes and control functions representing the goat hair fibre. This was simply a block with thin fiber surfaces and an internal control function that kept the front cloth *Al-Ghidfa* closed during night and when internal operative temperature is below 18°C (64.4°*F*). The evaporative contribution appears as a latent load representing the heat input necessary to support the production of water vapor by eight occupants. In conjunction with the network of energy flows through each surface, the model was prescribed in EnergyPlus taking into account infiltration and natural airflow. The tent was not perfectly sealed and this model used idealized cracks to allow leakage and air exchange to take place. The control options chosen were simulated for winter and summer conditions. For both seasons two control conditions were designed. The first assumed a closed tent, fully exposed to the sun with heat input derived only from the occupants. This control function was free floating and the occupants were represented by loads equivalent to those generated by occupants. The second control function assumed an open tent, shaded after noon with the same occupant's representation.

Table 1 lists the tent characteristics, including climate-specific characteristics.

Climate-specific characteristics		**Tent Canvas Specification**	
City	Wadi Rum	Composition and Color	Goat hair fiber, Silky black, not dyed
Latitude and Longitude	29.3-35.4	Density	22kg/m^3 (+-15%) in finished state
Altitude	1600	Water vapour permeability ISO 17229	2000g/m^2/24h
ASHRAE Zone	3	Water penetration resistance ISO 811	30hPa minimum, increasing speed at 100mm per min
Tent Canvas Specification		Water Absorption @ 100% RH	~15%
Thermal diffusivity (α)	80 m²/s	Thermal resistance (R),	0.1 (m^{2}K)/W
Thermal emissivity (ε)	0.1	Specific heat capacity (cρ),	1.4 kJ/(Kg·K)
Thermal conductivity (λ)	0.05 W/(m·K)	Fabric thickness at 250 Pa (h)	0.005m

RESULTS

The assessment of thermal performance of Bedouin tent aimed to analyse and understand the dynamics in which the tent interior environmental conditions vary in relation to the external climatic conditions. From the climate analysis we found that the direct solar radiation in Wadi-Rum is very intense reaching values of up to 1200 W/m^2, low humidity and clear sky conditions result in very large temperature variation as 20°C (68°*F*) between day and night, the changes in wind direction and increase of speed reach a maximum in the afternoon frequently accompanied by whirlwinds and sand dust Several initial conclusions are drawn from this study which are detailed below.

Measurements and Model Calibration

The tent's thermal performance was measured with occupants inside. The results in Figure 3 show that average temperatures during the day are kept slightly lower than those of the outside extremely high temperatures. From the work carried out it was clearly observed, as expected, that internal conditions within the Bedouin tent closely follow those of the outside. During day the average external temperature kept raising gradually following the radiant temperature until it reach the maximum value of 30°C(86°*F*) at 14:00 during the first day and at 13:00 during the second day. Then temperatures keep decreasing until it reaches the minimum temperatures of 13°C(55.4°*F*) at 05:00 during the first day and 15°C(59°*F*) at 06:00 during the second day. The temperature variation the tent reaches 17°C(62.6°*F*) with almost no time lag during the daily cycle. Maximum relative temperature is reached in the tent during morning and at night, when temperatures are at their lowest value. The interior of the tent, which was open to the exterior, had higher RH values closely following the outside. The wind speed in the tent is on average significantly lower in the tent but they also follow the wind speed outside.

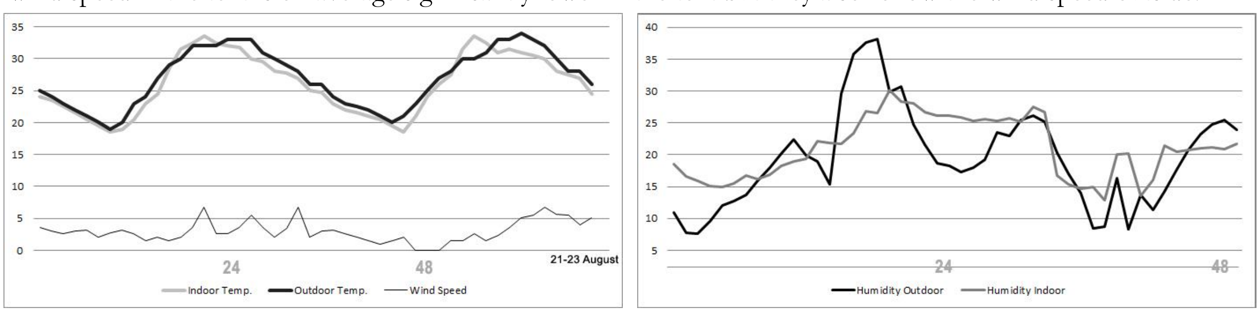

Figure 3 (a) Measurements comparison of temperatures (b) and humidity between indoor and outdoor

To calibrate the model in EnergyPlus the tent was simulated using the environmental conditions collected from the field measurement results. The tent thermal properties, infiltration rate and air change rate were varied until the temperature at the inside was equal to the average, steady state air temperature measured in the tent. With the internal temperature profile of the EnergyPlus model set to agree with the temperature recorded during field measurements the infiltration rate and air change rate were calibrated. This initial air change rate (1) was solely a result of buoyancy driven infiltration during night when the tent is closed. A crude approximation was achieved by calculating the air velocity by the zone volume, summing these volume weighted temperatures and dividing by the total volume. This temperature-by-volume estimate was refined to interpolate the results between data points and then to calculate an estimated temperature-by-area for a large but finite number of points inside the shelter. Finally, the mean average temperatures were taken to calibrate the model.

Simulation Results

The average air temperature was used to calibrate a model constructed using EnergyPlus. Figure 4 shows the minimum annual temperature inside the tent during winter and summer. The tent experienced a minimum average temperature of 16°C(60.8°*F*) during winter day time and 28°C(82.4°*F*) during summer daytime During winter night occupants require the greatest annual heat input because of the high wind speeds and low solar gains. Wadi Rum experiences solar gains but these are outweighed by very low winter temperatures. Thus the greatest discomfort problems occur with high humidity caused by cooking in the unheated tent because the lower internal temperature suppresses buoyancy driven infiltration and humid air becomes more difficult to purge. During summer the intense solar radiation in this Wadi Rum imposes a large thermal load on the tent that affects comfort. The simulation model assumed an increase of air change rate up to 12 ACH which is the main reason to drop the operative temperature. As shown in Figure 4 the operative temperature follows the radiant temperature profile during day before yielding and curbing the profile to follow the outdoor temperature. In the same time, the ventilation rate falls below the 12 ACH due to still wind.

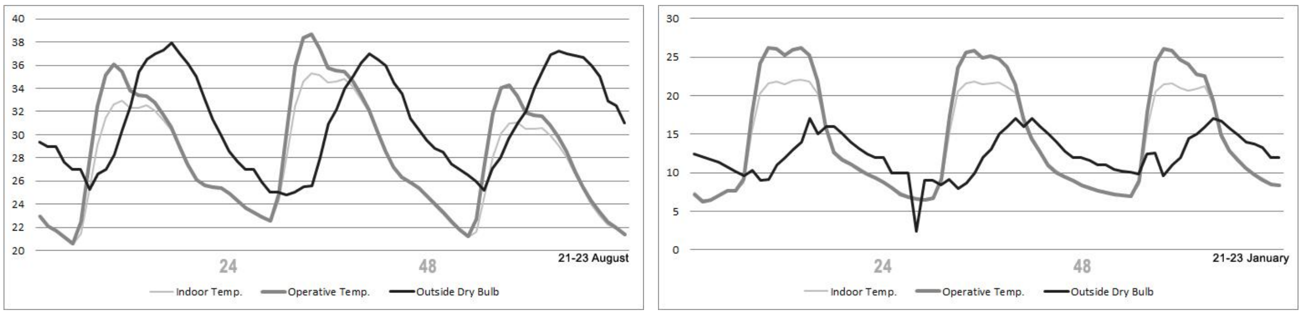

Figure 4 (a) Simulation of the hottest three summer days (b) simulation of the coldest three winter days

The simulation results helped in interpreting the tent thermal performance. The tent is constructed out of thin layers with low resistance to heat flow. The solar radiation warms up the structure causing an increase in radiant temperature. Since the thermal mass is low the internal temperature follows the external temperature quickly. This means that the tent absorbs and releases the radiated energy very fast and reflects the temperature fluctuations consequently. According to the operative temperature profiles the thermal comfort is hardly achieved within the tent. During the summer natural ventilation is not enough to dissipate the heat and during winter the tent air tightness and cloth resistance are not enough preventing the temperatures from going below 18°C (64.4°*F*). Despite the extreme operative temperatures the Bedouin adapt to achieve their thermal comfort. The next section will explain those adaptation measures.

Bedouin Comfort Adaptation

From the carried out conversation with the occupants we found that the tent is occupied all day with women and children. The interview results indicated that during cold winters the temperature inside the tent could drop to a minimum of 4°C (39.2°*F*). Women described the winter as cold. Even enough clothing and blankets restrict people's mobility and increases discomfort especially when they need to answer the call of nature in the open field. In general Bedouins prevent the temperature falling below 15°C (59°*F*) during day by using a stove. During night inhabitants use additional blankets equivalent to a winter sleeping bag per occupant to keep them alive during the night. During night time hours clothing and bedding are vital. Interviewees reported the greatest discomfort problems occurring during winter when humid air become more difficult to purge. The tent is closed and cooking takes place inside with high humidity and reduced infiltration and poor indoor air quality. During hot summers, where the ventilation rate falls, occupants take action to ventilate the tent themselves by lifting *Al-Ghidfa*. The tent is left open all day long. Also owners move the tent and position it facing the prevailing wind and locate next to a steep mountain to make sure they will fall in the shade after noon. When this condition applies, the tent is assumed to be comfortable and occupancy pattern has little or no effect on the environmental conditions inside the tent. The cooking and washing are made either outside or within the ten during the day.

When the interviewees asked on the comfort adaptation strategies during summer mentioned several strategies. First of all, Bedouins avoid having furniture due to their ability to warm up the tent. Bedouin's tradition is to sit on the ground with almost no furniture. The idea is to reduce the internal heat loads and make it easy to move or orient the tent towards the prevailing wind direction. Natural ventilation is effective during summer, highlighting the importance of encouraging buoyancy driven ventilation in the tent. Also during summer they reduce their activity, for example having an afternoon nap, and so the metabolic rate is kept low. Another strategy is to sleep outside to achieve comfort. In fact, Bedouin's sleep most of the year outside the tent except during winter. Another way of reducing the effect of direct radiation is clothing. The Bedouin's typical dress *Jalabiya*, of usually white cotton with long sleeves with a headwear *Kufiya,* is worn by most Bedouin. This dress protects the sky from direct sun radiation and creates a chimney stack effect, allowing ventilation between body and the dress due to air rising from the feet to the neckline (Fathy, Shearer et al. 1986). People tolerate more variation in thermal conditions, and are comfortable over a wider range of temperatures. Acceptable indoor air temperature, range between 24°C(75.2°*F*) and 29°C(84.2°*F*), with relative humidity between 20% and 50% and air velocity 0.5 to 1.5 m/s (Attia 2013).

CONCLUSION

The assessment of thermal performance of Bedouin tent is something new. Certainly it is difficult to draw conclusive findings, however, the field measurement, interviews and modeling allowed comparing the tent performance from different sources. The Bedouin tent is considered as successful dwelling made from light weight sustainable materials and which to some extent provide a certain comfortable internal live in it. The black color blocks the direct solar radiation and controls the reflected radiation from the ground reducing glare. The black tent provides shade and in the same time absorbs more heat, the loose fabric weave lets the heat disperse so that the air flows through the tent and increases the air velocity and improves the thermal comfort. Three crucial factors must be addressed in discussing the validity of the shelter model: (1) computational errors resulting from the numerical methods used by EnergyPlus, (2) over-simplification of the air flow, (3) accuracy of the calibration data. A series of monitoring procedures are scheduled to take place to reduce the uncertainty inherent in this model simplification. Other sources of error include thermocouple measurements of tent cloth, which have been called into question since these tests were carried out. Finally, the structured interviews provided very valuable input on the use of the tent and Bedouin response and life style.

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