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Analysis of behaviour patterns and thermal responses to a hot–arid climate in rural China

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ABSTRACT

Climate can greatly affect building design, life style and thermal perception for all groups of people; however, this phenomenon has not yet been rigorously evaluated in China's hot–arid climate. The aim of this paper is to present the results of a thermal comfort survey by evaluating the influence of the hot–arid climate upon the behavioural patterns and thermal comfort responses of 160 residents in 65 traditional vernacular houses in Turfan, China, in 2011. In this survey, there were 206 sets of effective data, and the features of the traditional residential buildings and the human behaviour patterns in Turfan were described and analysed. The results showed that the diversified courtyards and shade spaces were the most obvious features of traditional houses in Turfan. People here typically spend most of their time in one of two spaces for eating, resting, and entertaining. It was found that the preferred temperature was 26.5 °C. The preferred air velocity occurred at 0.62 m/s. A suitable air velocity range of 0.15–1.24 m/s was suggested in Turfan. Moreover, the neutral temperature of the local people was 30.1 °C (t_g or t_o). The upper limits of the 80% acceptable zone by using the direct and indirect acceptability method were 32.7 and 33.8 °C, respectively. The neutral temperature and upper limit of the acceptable zone in Turfan were higher than those of the adaptive standards. Attention should be paid to the role of thermal comfort in influencing building design by using simple passive cooling strategies. The above results are believed to be potentially valuable for the design and evaluation of residential buildings located in hot–arid climate.

1. Introduction

Thermal comfort and energy saving are two important factors in the sustainable development of human society. Humans, however, tended to consume more energy and resources when they are in a more comfortable living environment (Yang et al., 2014). Building energy consumption accounts for a significant part in China's annual energy consumption, at approximately 10% in 1978, 30% in 2006, and approximately 35% in 2020 (Chen et al., 2008). To improve the indoor thermal comfort, a large amount of energy was consumed for space heating and cooling; this portion of consumed energy is known as building operation energy consumption and, accounted for 80% of the total building energy consumption. In recent years, there has been an upward trend in the operation energy consumption as living standards have improved. Thus, the requirement of thermal comfort and the indoor thermal environmental conditions have a great impact on building energy consumption, and creating a comfortable thermal environment with less consumed energy has become a focus of recent research and policy attention.

Climate has an overarching influence on the culture and thermal attitudes of all groups of people and on the design of the buildings they inhabit (Nicol and Humphreys, 2002; Toe and Kubota, 2013), especially in the hot–arid climates (Cena and de Dear, 2001). Based on a review of the literature, it is apparent that previous thermal comfort studies in hot–arid climates have focused primarily on two different aspects:

1.1. Outdoor thermal comfort

This aspect includes the influence of the height/width ratio on urban heat island/outdoor thermal comfort (Ali–Toudert and Mayer, 2006; Bakarmana and Changa, 2015), the relationship among geometry, vegetation and thermal comfort around buildings in urban settings (Masmoudi and Mazouz, 2004), the microclimatic and human comfort conditions in an urban park (Mahmouda, 2011), and the effect of tree shade in urban planning

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Table 1.
Summary results of thermal comfort in hot–arid climate.

Research	Country	Building operation mode	Neutral temp. (°C)	Comfort zone (°C)
Cena and de Dear (2001)	Australia	AC offices	23.3	22–25 (ET*)
Al-ajmi (2010)	Kuwait	AC domestic buildings and mosques	25.2 (local residents)	23–27
			26.1(devotees)	22.4–29.8 (t_o)
Taki et al. (1999)	Libya	AC buildings	29.4	25–31 (t_g)
		FR buildings	31.6	–
Indraganti (2010a, 2010b)	India	NV apartments	29.23	26–32.45 (t_g)
Nicol et al. (1999)	Pakistan	FR buildings	–	20–30 (t_g)
Farghal (2011)	Egypt	FR buildings	22.9 (NV) 22.0(Mix mode)	< 26 (t_a)
Akair and Bánhidi (2007)	Libya	FR houses and working places	–	16–26.5 (t_g)
Bouden and Ghrab (2005)	Tunisia	FR buildings	–	16–26.5 (t_g)
Rijal et al. (2010)	Nepal	FR (traditional buildings)	–	21.1–30.0 (t_g)

Notes: ET* means the effective temperature, t_o means the operative temperature, t_g means the globe temperature.

(Gómez–Munoz et al., 2010). In addition, a Thermal Comfort Index was developed for outdoor space assessment (Ruiz and Correa, 2015).

1.2. Indoor thermal comfort

This factor has been examined in Pakistan (Nicol et al.,1999), Austrian (Cena and de Dear, 2001), Egypt (Farghal, 2011), Kuwait (Al–ajmia and Loveday, 2010; Al–ajmi, 2010), Libya (Taki et al., 1999; Ealiwa et al., 2001; Akair and Bánhidi, 2007), Tunisia (Bouden and Ghrab, 2005) and India (Indraganti, 2010a, 2010b). A summary of the neutral temperature and comfort zone of subjects found in the above studies appears in Table 1. Cena and de Dear (2001) conducted a field survey in AC offices in Australia, and obtained a comfort zone between 22 and 25 °C ET*(effective temperature) with a neutral temperature (in terms of operative temperature) of 23.3 °C in summer. Al–ajmi et al. (2010) conducted the surveys in AC domestic buildings and mosques in Kuwait; the neutral temperature for the local residents and the devout devotees was found to be 25.2 °C and 26.1 °C and the comfort zone to be 23–27 °C and 22.4–29.8 °C, respectively. In a study performed in the new AC buildings in Libya by Taki et al. (1999), residents were neutral between 25-31 °C (globe temperature). On the other hand, free running buildings in hot–arid climates can have comfort zones from rather low to rather high temperatures. While the data from India (Indraganti, 2010a, 2010b), Libya (Taki et al., 1999) and Pakistan (Nicol et al., 1999) sit at the upper limit of the acceptable temperature of 29.3–32.5 °C (globe temperature), the surveys from Libya (Akair and Bánhidi, 2007), Egypt (Farghal, 2011) and Tunisia (Bouden and Ghrab, 2005) concur on the upper limit of 26.5 °C. A survey carried out by Rijal et al. (2010) in indoor and semi–open spaces of traditional houses during the summer in five districts of Nepal, showed that the indoor neutral temperature was highest in the sub–tropical climate area, medium in the temperate climate area, and lowest in the cool climate areas. The research conducted by Dili confirmed that traditional residential buildings in Kerala were very effective in providing a comfortable indoor environment (Dili et al., 2010).

Located in the Turfan Basin at the southern foot of the Tianshan Mountain in Northwestern China, Turfan has been experiencing an extreme climate: extremely hot and dry in summer. Most local people are Uyghur with Islam religion. The distinctive climate, socio–economic background, the living environment and traditional way of life in Turfan's rural areas play a significant role in affecting the occupants' perceptions of thermal comfort. Thus, the objectives of this study are to investigate the building features and behaviour patterns of the hot–arid rural areas in the summer and to evaluate the influence of a hot–arid climate on the residents' thermal comfort responses. The results of the study are believed to be potentially valuable for the design and evaluation of the residential buildings in other hot–arid areas.

2. Methodology

2.1. Geography and climate

Turfan is located between N 41°20′–43°35′ and E 88°5′–89°54′ and sits at 154 m below sea level. Being the lowest spot in China and the second lowest depression in the world after the Dead Sea, Turfan city has an area of 15738 km^2 and a population of 653,000 (2014), more than 70% of which are Uyghurs. The remainder of the population includes Han, Hui and other minority groups. Kyzyl village is located in the western part of Turfan city, 4 km from the centre of the Turfan city. A total of 65 families from the village were selected to be surveyed. Among these surveyed families, 63 were Uyghurs, one was Hui, and one was Han; The Uyghur and Hui families all practice Islam.

Also known as Fire City, Turfan is possibly the hottest place in China. The distributions of daily outdoor air temperature and relative humidity during the survey period in summer are shown in Fig. 1. It can be seen that the daily average outdoor temperature is approximately 35 °C while the maximum outdoor temperature is approximately 45 °C. The daily average outdoor relative humidity is only approximately 24.9%, which indicates that the summer climate in Turfan is extremely hot and dry and that residents experience extreme heat stress in summer.

2.2. The building features

The building features are represented by two factors: building plan and building envelope, as shown in Table 2. Table 2 shows that the most obvious features of the vernacular houses in Turfan are their diversified courtyards and shade spaces. The shade spaces, also defined as semi–open spaces, are characterized by dynamic, variable, unstable, or fluctuating conditions (Chun et al., 2004). Semi–open conditions are quite complicated and are compounded by the effects of variables such as temperature differentials, solar radiation, wind, and localized microclimates (Berkovic et al., 2012). Meanwhile, the physical environments of the semi–open spaces vary with the type of space and architectural characteristics (Du et al., 2014). There are three typical semi–open spaces in the layout of the buildings. All three types of spaces are equipped with canopies that are supported by walls or wooden stakes, connecting the building and the courtyard. In the first type of canopy shown in Fig. 2(a), most are covered by reed mats, while a few are covered by cardboards or polyester plastics. The second type is the green arbor covered by grapes or ivy (Fig. 2(b)). Greening can reduce the localized thermal load (Edward and Cheng, 2012; Lin et al., 2013); if possible, the local people will