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Assessment of thermal comfort in transitional spaces

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ABSTRACT

Transitional spaces refer to those spaces located in-between interior and exterior environments acting as both buffer spaces and physical links, such as entrance canopies, foyers, lift lobbies, corridors, stairwells, etc. As transitional spaces may constitute a significant portion of the building volume and have large implications to occupants' experience and building energy consumption, many research studies have come up in recent years to examine their conditions and characteristics. This research aims to investigate the thermal conditions and subjective thermal perceptions of occupants in the different types of transitional spaces. Semi-opened and fully enclosed lift lobbies and corridors in The University of Hong Kong (HKU) campus were chosen for the field study. Theoretical study, survey questionnaires and simple energy simulation have been implemented to examine the thermal comfort requirements, people's perceptions and energy impact of transitional spaces.

It was found that an opened area is easily influenced by variable weather conditions as it is close to natural environment while an enclosed one is totally separated from the exterior environment and commonly air-conditioned. This may lead to different subjective thermal responses in these two types of spaces. It was also discovered that people can accept wider thermal environment in transitional spaces and their thermal response varies with dressing, activity level, past thermal experience and prior thermal preference. It is believed that the current comfort standards and criteria are not designed for transitional spaces. The proposed thermal comfort ranges for transitional spaces were examined in this study using modified adaptive comfort model. This could be used to consider possible changes to the current design guidelines and standards. If the transitional spaces are designed with appropriate energy saving strategies such as passive design, hybrid ventilation and flexible HVAC controls, it can help achieve more energy efficient and healthy buildings in the future.

Keywords: Transitional spaces, thermal comfort, energy impacts.

1. INTRODUCTION

Transitional spaces are spaces located in-between interior and exterior environments acting as both buffer spaces and physical links, such as entrance canopies, foyers, lift lobbies, corridors, stairwells (Chun, Kwok and Tamura, 2004). They account for 10% to 40% of total volume in different types of buildings and are considered as one of the alternative means for optimizing building performance (Pitts and Jasmi, 2007). As transitional spaces have large implications to occupants' experience and building energy consumption, many research studies have come up in recent years to examine their conditions and characteristics (Chun and Tamura, 2005; Hwang, *et al.*, 2008; Jitkhajornwanich and Pitts, 2002; Jitkhajornwanich, *et al.*, 1998; Kwong and Adam, 2011; Kwong, Tang and Adam, 2009; Mohanmmad, Martin and Andy, 2012; Potvin, 2000).

However, there is still a lack of information on response to conditions in transitional spaces and current thermal comfort standards do not clearly address such spaces (Chun and Tamura, 2005). This research aims to investigate the thermal conditions and subjective thermal perceptions of occupants in the different types of transitional spaces. Semi-opened and fully enclosed lift lobbies and corridors in The University of Hong Kong (HKU) campus were chosen for the field study. Theoretical study, survey questionnaires and simple energy simulation have been implemented to examine the thermal comfort requirements, people's perceptions and energy impact of transitional spaces. It is hoped that the results could provide information for planning, designing and managing such spaces.

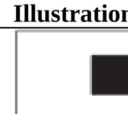
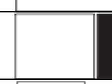
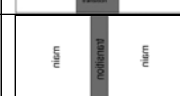
2. TRANSITIONAL SPACES

A transitional or transient space is not directly occupied concerning the major activity of the building (Pitts and Jasmi, 2007). In general, conditions in such zones are characterized as transient, dynamic, variable, unstable or fluctuating features.

2.1 Types and Classification

Chun, Kwok and Tamura (2004) defined the proposed zone as an architectural bridge where the indoor and outdoor climate is modified, without mechanical control systems and the occupant might experience the dynamic effects of this change. Table 1 shows the classification of transitional spaces by different researchers.

Table 1. Classification of transitional spaces

Literature	Types	Illustration
(Chun, Kwok and Tamura, 2004)	Spaces contained within a building where conditions are constantly mixed as people move in and out of the building	
	Attached, covered space connected to the building or between buildings, where outdoor conditions predominate	
	Unattached to a building, entirely influenced by how the design of the structure modifies the outdoor climate	
(Pitts and Jasmi, 2007)	Linear transition space along the shorter façade of a rectangular plan building	
	Area set into the middle portion of longer façade of a rectangular building	
	Space ran parallel to the longer axis of the building	
	External perimeter corridor running around the outside of the building	
(Kwong, Tang and Adam, 2009)	Opened to the environment (corridor)	
	Fully enclosed (lift lobby, passageway, etc.)	
(Pitts, 2013)	Entrance Zones: attached areas with strong connections to the exterior	
	Circulation Zones: internal spaces with greater compartmentalization and separation from exterior	
	Longer-term Occupancy Zones: semi-occupied places with secondary use	

To do the further analysis, this research focuses on the relatively simple categorization: enclosed and opened transitional spaces. The former type refers to the area which is air-conditioned under the normal situation, and the latter type can be fully opened or semi-opened to the external environment which is naturally ventilated.

2.2 Importance

Many people pass through transitional space during their daily life. It is an efficient way to moderate its conditions with the free source available from the nature (Mohanmmad, Martin and Andy, 2012). Reduction of thermal shock for occupants moving into and out of spaces so as to modify comfort expectation also makes sense. For instance, in hot and humid climate like Hong Kong the exterior environment in summer is quite different from the air-conditioned internal conditions. When people move into a transitional space from outside, they can experience step variation in temperature firstly to prevent dramatic thermal discomfort due to the sudden temperature change (Nakano, *et al.*, 1999). Also, the location of opening doors and the use of glazing between some transitional and internal spaces contribute to the stronger thermal connection between those areas with the exterior environment, creating weaker thermal separation.

It is possible for transitional space to consume more energy than the other occupied parts of building of similar size when being conditioned to achieving same comfort requirement (Kwong, Tang and Adam, 2009). One considerable feature of such spaces is that they are frequently placed in the perimeters of buildings with large areas of glazing. This kind of spaces also experience significant air exchange with outdoor climatic conditions. Therefore, they may generally require more building services provision for comfort conditioning and contribute to higher energy use. The energy demand in transitional spaces per unit area or volume may be three times as high as that of the remaining of the building interior (Pitts and Jasmi, 2006).

Moreover, transitional spaces can be regarded as emergency exit routes in the event of fire, therefore, the design of these spaces is crucial for safety, aesthetics and health considerations (Pitts and Jasmi, 2007).

3. THEORY STUDY

3.1 Thermal Comfort Standards and PMV-PPD Method

According to ASHRAE (2013), thermal comfort refers to “conditions of mind that express satisfaction with the thermal environment”. This widely used definition implies that thermal comfort varies from person to person and cannot be defined in an absolute way. The major contemporary comfort standards and assessment tools has been investigated and developed over a period from the middle part of the 20th century (ISO, 2005). To evaluate thermal comfort, a method based on heat balance of the human body was created, taking account of six parameters: air temperature, mean radiant temperature, relative humidity, air velocity, clothing level, and metabolic rate. These parameters were utilized to develop predicted average occupant response on sensation scales, what is called predicted mean vote (PMV) and predicted percentage dissatisfied (PPD).

3.2 Adaptive Method

In recent years, the adaptive method is also provided to adjust the framework of the design standards. The adaptive method is adopted to predict comfort conditions by gathering data about the thermal environment and the simultaneous thermal response of subjects in real situations (Nicol, Humphreys and Roaf, 2012). It indicates that if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort. The adaptive approach to thermal comfort is based on the findings of surveys of thermal comfort conducted in the field. The researchers use statistical methods to analyze the data using the natural variability of conditions. The aim is to predict the temperature or combination of thermal variables (temperature, humidity, and air velocity), which will be found comfortable (Brager and de Dear, 1998).

The adaptive model is defined as a linear regression model that relates indoor design temperatures or acceptable temperature ranges to outdoor meteorological or climatological parameters (ASHRAE 2013). Data from the ASHRAE RP-884 project was used to develop the aforementioned Adaptive Comfort Standard (ACS) for inclusion in ASHRAE Standard 55 (de Dear and Brager, 2001). In the most current version of ASHRAE Standard 55, the applicability of the ACS is limited to optional use in the same types of naturally ventilated buildings that its underlying T_{comf} equation comes from for a prevailing mean outdoor temperature ($t_{\mathrm{mda(out)}}$) range of 10°C-33.5°C. It is further stipulated that these buildings may not employ any kind of mechanical ventilation system for the standard to apply.

3.3 Current Research

Review of recent researches reveals a lack of information for occupant response to conditions in transitional spaces. The majority of standards and criteria focus on the stable and neutral environmental conditions. However, transient areas increase the dimensions of complexities in maintaining comfort level and have more variable thermal environment to produce more fluctuated results in air-change, number of people, clothing, time spent in transit as well as thermal sensation of occupants (Pitts and Jasmi, 2006). The period of time which heat balance can be achieved varies from 15 minutes to 60 minutes. For some transitional zones, the period of time spent there is unlikely to be as long as an hour and may always be less than 15 minutes; and therefore irregularly affect the comfort feeling of occupants.

The majority of comfort assessment reported in the literature and referred to by approved standards concerns indoor environment in which occupants are likely to be engaged in largely sedentary activities and wearing typical indoor clothing ensembles. To use the comfort zone provided in ASHRAE (2013), the metabolic rate is recommended between 1.0 and 1.3, and I_{cl} from 0.5 to 1.0 clo. It could be argued that the activity level in transitional spaces is higher as occupants always move around in such areas, and also because they could be wearing clothing adjusted to the environment they have just experiences (e.g. outdoor) with higher clothing insulation level. Although a transient area is attached to interior, or as a part of the heated and/or cooled buildings, the thermal condition is more like free-running spaces due to its stronger thermal connection to exterior. At the same time, transitional spaces clearly affect this perception and pre-condition expectation.

4. FIELD STUDY AT HKU

The field study concentrated on two categories of transitional spaces, namely semi-opened areas and fully enclosed corridors. Two sites include part of the university street (U-street) in the main campus and an interior corridor in the lower ground floor of the podium in the Centennial Campus (CPD). They were chosen due to the high density of occupants passing through them or their considerable design. The study was conducted in the selected dates with typical weather features (i.e. relatively hot, cold, windy, wet, dry, etc) from December 2013 to April 2014. The subjects were randomly selected on the sites at the chosen days. The responses and exposure data for subjects were acquired simultaneously to ensure that the results were comparable.

The number of subjects in the field survey conducted in the corridor was 83 in total: 41 in the cold season and 42 in the warm day. The subjects were almost equally male and female. The majority of subjects were studying or working in HKU for 1 year to 5 years. Another online questionnaire was set up to collect opinions on thermal conditions in transitional spaces. Total 84 persons took part in this online questionnaire and most of them are university students from Mainland China, Hong Kong, United Kingdom and USA.

4.1 Measurements and Assessments

Objective measurements were carried out in the two proposed sites. Environmental parameters related to the body thermal balance were measured at 1.1 m above the floor level in the center of each site. The results obtained from the objective measurements were tabulated and applied for calculation of PMV and PPD. Temperature sensors connected to a data logger were employed to measure the air temperature and globe temperature which can be used to determine the mean radiant temperature. Air velocity and relative humidity were measured using a portable hotwire anemometer and a 4-in-1 thermal comfort meter, respectively. For subjective assessment, the questionnaire surveys were implemented with a transverse design by randomly inviting people who go through the proposed transitional spaces to answer a questionnaire on each experimental day. The questionnaire, developed in both English and Chinese, was based on the ASHRAE Standard 55. A major section tried to explore the subject thermal perception of the surroundings.

4.2 Thermal Comfort Parameters

The environmental parameters, namely air temperature (t_a), globe temperature (t_g), relative humidity (RH) and air velocity (v), were collected by the data-logger and meters. In terms of thermal comfort analysis, the mean radiant temperature (T_r or MRT) and operative temperature (T_o) should be considered. They can be calculated from the following equations. Table 2 shows a summary of the measurement results.

$$T_r = t_g + 4.02\sqrt{v} \times (t_g - t_a) \qquad T_o = (t_a + T_r)/2$$

Table 2. Mean values and ranges of environmental measurements in the corridors

Location/weather	t_a (ºC)	**T_r (ºC)**	T_o (ºC)	RH (%)	v (m/s)
U-street_cold	18.20 (17.6-19.1)	**19.01**	18.61	56.89 (55.1-60.5)	0.35 (0-0.9)
CPD LG_cold	21.31 (18.2-21.9)	**20.52**	20.91	52.87 (51.0-58.3)	0.11(0-0.3)
U-street_warm	27.32 (26.7-28.1)	**33.65**	30.49	52.39 (50.2-58.1)	0.38 (0-1.2)
CPD LG_warm	25.62 (23.5-28.5)	**26.83**	26.22	63.80 (53.3-66.8)	0.16 (0-0.6)

U-street = University street; CPD LG = Centennial Podium Lower Ground

It is interesting that the mean radiant temperature of U-street was lower than that of CPD corridor in the cold day while the MRT was much higher than the one of CPD corridor in the warm day. This may be because the different weather features in the corresponding experimental days. It was cloudy and windy outside in the cold season, resulting in less solar radiation and high heat conduction and then substantial heat loss. However, it was hot and sunny outside in the proposed warm day so that the MRT was higher. In terms of interior thermal environments, the mean radiation temperature was almost the same in both cold and warm seasons. This may result from relatively stable thermal conditions and less heat transfer.

In general, the air temperature in the U-street semi-opened corridor was higher than that in the CPD interior corridor. In both warm and cold season, the air velocity in the U-street considerably changed with time while that in the CPD corridor did not have apparent change. This is because the U-street is close to the nature and its thermal conditions are greatly affected by the exterior environments.

4.3 Comparing Field Survey with PMV Equation

This research tries to compare average PMV obtained from the field studies and PMV calculated from the equation using the six thermal comfort parameters. Table 3 shows the results of PMV value, which indicate that the PMV from field study is quite different from the one based on the equation. For instance, the average PMV index obtained from the field survey in warm season was 0.05 while it was 1.18 based on the equation. The primary reason may lie on overestimation of the PMV model which predicted slightly warm when the respondents actually felt neutral at certain temperatures (Kwong and Adam, 2011).

Table 3. PMV and PPD for the corridors

Location/weather	Avg. PMV (field survey)	PMV (from equation)	PPD (%)
U-Street_warm	0.864	1.14	32
CPD LG_warm	0.05	1.18	34
U-Street_cold	-1	-0.45	9
CPD LG_cold	-0.381	0.49	10

The PMV indices in the cold day were -0.381 and 0.49 for enclosed corridor though the thermal condition in such site was within the ASHRAE-55 comfort zone. It is interesting that PMV calculated from the equation shows that the thermal sensation of subjects is biased on the warm side which is totally opposite to the result from field studies.

The difference between PMV from field study and theoretical equation was considerable in the enclosed transitional spaces. It is because that people in such spaces have less expectation for experiencing conditioned air (Kwong and Ali, 2011). While considering the PPD based on the calculated PMV, disagreement also happened between the calculated PPD value and the vote on the unacceptability by test subjects in each site. The calculated values of PPD were significantly large, especially for the thermal conditions in the interior transitional spaces in the warm season. However, just 10% of subjects felt discomfort and unacceptable to such thermal environments.

5. SURVEY RESULTS AND ENERGY SIMULATION

5.1 Thermal Sensation and Acceptability

Figure 1 shows the distribution of thermal sensation. From the field study, more than half subjects in the CPD interior corridor voted on scale 0 in the cold day. This kind of thermal conditions in the corridor may be the most neutral for such kind of spaces. Considering the U-street, almost all the participants in the warm season choose scale 0 to +3, while the subjects in the cold season had a thermal sensations biased on the cold side. This implies that the thermal sensations of subjects in the semi-opened corridor mainly depend on the outside weather condition. For the interior corridor, most people feel neutral in both warm and cold days. The distribution of the sensation votes was wider than that in the semi-opened corridor and the votes did not move towards to one side (i.e. warm side or cold side). In the warm season, the subjects voted almost every thermal sensation scales, except scale +2, as they may have different dressing, activity level and past thermal history.

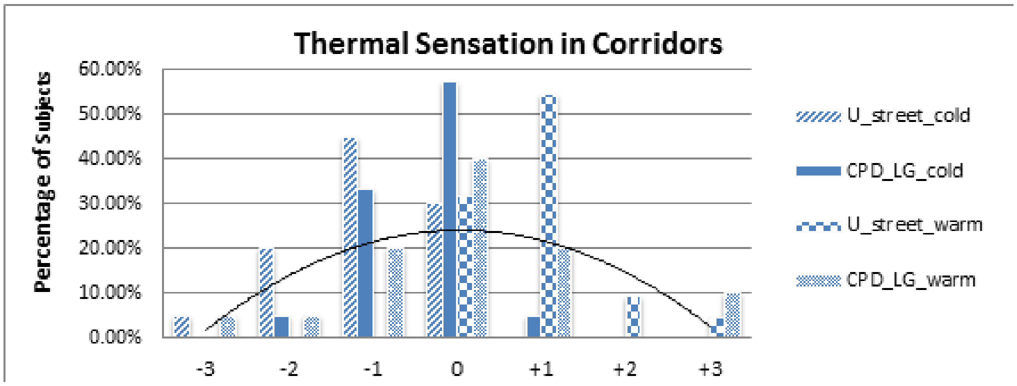


Figure 1. Distribution of thermal sensation in the corridors

In summary, more than 90% subjects can accept the thermal conditions in both naturally ventilated walkway and fully air-conditioned corridor and most of them felt comfort at the same time. It is indicated from Figure 2 that even though the respondents felt discomfort, they can also accept the proposed thermal environment. The acceptability of people in the transitional spaces tends to be large and this brings about the wider tolerance to the thermal conditions in such space.

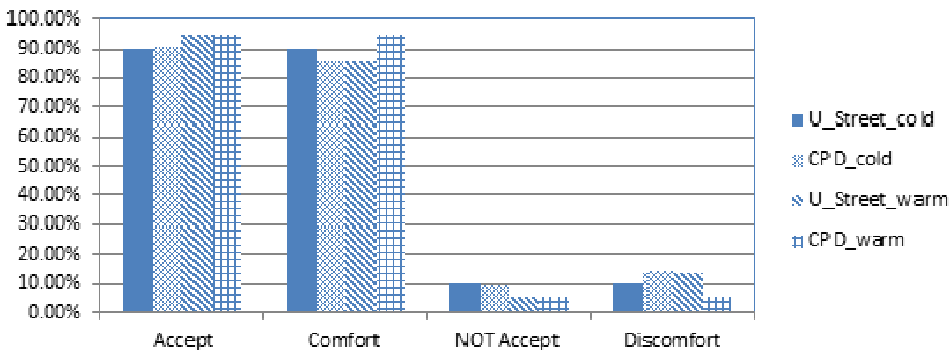


Figure 2. Distribution of thermal acceptability and comfortability vote in corridors

5.2 Thermal Preference and Discomfort

Thermal preference of respondents in the corridors is shown in Figure 3. It can be observed that most of the test subjects wish to maintain the existing environment of both exterior and interior corridors in the warm seasons. This may be because that they have adapted the warm climate in the subtropical countries. There were still more than 40% respondents preferring to experience cooler temperature in the U-street as more than half voted on scale +1.

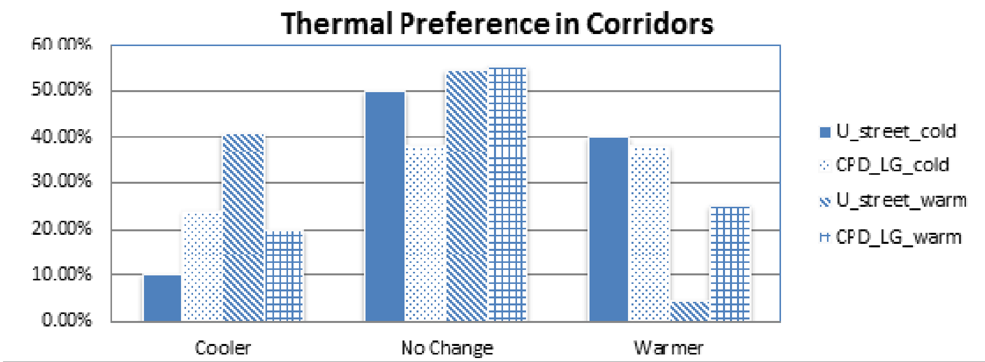


Figure 3. Distribution of thermal preference in the corridors

The reasons why the respondents felt uncomfortable in the corridors were illustrated in the Figure 4. It is interesting that in the same location and under the similar weather conditions, some subjects felt too cold while some of them felt too hot. This may vary with their clothing, activity level, thermal preference and past thermal experience. Most respondents in the U-street found it was too hot and too much sunshine in the warm day and thought it was too cold and too windy in the winter day. This indicates that the semi-opened transitional spaces are quite close to the nature and thermal perceptions of people in such space largely rely on the external environment. For the interior corridor, the thermal sensation of the subjects may be also related to the external environment when people enter into the corridor from outside. They may experience temperature shock and feel discomfort.

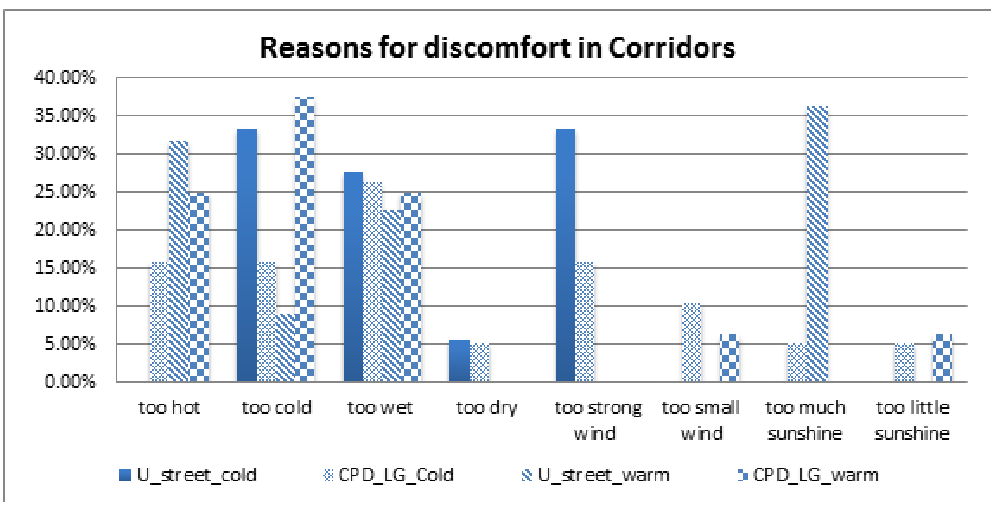


Figure 4. Distribution of discomfort reasons in the corridors

5.3 Tolerable Extent of Thermal Conditions

The results of the online questionnaire indicate that 77% respondents expressed that they can tolerate a wider range of thermal conditions in the transitional spaces. Figure 5 indicates that those subjects might tolerate wider temperature range than humidity change as more people (one third) accept more than 10% temperature change. Considering the extent of less than 5% and 5%-10%, at these levels of temperature changes, tolerances were almost equal, while more subjects chose 5%-10% change of relative humidity.

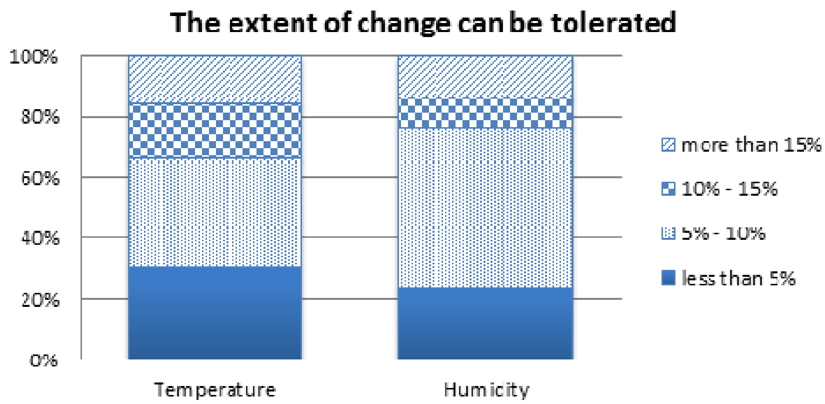


Figure 5. Tolerable extent of change in temperature and humidity

5.4 Energy Saving Potential

To explore the energy use of transitional spaces, ENERGY-10 simulation tool was applied for Hong Kong. Two models were estimated for each type of the transitional spaces (i.e. lift lobby and corridor). The development of modeling of the proposed transitional spaces with the same geometrical configuration, fabric factors and operation parameters, except the thermostat settings is crucial in this research. The results provide a general idea of the energy saving when the range of set-points of air-conditioning system is enlarged and the schedule of operation time is changed. It was assumed that the corridors has 92.9 m^2 (1000 ft^2) of floor area and are commonly occupied by 10 people and used for 5 days a week. The modifications were similar to the lift lobbies, referred to shortening the operation time of HVAC systems and extending the setpoints of heating and cooling thermostats. It was estimated (see Figure 6) that 26% of energy use in the corridors was significantly decreased and cooling energy is the most important factor.

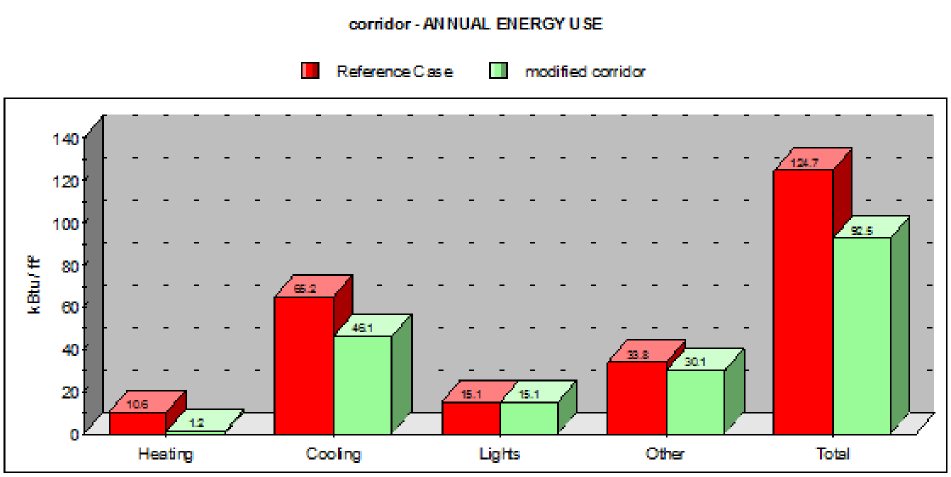


Figure 6. Estimated annual energy use in the transitional space (lift lobby and corridor)

6. DISCUSSIONS

6.1 Use of PMV-PPD method for transitional spaces

As shown in Table 3, the clothing level and metabolic rate in transitional spaces may cause difference between the field-based PMV and equation-based PMV. The difference may also arise from the less expectation of subjects for experiencing conditioned air in the transitional spaces. The relatively high value of PPD is mainly due to the overvalued PPD index which predicts warmer temperature than actual thermal sensation (Wong and Khoo, 2003). In addition, this can be explained in terms of thermal adaptation, where people in the subtropical countries are generally more tolerant towards their thermal environment than people living in temperate regions (Brager and de Dear, 1998). Thus, the PMV-PPD method is of reduced value in the transitional spaces because it uses a steady-state model. Fanger and Toftum (2002) has proposed the extension of PMV model where expectation factor of occupants was provided and this concept may be considered in transitional spaces.

6.2 Adaptive comfort model

The proposed thermal comfort ranges for transitional spaces were examined in this study using modified adaptive comfort model. According to ASHRAE (2013), the comfort temperature (T_{comf}) and acceptable temperature (T_{accept}) for the naturally conditioned spaces can be obtained as:

$$T_{comf}\ (°C) = 0.31\overline{t_{mda\,(out)}} + 17.8$$

$$T_{accept}\ (°C) = 0.31\overline{t_{mda\,(out)}} + 17.8 \pm T_{lim}$$

$\overline{t_{mda\,(out)}}$ is the average of the daily average outdoor dry bulb temperatures, which was measured in the field study. T_{lim} is the range of acceptable temperature and is assume that T_{lim} (80) = 3.85 K and T_{lim} (90) = 2.75 K for the transitional spaces.

For the sites at HKU, the comfortable temperature for warm season and cold season can be calculated as:

$$T_{comf}\ (\text{warm}) = 0.31 \times 27.32 + 17.8 = 26.27\ °C$$

$$T_{comf}\ (\text{cold}) = 0.31 \times 18.20 + 17.8 = 23.44°C$$

$$\text{Warm season: } 22.4°C \leq T_{accept}\ (80\%) \leq 30.1°C$$

$$\text{Warm season: } 23.52°C \leq T_{accept}\ (90\%) \leq 29.0°C$$

$$\text{Cold season: } 19.6°C \leq T_{accept}\ (80\%) \leq 27.3°C$$

$$\text{Cold season: } 20.7°C \leq T_{accept}\ (90\%) \leq 26.2°C$$

6.3 Thermal comfort range

The thermal comfort ranges obtained from the field study are much wider than the commonly used comfort zone and biased on warmer side in the cooling seasons. This provides a strong evidence to indicate that people have wider tolerance range of thermal environments in the transitional spaces. From Figure 2, about half of the thermal environments were out of the thermal comfort zone while more than 85% of the respondents felt comfort in proposed transitional spaces.

More than 80% of the respondents of online questionnaire can accept the thermal conditions in both the lift lobbies and corridors. From Figure 5, approximately 70% of subjects can accept more than 5% change of temperature and more people could tolerate the same change extent in relative humidity. Moreover, people in such spaces have relatively high clothing level and metabolic rate, and can tolerate wider change of thermal conditions. Under this situation, certain adaptive opportunities are available and appropriate the comfort zone may be much wider. This means the range of acceptable temperature can be increased by 10%, such as ± 2.75 K for 90% satisfaction and ± 3.85 K for 80% satisfaction.

6.4 Energy-saving strategies for transitional spaces

The external transitional spaces are often open to the nature and are largely influenced by the exterior thermal conditions. Certain passive strategies have potential to be employed to increase the thermal satisfaction of people. For instance, adding controllable shading device or planting deciduous trees in the sunward side could reduce the excessive solar heat gain into the open transitional spaces in the sunny day and can also prevent the strong wind.

For the fully closed transitional spaces, there is little impact of seasonal variations with respect to the thermal comfort. The discomfort may be caused by the interior HVAC control. Shortening the operation time of HVAC systems in the transitional spaces and adjusting the set points have potential to reduce significant amount of energy. For example, passive cooling and hybrid ventilation systems may be applied in these spaces to achieve energy optimization.

The most efficient architectural shape of transitional spaces is related to the corresponding regional climatic conditions. As they can help to reduce the thermal shock and decrease the energy loss, such spaces would be effective in extreme climatic conditions (Chun, Kwok and Tamura, 2004). New initiative and modifications to the way in which occupants experience, use and interact with buildings will be necessary in order to exploit other options for energy saving (Pitts, 2013). There is a trend in the world for green and energy efficient buildings to include more transitional spaces and reduce the reliance and operation of full air-conditioning system. If the research on thermal design of transitional spaces can be enhanced further, it can help achieve high performance green building.

7. CONCLUSIONS

This research paper provided the basic knowledge of transitional spaces and evaluate the current thermal comfort theories. Field study and surveys were conducted to investigate the thermal performance of semi-opened and fully enclosed transitional spaces in HKU and seasonal variations of subjective responses. It was found that an opened area is easily influenced by variable weather conditions as it is close to natural environment while an enclosed one is totally separated from the exterior environment and commonly air-conditioned. This may lead to different subjective thermal responses in these two types of spaces. It was also discovered that people can accept wider thermal environment in transitional spaces and their thermal response varies with dressing, activity level, past thermal experience and prior thermal preference. It is believed that the current comfort standards and criteria are not designed for transitional spaces. The proposed thermal comfort ranges for transitional spaces were examined using modified adaptive comfort model. This could be used to consider possible changes to the current design guidelines and standards. If the transitional spaces are designed with appropriate energy saving strategies such as passive design, hybrid ventilation and flexible HVAC controls, it can help achieve more energy efficient and healthy buildings in the future.

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