DEVELOPMENT AND PERFORMANCE ANALYSIS OF PERSONALIZED CONDITIONING SYSTEM BY USING RADIANT PANELS

Ravi Garg[1], Vaibhav Rai Khare[1*], Jyotirmay Mathur[1], Vishal Garg[2]

[1]Centre for Energy & Environment,
Malaviya National Institute of Technology, JLN Marg, Jaipur, India
[2]Center for IT in Building Science,
International Institute for Information Technology, Hyderabad, India

ABSTRACT
The building industry nowadays is facing two major challenges–the increased concern for energy consumption reduction and the growing need for comfort improvements. These problems have led many researchers to shift their focus towards Personalized Conditioning System (PCS). It is a method for providing occupants with control of a local supply of air so that they can adjust their individual thermal environment. The objectives of this study are 1) to develop a personalized conditioning system and, 2) to investigate the thermal performances and the effect on the thermal comfort of an occupant using thermal comfort models. An experimental setup of an office cubicle has been designed and fabricated using radiant panels. This system is used for both cooling and heating purpose. For this study, the system is used for heating purpose. During the experiment, different cases were analyzed by varying water temperature and flow rate of water and responses were collected from various subjects. The comfort temperature was found to be in the range of 23.4 °C to 27.3 °C. It was concluded that there is not significant effect on Standard Effective Temperature (SET) by varying the inlet water flow rate. The study concludes that if supply water temperature in kept in the range of 36 °C to 37 °C then achieved SET will be in comfortable range for the winter season in composite climate region of India.

KEYWORDS
Radiant Heating, Personalized Heating, Personalized Radiant Conditioning Systems

INTRODUCTION
Buildings currently account for 40% of primary energy consumption in many countries and are a significant source of carbon dioxide emissions (OECD/IEA). The floor area of commercial and institutional buildings is expected to grow by almost 195% by the year 2050 (IEA 2013) so reducing building energy consumption is a priority.
Despite the significant energy used to serve the demand for thermal comfort, poor thermal comfort is one of the most common complaints from building users. The existing HVAC systems are a major channel for providing indoor thermal comfort, but it contributes to more energy consumption in the buildings. This has led to the urgency to develop and design an alternative system to lower the energy consumption. By considering these problems, researchers have come up with the concept of hydronic radiant heating and cooling. The main advantage of this system is that it

* Corresponding author email: vrk1007@gmail.com

provides sufficient heating at moderate temperatures and adequate cooling at high temperature. In addition, an integrated radiant cooling system treats the cooling load individually and more uniformly and thus improves thermal comfort (Y. Khan et. al. 2015),

The heating and cooling set-points have a significant impact on the overall energy consumption of the mechanical system, and they are chosen based on temperatures at which the most number of people are likely to be comfortable. Standards for indoor thermal environments such as ASHRAE Standard 55 assume that neutral is the most desirable thermal sensation and that the interior temperature should be uniform and steady-state (ASHRAE 55-2013). However, some thermal comfort research suggests that people may be comfortable in wider ambient conditions if their people experience localized heating and cooling of targeted body parts (Y Zhang et. al. 2008).

This motivates the scientists to develop a system which is energy efficient and also fulfills the personal comfort requirement. Personal Conditioning Systems (PCS) are a promising technology for both improving occupants' thermal comfort and simultaneously reducing buildings' heating and cooling energy. They provide comfort by targeting a relatively small amount of energy directly onto occupants. It has been shown that with the use of the personalized cooling system, thermal comfort can be well maintained even at the room air temperatures reaching 30 °C and at a relative humidity of 60–70% (Y Zhai et. al 2013). Several laboratory studies (H Zhang et. al. 2010, E Arens et. al. 2011, H Amai et. al. 2007, C Sun et. al. 2013, V Khare et. al. 2015) have established that PCS can produce comfort across ambient temperature ranges in the vicinity of 18-30 °C. By widening the comfortable ambient condition, personal comfort systems allow energy to be rather easily saved in new and existing buildings, improve buildings flexibility to future climate change, and serve to develop demand response during peak temperatures. PCS can be deployed to assist existing air conditioning (AC) systems or, in climates characterized by moderate temperatures, to enable low-energy conditioning strategies or the avoidance of AC altogether.

This study is focused on development and analysis of office cubical Personalized Conditioning System. This system works on the principle of radiant heat transfer. This system can be used for both cooling and heating purpose. In this study, a radiant heating system is used as a PCS to test the effectiveness of a heated/cooled office cubicle at producing comfort in a realistic work environment with an expanded ambient temperature range.

DESCRIPTION OF EXPERIMENTAL SETUP

The Personalized Radiant Conditioning System (PRCS) experiment was only for concept testing; therefore a very simple cubicle made by plywood was selected. The dimension of the cubicle is taken as 1.4 m x 1.3 m as a standard office cubicle size for one person. The height of the cubicle is taken as 1.3 m considering the average distance of the head from the ground of a person.

The room in which PRCS is placed is a single story room (18 m^2) with concrete exterior walls and floor and having 2 south facing glass windows. The schematic of complete system setup and its location is shown in figure 1.

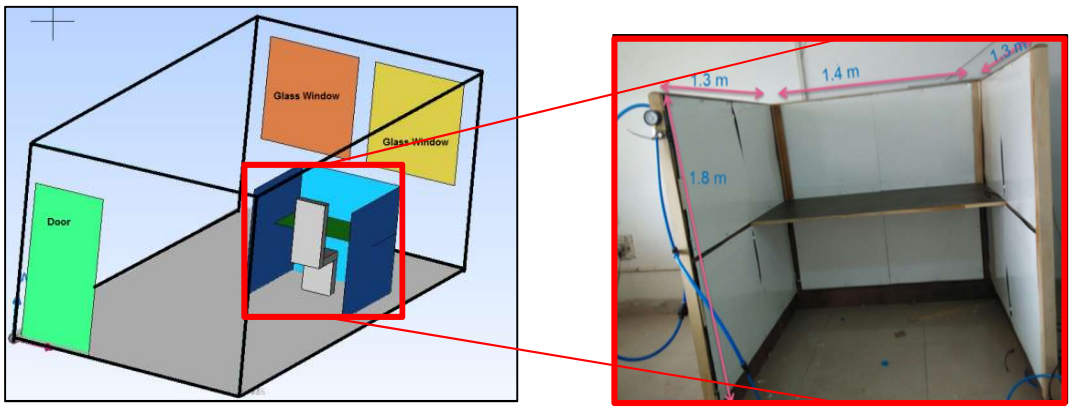

***Figure 1**: Schematic of Experimental setup*

The radiant panel used in this system has been made up of Aluminium with high reflectivity coating to enable radiative heat exchange having a 3 mm small void inside the panel to flow the water from it. This system contains 12 radiant panels of dimension 0.6 m x 0.6 m in 2 loops. An insulation of 9 mm thick sheet of nitrile rubber applied between panels and structure to minimize the heat losses. Hot water is circulated through radiant panels at desired temperature.

METHODOLOGY

The experiments were carried out at the Centre for Energy and Environment at Malaviya National Institute of Technology, Jaipur, INDIA. The PRCS is connected to water supply system by which hot water was flowing inside the panels. Several cases have been selected by taking two factors which are inlet water temperature and water flow rate with the help of Design of experiments (DoE). It is a systematic method to determine the relationship between factors affecting a process and the output of that process. Figure 2 shows the various cases taken for experiments.

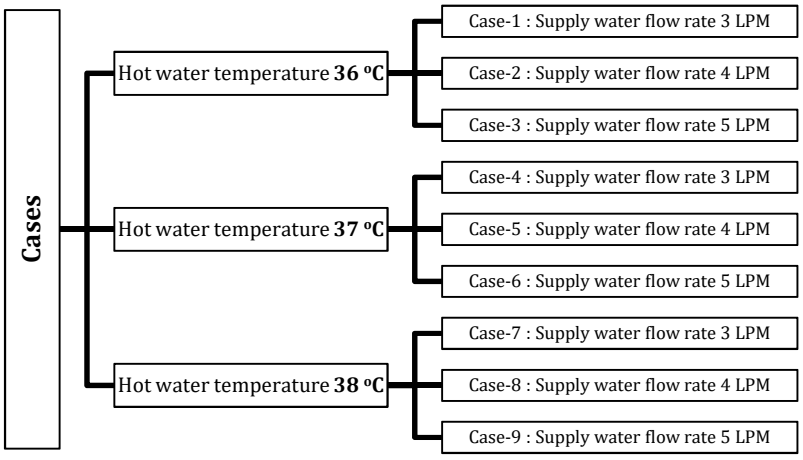

***Figure 2**. Methodology Flowchart*

Test Conditions

Human subjects using the PRCS had their comfort evaluated under mentioned water temperatures. As per DoE total of 9 cases were considered with a combination of 3 different temperature and 3 different flow rates and performed an experiment for all

possible cases. All experiments conducted in between December 2015 - January 2016. The ambient temperature varied from 14 °C to 20 °C for given time duration. Repeated numbers of experiments were performed for each case.

The relative humidity of the chamber maintained at 40 ± 5 % during the analysis period. The air velocity was less than 0.2 m/s. Different subjects of 25-30 age group surveyed for each test conditions using the system to find out thermal comfort. After reaching the steady state of the system, each subject was asked to sit in the PRCS for desired time i.e. 15 minutes to adapt the conditions and stabilize. During the test, subjects were allowed to perform computer-related activities, including their own assignments.

Thermal Comfort Survey

A questionnaire consisted of subjective rating on scales of the thermal sensation, comfort and acceptability were used in the present study to obtain the most significant thermal responses of subjects. Thermo-physical responses using ASHRAE's seven-point Thermal Sensation Scale (TSS) were categorized into cold '-3', cool '-2', slightly cool '-1', neutral '0', slightly warm '1', warm '2', and hot '3'. The traditional assumption is that people voting within the central three categories of the thermal sensation (-1, 0, +1) are deemed comfortable (S Dhaka et. al. 2015).

RESULTS AND ANALYSIS

During the experiment Mean Radiant Temperature (MRT), air temperature, relative humidity, air velocity, inlet outlet water temperature and flow rate, panel temperature, room temperature etc. were measured continuously at 10 minutes intervals with the help of data loggers. The experiments were conducted between 9 AM to 5 PM after achieving steady state. Room air temperature, MRT, and humidity were measured at 1.1 m height defined by ASHRAE Class-II Protocol (ASHRAE 55-2013).

Subjective Evaluation

The standard effective temperature of each subject has been calculated by considering mean radiant temperature, air temperature, air velocity & relative humidity, clothing level and activity level of sitting condition for an office cubical at the time of surveying. Clothing insulation has been calculated as per ASHRAE Standard 55 checklist. Figure 3 depicts the percentage sensation votes collected during the present field study of thermal comfort.

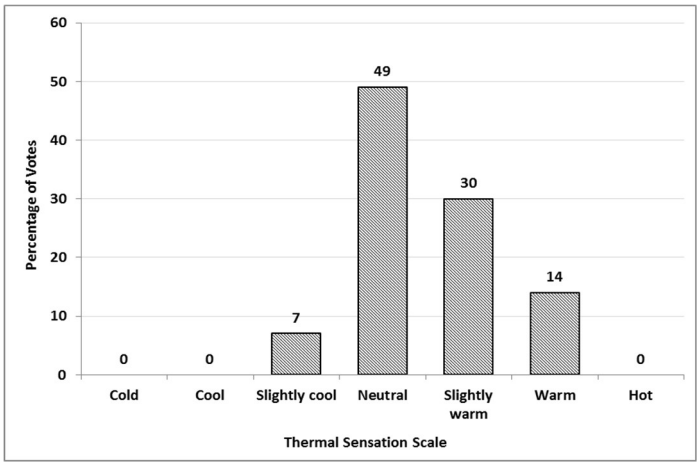

Figure 3. *Thermal sensation votes on ASHRAE 7-point scale*

It can be concluded from the figure that a total of 86% subjects felt thermally comfortable (i.e. votes found within three central categories of thermal sensation) at dominant indoor thermal conditions. A total of 14% subjects were thermally dissatisfied due to warm thermal conditions (sensation higher than +1) and none subject felt thermal dissatisfaction due to coolness (sensation less than -1).

Thermal Neutrality and Comfort Bandwidth

Thermal neutrality refers to particular room air temperature corresponding to mean thermal sensation vote of 'zero' on thermal sensation scale. Linear regression was performed for all data between subject's Thermal Sensation Vote (TSV) and SET to determine the neutral temperature. A curve has been plotted between SET values of each subject and their thermal sensation scale. Figure 4 shows the regression analysis of the SET and TSV. Equation (1) shows the relationship between thermal sensation and SET.

$$TSV = 0.5114*(SET) - 12.974, \quad R^2 = 0.60 \tag{1}$$

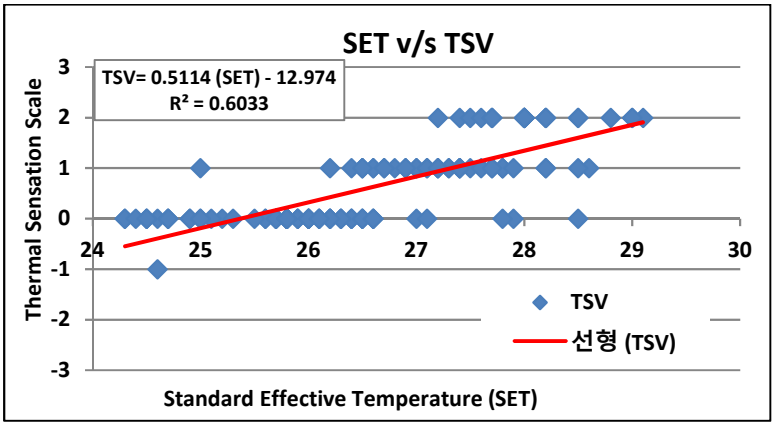

Figure 4. *Regression analysis of thermal sensation vote and SET*

Neutral SET was found to be 25.3 °C considering all subjects response. Similarly the comfort bandwidth 23.4 °C to 27.3 °C obtained through regression analysis. Survey sample data have been plotted on a psychometric chart with respect to Operative Temperature, and it has been found that more than 80% points lie within the thermal comfort bandwidth for the heating zone. Figure 5 shows the operative temperature plot of survey data.

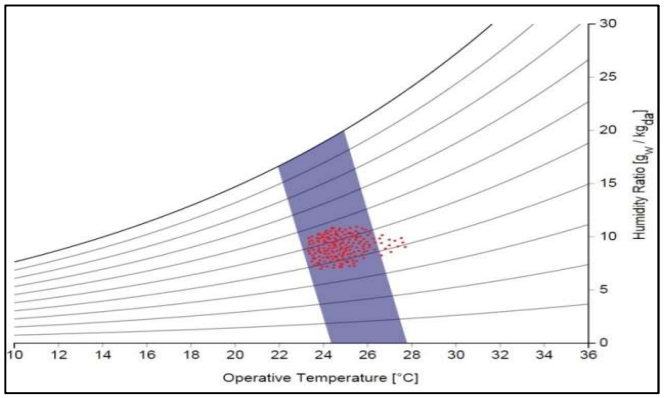

Figure 5. *Sample Plot for Operative Temperature*

Assessment of Performance of the System

The performance of the system was analyzed on the basis of Standard Effective Temperature (SET). Effect on the performance of the system was examined by varying different factors – supply water temperature and flow rate. A mathematical equation was developed between the performance affecting factors and SET to understand the effects of variables on the system. The mathematical equation is shown below which illustrates the relation of SET with supply water temperature and flow rate is given as:

$$\text{SET} = 632.9 - 33.7\,T_i - 6.3\,V_f + 0.17\,T_i V_f + 0.46\,T_i^2 + 0.017\,V_f^2 \qquad (2)$$

where Ti = Supply water Temperature (°C) and V_f = Supply water flow rate (LPM)

The R-square value of this equation was found 0.97 i.e. 97% values were fitted to the above equation, so this model can be used to navigate the design space. Figure 6 shows the plot of variation of SET, supply water temperature and supply water flow rate. It can be stated from the graph that SET increase with increasing supply water temperature.

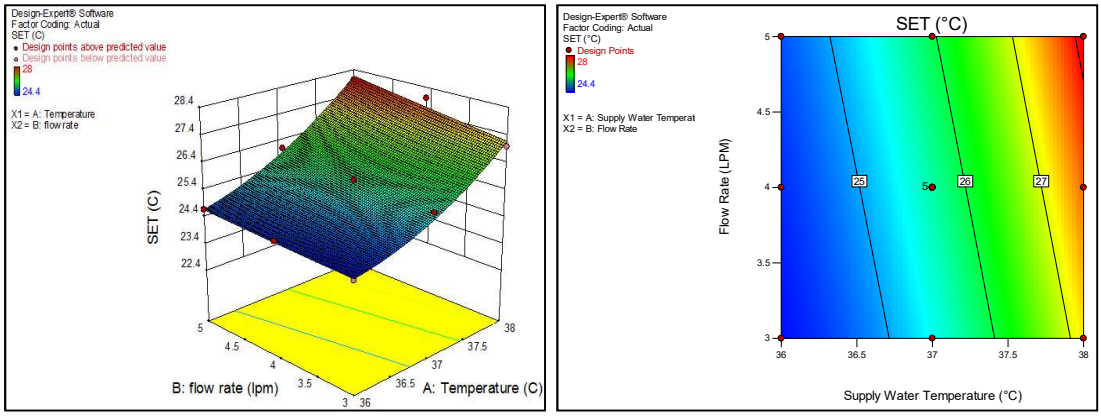

Figure 6. *Plot of Variation between SET, flow rate and flow temperature*

To analyze the effect of parameters i.e. supply water temperature and water flow rate on SET, kept another parameter as a constant alternatively. At first, a constant flow rate has been taken i.e. 4 LPM as it is the mid value of the flow rates. Figure 7(a) shows the variation between SET and supply water temperature. Second, inlet water temperature has been taken as a constant i.e. 37°C.

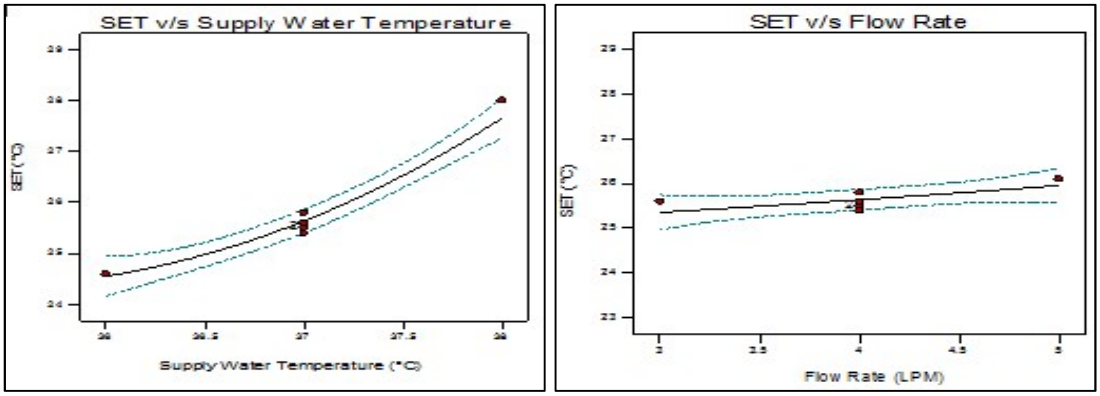

***Figure** 7. Effect on SET by (a) Supply water temperature, (b) water flow rate*

The dotted line indicates the boundary of 95 % confidence interval. It is seen from Figure 7(a) that by varying the supply water temperature from 36 °C to 38 °C, SET varies from 24.4 °C to 27.4 °C or it can be said that variation of 1 °C in supply water temperature results in variation of 1.3 °C in SET. In case of flow rate, it is shown from the Figure 7(b) that variation of flow rate does not significantly affect the SET. The reason behind this is because of very small tube diameter so the potential of heat transfer was not much affected by varying flow rate.

System Performance Analysis for Maximum Utilization

This experiment gives a comfort range and SET for all different combinations of water temperature and flow rate. To generate the most suitable outcome for maintaining thermal comfort, a process has been applied for the neutral SET (23.5 °C) to find out appropriate water temperature and flow rate. This process is carried out for the thermal comfort bandwidth as well and it was observed that if the system runs between inlet temperature 36 °C and 37.6 °C then the desired temperature for thermal comfort achieved.

***Table 1**. Temperature and flow rate for maximum utilization*

		SET (°C)	*Inlet temperature (°C)*	*Flow rate (LPM)*
Neutral SET		25.3	36.8	3
Comfort Bandwidth	(min)	23.4	36.0	3
	(max)	27.3	37.6	3

A graph has been plotted of temperatures for different water temperature 36 °C and 37 °C. It was found that the SET lies in between thermal comfort criteria whereas for 38 °C, after a certain time, the occupant will feel slightly warm. Figure 8 shows the graph of different temperatures for different supply water temperature with respect to time.

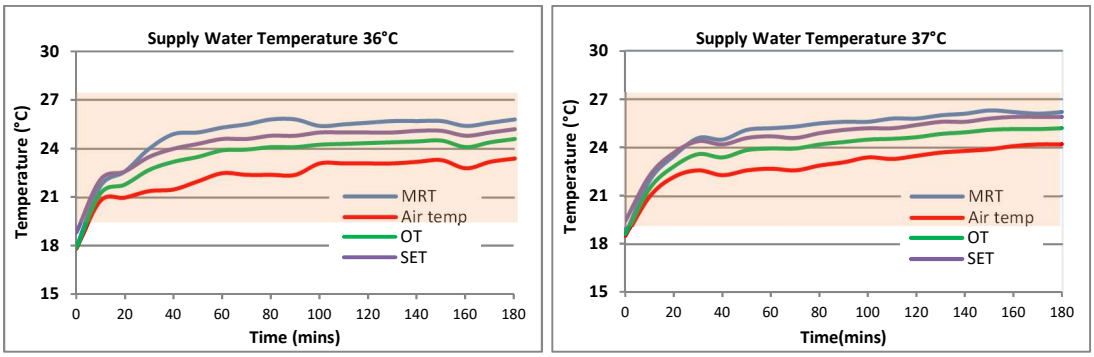

Figure 8. *Thermal comfort representation for different supply water temperature*

CONCLUSIONS

Personalized Radiant Conditioning System in an office has been developed to fulfill the individual thermal comfort requirement. Several experiments performed by varying water temperature and flow rate. A Field study of thermal comfort was carried out on the setup in the composite climate of Jaipur, India. The questionnaire was administrated to building occupant to record sensation for room temperature. Simultaneously, indoor environment variable and surrounding condition of the subjects were recorded considering class-II protocol of measurement. The present study evaluated the effect of thermal environmental conditions on a group of 15 subjects in the office. The main conclusions of this study were

- Correlation between Thermal Sensation Vote (TSV) of subjects and Standard Effective Temperature (SET) has been developed to find out the neutral temperature within thermal comfort range.
- Neutral SET and comfort bandwidth of SET for the system recorded as 25.3 ˚C and 23.4 ˚C to 27.3˚C respectively.
- A mathematical model showing the relationship of SET to supply water temperature and flow rate has been developed.
- For maximum utilization of the system, inlet water temperature and water flow rate has been found for neutral SET and suitable values were 36.8 °C and 3 LPM respectively.

It was found that the designed system was working satisfactorily and fulfills the demand of thermal comfort of each individual.

REFERENCES

Amai H, Tanabe S, Akimoto T, Genma T. Thermal sensation and comfort with different task conditioning systems. Building and Environment 2007;42:3955-64.

ANSI/ASHRAE 55-2013: Thermal environmental conditions for human occupancy. American Society of Heating, Refrigerating and Air-Conditioning Engineers 2013;55.

Arens E, Zhang H, Pasut W, Warneke A, Bauman F, Higuchi H. Thermal comfort and perceived air quality of a PEC system. 2011.

IEA. Technology Roadmap. Energy-efficient Buildings: Heating and Cooling Equipment. 2013.

OECD/IEA. http://www.iea.org/topics/sustainablebuildings/. 2014.

Shivraj Dhaka, Jyotirmay Mathur, Gail Brager, Anoop Honnekeri. Assessment of thermal environmental conditions and quantification of thermal adaption in naturally

ventilated buildings in composite climate of India. Building and Environment 86 (2015) 17- 28.

Sun C, Lian Z, Lan L, Zhang H. Investigation on temperature range for thermal comfort in nonuniform environment. HVAC&R Research 2013;19:103-12.

V Khare, A. Mathur, J. Mathur, M. Bhandari; Development of Personalized Radiant Cooling System for an Office Room, 14th International Conference of the International Building Performance Simulation Association – BS 2015, Hyderabad, India; pg. 933-939.

Y. Khan, V. Khare, J. Mathur, M. Bhandari; Performance evaluation of radiant cooling system integrated with air system under different operational strategies, Energy and Buildings 97 (2015), 118–128.

Zhai Y, Zhang H, Zhang Y, Pasut W, Arens E, Meng Q. Comfort under personally controlled air movement in warm and humid environments. Build Environ 2013;65:109–17.

Zhang H, Arens E, Kim D, Buchberger E, Bauman F, Huizenga C. Comfort, perceived air quality, and work performance in a low-power task–ambient conditioning system. Building and Environment 2010;45:29-39.

Zhang Y, Zhao R. Overall thermal sensation, acceptability and comfort. Building and Environment 2008; 43:44-50.