EMPIRICAL AND HUMAN RESPONSE STUDIES OF PERSONALIZED VENTILATION COMBINED WITH UNDERFLOOR AIR DISTRIBUTION SYSTEM

LI RUIXIN

NATIONAL UNIVERSITY OF SINGAPORE

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LI RUIXIN

(Bachelor of Eng., Tianjin University;

Master of Eng., Tianjin University)

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Summary

This doctoral research is aimed at exploring the use of Personalized Ventilation (PV) system in conjunction with an Under Floor Air Distribution (UFAD) system (PV-UFAD) with focus on improvement of occupants' thermal comfort and inhaled air quality in an energy efficient manner. The problem of "cold feet" and "warm head" in conventional UFAD systems employed for cooling applications are well documented in the literature. In the present study, it is hypothesized that PV air will reduce the uncomfortable sensation of "warm head" by providing fresh air at the facial level while the UFAD system operates with a warmer supply air temperature, thereby addressing the "cold feet" issue.

The experimental conditions for the overall research project, including the physical and human response measurements involved different combinations of UFAD supply air temperature (22 ˚C and 18 ˚C) and PV supply air temperature (22 ˚C and 26 ˚C) as well as three experiments at reference conditions without PV, i.e. UFAD with supply air temperature at 22 ˚C and 18 ˚C as well as ceiling supply mixing ventilation (CSMV) air diffuser. The PV air flow rate was tested with 10 L/s and 5 L/s which result in 0.7 m/s and 0.3 m/s facial velocity respectively. Objective measurements and subjective assessments were employed in this research to investigate the thermal and IAQ performance of UFAD-PV and to assess the acceptability of the UFAD-PV system by tropically acclimatized subjects. A breathing thermal manikin was employed for the objective measurements. Temperature and velocity parameters were measured as well. Subjective responses were collected by means of a questionnaire survey.

The results of the manikin measurements reveal that the warmer UFAD supply air temperature can result in a warmer thermal environment in the lower space of the occupied zone. Subjective responses also showed that the warmer thermal environment created by the warmer UFAD supply air temperature has a positive effect on the thermal sensation and acceptance of air movement at feet level. The performance characteristics of combining PV with UFAD revealed that the use of PV provides cooler thermal sensation at face and improves the whole body thermal comfort and the acceptability of air movement in comparison with use of the UFAD or CSMV alone. By granting the occupants opportunity to choose the PV flow rate, more occupants could make themselves comfortable with the air movement. The measured inhaled air quality and perceived inhaled air quality were also improved by elevated PV air flow rate.

Furthermore, the potential to save energy using the PV-UFAD system is explored by comparing with the conventional mixing ventilation system. Heat removal abilities were found 20% ~40% improved by using UFAD-PV system when compared with that of CSMV system. Moreover, by incorporating the heat-pipe unit into the PV Air Handling Unit (AHU) the energy savings from pre-cooling and reheating was up to 35.6% of total energy consumption of the cooling the outdoor air when compared with a conventional system. The most demanding conditions for the PV supply air temperatures could be achieved by using less reheat energy when the heat pipe was involved.

In view of increased acceptability of perceived air quality and low risk of thermal discomfort combined with the enhanced benefits of PV system (such as increased personal exposure effectiveness), the present study identified that a combination of UFAD and PV consisting of a warmer UFAD supply air temperature (22 ˚C), higher PV flow rate and cooler PV air temperature (10 L/s and 22 ˚C) would be ideal in a hot and humid climate.

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Nomenclature

Abbreviations

AHU	Air Handling Units
AQ	Air quality
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ATD	Air Terminal Device
BAS	Building Automation System
CFD	Computational Fluid Dynamic
CSMV	Ceiling Supply Mixing Ventilation
DR	Draught rating
DV	Displacement Ventilation
FEC	Field environmental chamber
IAQ	Indoor Air Quality
ISO	International Organization for Standarization
MRT	Mean radiant temperature
PAF	Perceived air freshness
PAQ	Perceived air quality
PAT	Perceived inhaled air temperature
PC	Personal computer
PD	Percentage of dissatisfied due to draught
PEE	Personal exposure effectiveness
PEI	Personal exposure index
PEM	Personal Environment Module
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied
PV	Personalized ventilation
RH	Relative Humidity
SBS	Sick Building Syndrome
SIMPLE	Semi-Implicit Method for Pressure-Linked Equations
TAM	Task air module
UFAD	Under Floor Air Distribution
VDG	Vertical desk grill

Symbols

Δt	temperature difference
C	constant dependent on clothing, body posture, chamber characteristics and thermal resistance offset of the skin surface temperature control system ($K.m^2/W$)
C_∞	contaminant concentration in the outdoor supply air (ppm)
C_I	contaminant concentration in the inhaled air of a person (ppm)
$C_{I, SF6}$	SF_6 concentration of the tracer gas in the inhaled air (ppm)
$C_{PV, SF6}$	SF_6 concentration of the tracer gas in personalized air (ppm)
C_R	contaminant concentration in the exhaust/return air (ppm)
$C_{R, SF6}$	SF_6 concentration of the tracer gas in the exhaust/return air (ppm)
h	enthalpy (kJ/kg)
m_a	the air mass flow rate (kg/s)
Q_t	dry heat loss
t^*_{eq}	manikin-based equivalent temperature in reference conditions (°C)
t_0	supply air temperature (°C)
t_{eq}	manikin-based equivalent temperature in an actual environment (°C)
t_{ex}	exhaust air temperature (°C)
$t_{inhaled}$	measured inhaled air temperature (°C)
t_{oz}	average temperature of occupied zone (°C)
t_p	PV supply air temperature (°C)
T_{room}	room air temptterature (°C)
t_s	skin temperature (°C)
t_{set}	space set point temperature (°C)
t_{supply}	supply air temperature (°C)
Δt_{eq}	equivalent temperature difference (°C)
ε_{HP}	energy saving ratio
ε_t	temperature effectiveness
Φ	diameter

Chapter 1 Introduction

1.1 Background

The importance of indoor environment for human health, comfort and productivity is unquestionable (Wargocki et al. 1999, Tham, 2004), as a majority of us spend more than 90% of our time in indoor environments (ASHRAE 2004).

An optimal indoor environment for occupants should be thermally comfortable and should have a high level of indoor air quality (IAQ). The parameters for the indoor environment to satisfy most of the occupants are prescribed by existing standards and guidelines. Whilst ASHRAE Standard 55 (2004) specifies a thermal comfort zone, International Standard ISO 7730 (2005) specifies categories of thermal comfort. Moreover, thermal comfort categories are established in EN 15251 (2007) with corresponding temperature interval. Typically, the thermal comfort standards represent the optimal ranges and combinations of independent environmental variables (air temperature, mean radiant temperature, air humidity and air velocity) and personal variables (clothing thermal insulation and physical activity level), in which 80% or more of the sedentary or slightly active occupants are expected to perceive the environment as thermally acceptable. The acceptable IAQ is defined by ASHRAE Standard 62.1 (2007) as “air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction”. The IAQ is normally expressed as the required level of ventilation or CO_2 concentrations while the perceived air quality (PAQ) is defined as a criterion to achieve the design level of subjective acceptability and comfort which shall be specified in terms of the percentage of building occupants and/or vistors expressing satisfaction with perceived IAQ. (ASHRAE 62.1, 2007 and EN 15251, 2007)

1.2 Ventilation strategies

In order to achieve the indoor environment specified in the standards, the conditioned air should be distributed into the space to remove extra heat and/or indoor contaminants. Over the years, different room air distribution methods have been developed and adopted by HVAC designers and contractors to achieve optimal performance.

In current practice, the most commonly used room air distribution method is total-volume ventilation through ceiling supply system hereby, termed as ceiling supply mixing ventilation system (CSMV). The strategy of mixing ventilation is to control the temperature and/or the volume of the conditioned air, to mix it with the room air and thus to maintain a uniform indoor temperature distribution over the entire space and time. The air supply diffusers, usually mounted overhead, are far from the occupants and thus the supply air, clean or at a low contaminant concentration level, is mixed with the contaminated room air by the time it reaches the inhalation zone of the occupants.

In contrast to CSMV system, displacement ventilation is designed to minimize mixing of air within the occupied zone. The objective of displacement air distribution is to create conditions close to supply air conditions in the occupied zone. In displacement ventilation systems, conditioned air with a temperature slightly lower than the desired room air temperature (e.g. 4~5 °C) in occupied zone is supplied from air outlets at low air velocities (e.g. 0.25 m/s ~ 0.5 m/s). The outlets are located at or near the floor level. The supply air spreads over the floor and replaces the air entrained and moved upward by buoyancy flows generated by heat sources inside the room. Displacement ventilation system is typically differentiated from CSMV system by its lower supply air velocity (e.g. < 0.5 m/s), lower cooling capacity (e.g. 30 – 40 W/m^2) and its reliance on the "thermal flows" generated by heat sources for fresh air distribution (Yuan et al. 1999).

With the advent of electronic or automated office in recent decades, some integrated buildings have started to adopt raised floors to accommodate and conceal the cables and services that are laid underneath. The space created between the structure slab and the raised floor panel forms an under-floor cavity. Other than accommodating the cables, the under-floor cavity can also be used as a supply air plenum. This means that the air treated by AHU can be supplied to office space through the under-floor cavity. In general, under-floor air distribution (UFAD) system uses the same air-conditioning equipment, namely, chillers, pumps, cooling tower and air handling units (AHUs) as in conventional CSMV system. The main difference between the two is the manner in which air is being distributed. Conventional CSMV system supplies air from the ceiling level while UFAD supplies air from floor level and returns to the AHU from the ceiling. The upward air flow pattern and warmer supply air temperature are the most important characteristics of UFAD system that differ from CSMV system. The typical UFAD system supply air temperature is 16~18 °C, which is higher than that of CSMV systems (normally in range of 13~14 °C). UFAD systems are comparable to a DV system in that both systems sometimes supply cold air from diffusers at the floor level. While DV systems generally supply air at low velocity aiming for minimizing mixing and maximizing displacement and vertical stratification in the room, UFAD systems purposely supply air at high velocity (e.g. 0.8~2.5 m/s) with the goal of creating (i) a lower mixed zone that is directly next to the floor and varies in depth according to the vertical projection of the UFAD outlets; (ii) a middle stratified zone, where the air movement is entirely buoyant and the vertical temperature gradient is the greatest; and (iii) an upper mixed zone, which is caused by the rising thermal plumes of the contaminated air within the space. The higher velocities in the UFAD system provide air movement for occupant cooling to offset higher ambient temperatures and the higher supply air volume can tackle a larger amount of thermal load (e.g. 300 W/m^2) (Loftness et al. 2002).

Table 1.1 Comparison of characteristics of CSMV, UFAD and DV

Characteristics	CSMV	UFAD	DV
Space thermal load	wide range of space loads	Wide range of space loads	40-50 W/m^2
Room temperature distribution	Uniform	Uniform at lower space, Stratified at upper space.	Gradient <3 °C
Outlet velocity	2.5 m/s	0.8~2.5 m/s	<0.5 m/s
Supply air temperature	13~14 (°C)	16~18 (°C)	19~21 (°C)
Room air velocity at occupied zone (1.1 m)	<0.25 m/s	<0.25 m/s	0.1~0.2 m/s
$\Delta T_{(Room\text{-}Supply)}$	6~10 (K)	4~5 (K)	2-4 (K)
Ventilation effectiveness	0.5~1.0	1.0~1.2	1.0~2.0

UFAD by virtue of its design has the advantage of moving air in the same direction as the thermal lift in the room. The upward air flow pattern, vertical temperature gradient and warmer supply air temperature are the most important characteristics of the performance of UFAD systems that differentiate them from CSMV systems. Due to these features and characteristics, the UFAD systems have been identified with enhanced performance when compared to CSMV systems. Specifically, researches to date have shown that UFAD systems can provide modest increase in ventilation performance, compared to CSMV systems (Fisk et al. 1991, Faulkner et al. 1995, Tanabe and Kimura 1996, Cermak and Melikov 2006). The air that the occupants breathe will have a lower concentration of contaminants compared to conventional uniformly mixed system. Furthermore, energy savings of UFAD system are between 20%-35% due to reduced volume requirements for conditioned air resulting from the stratification benefits, better ventilation effectiveness for heat and pollutant removal and to higher supply temperatures (Sodec and Craig 1990, Hu et al. 1999, Loudermilk 1999, Bauman et al. 1999, Webster et al. 2000, Loftness et al. 2002, Bauman 2003, Lau and Chen 2007). In addition, the UFAD systems can offer full flexibility in changes to office layout by re-locating the floor diffusers (Shute 1992, 1995, McCarry 1995, Loudermilk 1999, Loftness et al. 2002, Bauman 2003). One further enhanced performance is thermal comfort when the occupants are given the opportunity to adjust the air flow rate and supply air temperature and air flow direction of the floor supply diffuser (Bauman 1995, Bauman 2003).

Although UFAD system has above mentioned benefits, the barriers in adopting UFAD system have also been identified. The main barriers in the adoption of UFAD systems are “cold feet” and draft discomfort, “warm head” and dehumidification.

In spaces served by UFAD systems, the “cold feet” complaint is often reported by occupants as un-comfortable thermal sensation. Leite and Tribess (2006) conducted laboratory study to investigate the subjective responses to different indoor environment at conditions served by UFAD system. The subjects were tropically acclimatized Brazillian college age students. In the condition with relatively higher supply airflow and lower supply temperature (15.4 °C), about 55% of the occupants reported that they felt cold near foot area. In a field study of UFAD in Singapore conducted by Sekhar and Ching (2001), it was found that occupant’s are likely to keep themselves away from the areas near the supply outlet to avoid “cold feet” sensation.

In the thermal comfort studies in non-uniform environments, draft is defined as an undesired local cooling of the human body caused by air movement (ASHRAE 2007). Draft has been identified as one of the most annoying factors in offices. Fanger et al. (1988) found that air temperature, velocity and turbulence intensity have significant influence on the percentage of people dissatisfied due to draft. Arens et al. (1991) reported on higher percent dissatisfied people due to draught when seated near the floor mounted outlet where the temperature was low (18 °C) and velocity was high (> 0.25 m/s). Similar results have also been found by Bauman et al. (1991). It was also identified by the two studies that the room air temperature and velocity distribution are mainly affected by the supply air volume, supply air temperature and the heat load location and density in the space.

To avoid "cold feet" problem, many researchers suggested that warmer UFAD supply air temperature should be used. For example, it was suggested in Bauman (2003) that the typical UFAD supply air temperature should not be lower than 16 °C. But the recommended values are mainly empirical values. Moreover, with warmer UFAD supply air temperature, another uncomfortable sensation, namely "warm head" will arise. In UFAD system, the cool supply air delivered into the room through floor mounted supply outlets is mixed with surrounding room air at lower space level and rises up when it reaches heat sources such as human body and other office equipments. The temperature distribution in the vertical direction of the space will then be stratified. The lower space has a lower temperature and the upper space has a higher temperature. The "warm head" uncomfortable sensation was found mainly due to the vertical temperature stratification and insufficient air movement around head level in a DV system (Zhang et al. 2005). Webster et al. (2002a, 2002b) found that the room vertical temperature stratification was mainly affected by the supply air volume of UFAD, heat load density and its location. The change of the supply air temperature over a range of 15~19 °C with constant supply air volume did not change the shape of vertical temperature profile but only moved it to higher or lower temperatures. When a warmer supply air temperature is adopted, the temperature at breathing level for seated office occupants may rise above the upper limit (25.5 °C, with 60% RH) specified in ASHRAE Standards 55 (2004). Human subject response to the thermal environment in rooms with displacement ventilation reveals that people prefer cooler environment at the head level (Zhang et al. 2005, Cheong et al. 2007). The main difference between DV air distribution and UFAD air distribution is that the air delivered by DV has lower momentum, which will result in different air temperature and flow distribution in the space. The higher momentum at the outlet diffuser of UFAD might increase the risk of draft when relatively cool supply air temperature is adopted.

The climatic conditions have also been identified as a barrier in adopting the UFAD system. Bauman (2003) stated that with warmer chilled water, the dehumidification capacity of the cooling coil will be abated, thus the UFAD system would not be applicable in hot and humid climate where the dehumidification demand is crucial. Similar conclusions have also been reported by Lau and Chen (2007), who conducted energy simulation in five kinds of US climate conditions. Control strategies such as bypass part of return air around the cooling coil and mixing it with the air leaving the coil have been adopted by engineers to produce the desired warmer supply air temperature. More flexible and energy efficient strategies need to be explored. For example, dehumidifying heat pipes is one of the optimal options to enable an air conditioning unit to dehumidify better and still efficiently cool the outdoor air.

1.3 Justification of this study

To gain the merits of UFAD system and to avoid these drawbacks, personalized ventilation (PV) system combined with UFAD system (UFAD-PV) is proposed in this research. Personalized ventilation system is found to have the ability to deliver clean, cool and dry air to the breathing zone of each workplace, thus making it possible to customize the environment to individual preference (Melikov 2004, Sekhar et al. 2003a, 2003b, 2005, Kaczmarczyk et al. 2004, 2006). It also has potential for decrease of risk of airborne cross-infection in spaces (Cermak and Melikov 2007). The combined system configuration consists of two systems: personalized ventilation and under-floor air conditioning (UFAD-PV) system. The UFAD system supplies re-circulated conditioned air in a warmer range to the space to remove the space heat gain. PV system provides 100% conditioned outdoor air at head level for each workstation. Present standards recommend supply of air at elevated velocity for improving occupants' thermal comfort at warm environment. Sekhar et al. (2003a, 2003b and 2005) reported that tropically acclimatized occupants prefer cooler air at facial level when they were in a warm ambient environment. However, these studies were conducted using PV in conjunction with CSMV systems. Cermak and Melikov (2004) and Cermak (2004) reported a study of the PV combined with UFAD system. It was found that the PV air could always protect the occupants from the pollutants. Moreover, when using PV, the inhaled air temperature decreased by about 5~6 °C and thus improved perceived air quality. It also recommended that the UFAD with short vertical throw has the lowest risk of thermal discomfort. However, the effects of the UFAD supply air temperature on the overall thermal sensation and the local thermal comfort at lower body parts, the cooling effect of PV air on the thermal sensation and thermal comfort at facial level in the space served by UFAD with warmer supply air temperature have not been studied and reported. The energy saving potential of PV combined with UFAD system was seldom discussed in the former studies.

Chapter 2 Literature Review

2.1 Overview of UFAD system

UFAD systems were originally introduced in buildings in the 1950s and were developed for computer room applications. The primary concerns of these early applications were to serve the equipment cooling, providing thermal comfort to occupants was not the major focus. In the mid 1970s, such systems began to be employed in general offices, primarily in European countries. Today, UFAD systems have achieved considerable acceptance in Europe, South Africa, Japan and North America. UFAD has been reported to have potential for providing enhanced indoor air quality, energy efficiency and thermal comfort as compared to conventional ceiling supply system (Shute 1992, 1995, McCarry 1995, Loudermilk 1999, Loftness et al. 2002, Bauman 2003, Cermak and Melikov 2006).

In the conventional ceiling supply mixing ventilation (CSMV) system, the ceiling diffusers are usually installed before the layout of workstation and the thermal load have been determined. This often leads to complaints that it cannot adopt the changed layout of workplaces in open-plan office. In addition, when the workstations are equipped with partitions, the air circulation within the workplace will be restricted if the location of the diffuser and partitions are not considered carefully. That will cause complaints of both thermal and IAQ discomfort from occupants. By adopting the UFAD system, the changed ventilation and thermal demand associated with the re-arrangement in the office layout can be accommodated by the flexibility of adding, removing or relocating the supply outlets on the floor. As the UFAD systems distribute the conditioned air directly to the vicinity of occupants', the partitions have less obstruction of the air flow than it does to the CSMV system (Bauman et al. 1991). Thus with UFAD system, enhanced performance of removing the heat and contaminants and improved thermal environment can be expected. Loftness et al (2002) and Bauman (2003) have made a comprehensive review about the UFAD system as one of the flexible HVAC distribution approaches. The UFAD systems were identified with lower cooling capacity compared to ceiling supply systems due to the higher supply air temperature and lower velocity. Greater thermal comfort can be achieved in UFAD system if air velocities are low and diffusers can provide effective mixing without draught. Ventilation effectiveness of UFAD systems were found only moderately higher than conventional ceiling supply system (1~1.2 vs. 0.5~1.0) (Fisk et al 1991, Akimoto 1995, 1999, Fisk et al 2004, Cermak and Melikov 2004, 2006). The improved contaminant and heat removal were found to contribute to the upward direction of air flow. The upward airflow momentum and buoyancy force removes the heat generated in the lower part of the room more efficiently than mixing mechanism which is associated with CSMV system. This indicates that the UFAD system can use less conditioned air or lower supply air velocity to achieve similar heat removal effect as CSMV system does. Thus, energy saving at the air delivery system (fan power) can be expected (Webster et al. 2000). Twenty to thirty five percent energy savings can be expected due to the characteristics of UFAD system such as improved ventilation effectiveness, stratification and higher supply air temperatures (Loftness et al. 2002). Benefit of warmer UFAD supply air temperature on energy saving can be expected but such studies are limited for certain climate condition. Studies in temperate climate (Matsunawa et al. 1995) reveals that with warmer supply air temperature, natural cooling period can be extended thus 30% of cooling energy saving potential can be estimated from air side economizer operation, also, the energy efficiency was increased approximately 5% at cooling plant side. This study also reported that the energy saving from night purge operation using the floor slab thermal storage was estimated to be 186 Watt·hour/day/m^2.

However, those benefits cannot be achieved coincidently. In the performance of UFAD system, since the conditioned air is supplied directly to the occupied zone, there might be a high risk of draught at those spaces. To avoid the draught risk, some researchers suggested that occupants should be kept away from the vicinity of supply diffusers. Warmer supply air temperature is commonly recommended as a method to protect occupants from draught. However, when warmer supply air temperature is used, due to the large temperature stratification, the problem of warm head sensation is introduced. From the studies of UFAD system in office context, higher risk of draught was normally found in the regions close to the floor diffusers. The local thermal environment around the floor diffusers were found closely related to the supply air flow rate, supply air temperature, and capability of the floor diffuser in promote mixing. Arens et al. (1991) and Bauman et al. (1991) performed experiments with TAM (Task air module, Figure 2.1) and reported on risk of draught discomfort at high flow rate and spread of cooler air close to the floor across all the area of the room due to the reduced mixing. Based on the study of thermal performance of TAM system with thermal manikin, Bauman et al. (1995) recommended that the distance between the TAM diffuser and occupants should be kept at 1~1.5 m to avoid cold draught when the supply air temperature in range of 16 °C to 21.6 °C.

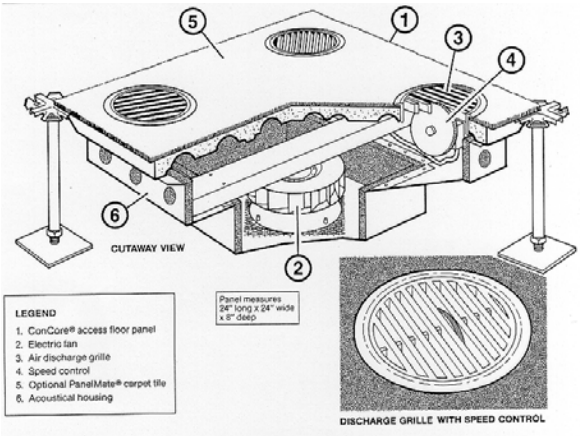


Figure 2.1 Task Air Module (TAM) [Source: Arens et al. (1991)]

The recommended minimum distances from UFAD diffuser are shorter in the studies which use floor diffusers with higher capability of promoting mixing. Matsunawa et al. (1995), based on measured heat loss from thermal manikin concluded that with fan powered swirl diffuser draught discomfort zone could be avoided beyond 0.8 m from a floor outlet. Lau and Chen (2007) reported on the performance of floor-supply displacement ventilation with swirl diffusers and found that draught risk can be high in an area within 0.5 m around the swirl diffuser. Chao and Wan (2004a, 2004b) studied Floor –Return (FR) type UFAD systems and reported that the decay of the air velocity against height was affected by the density difference between supply air and the room air. Near the region of floor supply outlet, higher draught risk (>15%) was found to be associated with high velocity. However in practice, it is difficult to restrict the occupants from approaching the higher draught risk area close to the floor diffuser.

Another method commonly recommended to prevent cold draught at occupied zone is to supply the conditioned air in a warmer range during cooling application. Empirically, the recommended supply air temperature of UFAD system is 3~4 °C warmer than conventional ceiling supply system (Loudermilk 1999, Bauman 2003).

Field studies on occupants' response to UFAD performed in different climatic conditions support the recommendation of a warmer supply air temperature with these systems. Matsunawa et al. (1995) found that cold feet complaint was continuously reported especially by female subjects (wearing skirts). They reported that with the implementation of the floor-based ventilation system, the supply air temperature could be kept at approximately 4 °C higher than that in the ceiling based system. Supply air temperature of 20 °C was found to be sufficient to serve high heat load (46 W/m^2) without bringing thermal discomfort for most of the subjects. Sekhar and Ching (2001) performed a field study of a FR type UFAD system and reported that the lower temperature measured close to the supply diffuser may lead to "cold feet" problem and localized discomfort. The air was both supplied and returned at floor level. Strong air movement (>0.25 m/s) were also found within a radius approximately 0.5 m away from the air supply diffusers. The thermal sensation reported by the occupants was in the range of "neutral" to "cold". Predicted Percent Dissatisfied (PPD) was in the range of 11.64%~52.4%). Fisk et al. (2004) conducted a field study on the performance of UFAD system installed in a medium-size office building in a temperate climate. It was found that the occupant's level of satisfaction with thermal conditions was well above the average. The authors related the high satisfaction rating to the high supply air temperature (approximately 21.7~23.9 °C). In a hot and humid climate context, Leite and Tribess (2006) conducted a series of experiments with UFAD system in an environmental chamber in Brazil. Internal heat load was relatively high (121 W/m^2) for these experiments. In the feet area, with conditions in which airflows were higher and temperatures were lower (15.4 °C), about 55% of the people felt draughty. The author recommended that the supply air temperature should be in the range of 19~20 °C to avoid cold draught at feet. The author also claimed that the better accepted thermal conditions were found with the warmest operative temperature (26 °C). It was also recommended that the range of operative temperatures for comfort in environments with UFAD system could have 22 °C as its lowest limit and 27 °C as its highest limit.

As the thermal stratification is an inherent characteristic of UFAD system, when warmer UFAD supply air temperature is adopted, the room air temperature at occupants head level might be raised to an unacceptable level. It has been found by many researchers that the stratification in the space served by UFAD system was strongly dependent on the supply air volume and location and thermal load density (Akimoto 1995, Akimoto et al. 1999, Webster et al. 2002, Kobayashi 2003, Lau and Chen (2007)). The results of laboratory experiments conducted by Webster et al. (2002) reveal that when supply air temperature is varied in the range of (15.8 °C ~19.3 °C) (Figure 2.2), the shape of the temperature profile does not change; it only moves to higher or lower temperatures.

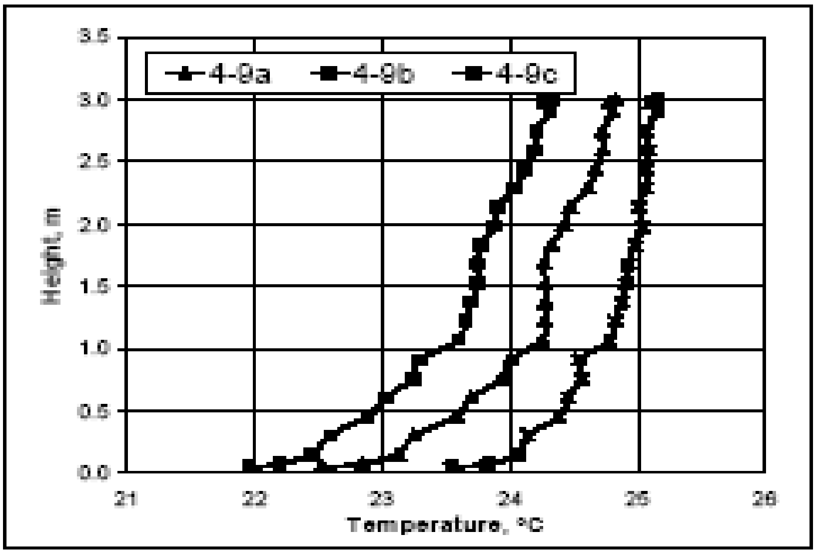


Figure 2.2 Effect of supply air temperature [Supply air temperature: 4-9a=15.8 ˚C; 4-9b =17.4 ˚C, 4-9c=19.3 ˚C. Source: Webster et. al. (2002a)]

Thus, with the increase of the supply air temperature, the mean room air temperature and air temperature at breathing zone will also increase and warm head discomfort will occur. Zhang et al. (2005) evaluates thermal comfort in stratified environments by using a new thermal sensation and thermal comfort model which has been developed to predict local and overall sensation, and local and overall comfort in non-uniform transient thermal environment. The results indicate that when the mean room air temperature moved away from the center of the comfort zone (i.e. at the lower end 23.6 °C and upper end 26.8 °C), even a small amount of stratification causes cold feet or warm head discomfort. The potential for using local air motion to reduce local discomfort in highly stratified conditions have been explored. When 0.8 m/s air motion was applied around the head, the acceptable stratification increased and the head comfort was increased from -1 (clearly uncomfortable) to 2.8 (clearly comfortable) and the overall comfort was also increased. The added air motion to the head area also improved comfort levels for other body parts (e.g. hands, feet, chest and back).

2.2 Overview of Personalized ventilation (PV) system

The idea of personalized ventilation (PV) is to supply clean outdoor air directly to the breathing zone of each occupant. Various air terminal devices of PV have been studied by researchers. Personal Environment Module (PEM) from Johnson Controls stimulated a great deal of research interest (Arens et al. 1991, Bauman et al. 1993, Faulkner et al. 1993, Faulkner et al. 1999). Five different designs of PV supply air terminal devices (ATD) had been investigated by Melikov et al. (2002), which are shown in Figure 2.3.

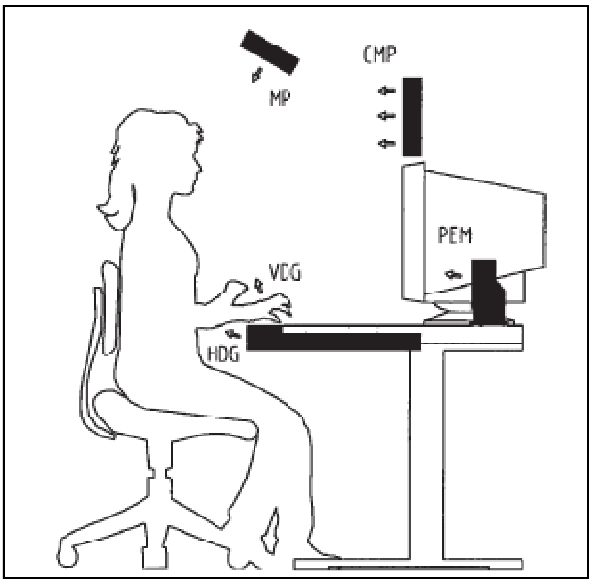


Figure 2.3 PV Air terminal devices: movable panel (MP), computer monitor panel (CMP), vertical desk grill (VDG), horizontal desk grill (HDG) and personal environments module (PEM)

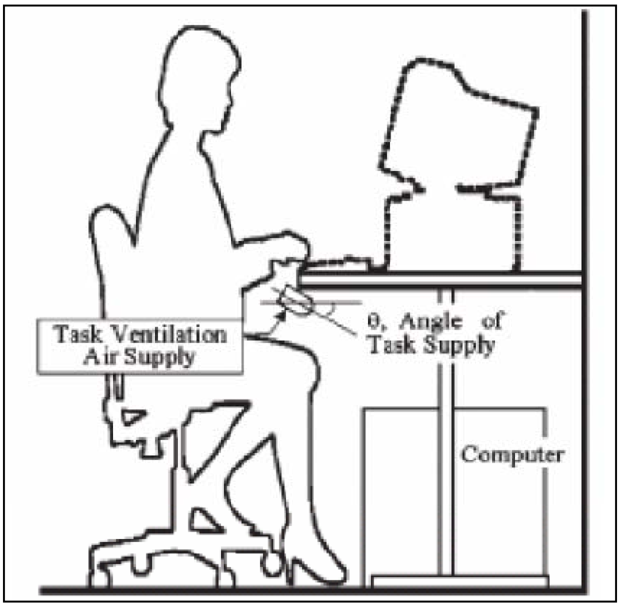


Figure 2.4 Desk-Edge-Mounted task ventilation system (Faulkner et al. 2004).

In order to reduce the mixing of clean personalized air and ambient air PV with air supply nozzles located close to the breathing zone, such as microphone shaped nozzles (Zuo et al. 2002,) or nozzles incorporated around the microphone of and headset (Bolashikov et al. 2003,) have been developed and studied.

The cooling effects of PV were found affected mainly by the supply air flow rate and direction, and to a lesser extent affected by the supply air temperature and the room air temperature point (Arens et al 1991, Tsuzuki et al 1999, Cermak and Majer, 2000, Melikov et al. 2002, Bolashikov et al. 2003). Although it was found in these studies that the higher PV air flow rate had stronger cooling effect and better ventilation performance than lower air flow rate, the most comfortable condition was usually found with the lower air flow rate. With PEM system, the most comfortable condition was found with air flow rate <=20 L/s (Arens et al. 1991, Tsuzuki et al.1999). With a VDG type PV terminal, air flow rate of 10 L/s provided greatest cooling of the manikin’s head (Cermak and Majer, 2000, Melikov et al. 2002). For the RMP shape PV terminal (Bolashikov et al. 2003), the maximum cooling of the manikin's body corresponding to a decrease in the whole-body equivalent temperature (Δt_{eq}) of 2.2 °C was achieved at 15 L/s. Studies of PV systems operated with lower flow rate (5 L/s ~ 23 L/s) revealed that ventilation performance increased with the increase of the personalized air flow rate up to a certain value where further increase of the flow rate had marginal effect (Cermak and Majer, 2000, Melikov et al. 2002). An acceptable air velocity range (0.3 m/s to 0.9 m/s) was identified by Gong et al. 2006.

2.3 Personalized ventilation in conjunction with total volume ventilation

2.3.1 PV in conjunction with mixing ventilation

With relatively lower flow rate, PV systems were usually integrated with total volume ventilation system to tackle the higher space cooling load. The integrated system is capable of creating a localized environment with better inhaled air quality and thermal comfort than mixing ventilation alone (Melikov et al. 2002, Melikov et al. 2003, Melikove 2004, Kaczmarczyk et al. 2002a, b, 2004, 2006, Cermak et al. 2006, Zeng et al. 2002; Sekhar et al. 2003a, 2003b, 2005, Gong 2004, Gong et al. 2006, Yang et al. 2002, 2003, Yang and Sekhar 2008, Yang et al. 2010).

Studies of human response to PV system in conjunction with ceiling supply mixing ventilation (CSMV) found that the thermal comfort and acceptability of inhaled air increases when PV air was introduced with higher flow rate and cooler temperature at higher background room air temperature (Zeng et al.

2002, Sekhar et al. 2003a, 2003b, 2005, Gong 2004, Melikov et al. 2003, Melikov 2004, Kaczmarczyk et al. 2002a, b, 2004, 2006).

With higher background room air temperature (26 ˚C), the optimum PV supply air temperature is 20 ˚C in regards to perceived air quality, intensity of Sick Building Syndrome (SBS) symptoms and thermal comfort (Kaczmarczyk et al 2002a, 2004, Zeng et al. 2002, Yang et al. 2003). The maximum acceptable PV flow rate was 20 L/s (Zeng et al. 2002). The preferred facial velocity was in the range of 0.42~0.74 m/s when the PV supply air temperature and ambient temperature was 20 ˚C and 26 ˚C respectively (Kaczmarczyk et al. 2004, 2006). The study of Yang et al (2002) showed that constant (not fluctuating) air movement is more preferred than that of fluctuating. The freedom of control over direction and flow rate of PV was found can reduce the risk of draught sensation and to improve occupants' satisfaction of IAQ and thermal comfort (Karczmarczyk et al. 2002b, 2004, Yang et al. 2003). The preferred direction of PV airflow was found toward the face (Kaczmarczyk et al. 2004, 2006). It was also found by Melikov and Kaczmarczyk (2008) that the positive impact of elevated velocity on perceived air quality was larger at 26 °C room air temperature than at 20 °C and it was larger at high pollution level than at low pollution level. The elevated velocity (0.3 and 0.6 m/s) at facial region was found significantly improves the acceptability of air quality at room air temperature of 26 ˚C and relative humidity of 70% and this may alleviate the energy consumption for dehumidification of outdoor air in some climatic conditions (Melikov et al. 2008).

The performance of the PV was studied in conjunction with mixing ventilation in hot humid climate by Sekhar et al. (2003a, 2003b, 2005). The ATD used was movable panel (MP) (Melikov 2004b). With warm room ambient 26 °C, PV air temperature at 23 °C and the PV air flow rate at 7 L/s/person, subjects reported that PV improved the their thermal comfort and IAQ acceptability by 58% and 64% respectively in comparison with CSMV alone. The energy saving potential of the PV system was about 30% when compared with the CSMV system alone. A recent study including tropically acclimatized subject's responses to a personalized ventilation system was conducted by Gong (2004). The PV ATD adopted in this study was used in the study of Melikov et al (2002). It was found that both thermal comfort and IAQ ratings generally increased as personalized air flow rate increased, and decreased as personalized air temperature increased at ambient temperature at 26°C.

Other than above mentioned PV which was usually attached with workstation, Ceiling mounted PV system integrated with CSMV was studied. Yang et al. (2009) investigated the interaction of the personalized airflow supplied from ceiling mounted nozzle (diameter of 0.095 m) with the thermal plume generated by a seated thermal manikin. They found that for the ranges of change of the three parameters (PV air temperature, PV flow rate and room air temperature) studied, the personalized airflow rate is the most important factor which influences the equivalent temperature, i.e. the heat loss from manikin's body. In another related study involving human subjects with the ceiling mounted PV and CSMV systems, Yang et al. (2010) concluded that the local and whole body thermal sensations were reduced when PV airflow rates were increased. They also found that the inhaled air temperature was perceived cooler and perceived air quality and air freshness improved when PV airflow rate was increased or temperature was reduced.

2.3.2 PV in conjunction with displacement ventilation

Other than integrating with mixing ventilation system, PV system was also studied in combination with displacement ventilation and under floor air distribution systems. The concept was to enhance the thermal comfort and IAQ performance of both local workstation and ambient environment.

In an earlier study, a concept of creating a microclimate by using desk displacement ventilation (DDV) was introduced by Loomans (1999). The DDV concept intended to combine the positive features of displacement ventilation with those of task conditioning. The supply unit was located below the desktop, against the back of the desk and in front of the lower legs of the occupant (Figure 2.5). Results showed that the effectiveness of entrainment in the human boundary layer measured at the occupant's mouth did not show an improvement compared to results for rooms with standard displacement ventilation. The flow rate of the cool supply air could not be increased significantly due to the risk of draught discomfort at ankles, restricting the cooling capacity of the DDV.

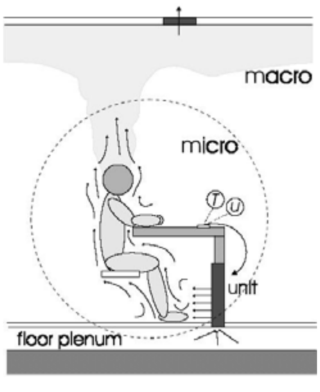


Figure 2.5 DDV concept (Source: Loomans (1999))

A recent research study to utilize the clean air of DV by a “novel” PV system was conducted by Halvonava and Melikov (2008). They studied a ductless PV in conjunction with displacement ventilation. The concept of this combined system is to bring the clean air which was supplied over the floor by DV to desk top PV ATD by using a short duct and small fan. The PV sucks the clean air at floor level and transports and supplies it to the breathing zone of the occupants. With 15 L/s PV flow rate, it was identified from the experimental results that the inhaled air quality was similar and in some cases, better than that obtained with displacement ventilation alone. The schematic of this ductless PV system is shown in Figure 2.6.

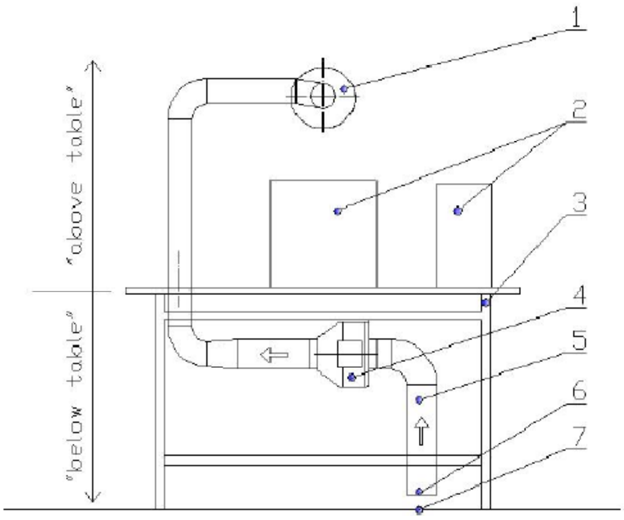


Figure 2.6 “Ductless” personalized ventilation system: (1) Round moveable panel (RMP) terminal device, (2) heat sources on the working table, PC monitor and tower, (3) desk, (4) installed duct fan, (5) short duct system, (6) clean air is sucked few centimeters above floor level, (7) floor level. (Source: Halvonava and Melikov (2008))

Other studies involving the performance of PV in conjunction with displacement ventilation also found that PV can always protect occupants from pollution and thus increase the quality of inhaled air in rooms with mixing air distribution (Cermak et al 2004). The performance of PV systems tested with regard to total and segmental equivalent temperature (heat loss) was similar when combined with either mixing or displacement ventilation (Melikov et al 2003, Cermak and Melikov 2004, 2006, Forejt et al. 2004). The personalized ventilation supplying air from the front towards the face provided better thermal and ventilation performance than the personalized ventilation supplying air from the below towards the face (Cermak et al 2004, Forejt et al. 2004). Moreover, the PV system supplying air against the face improved the ventilation efficiency in regard to the floor pollution up to 20 times and up to 13 times in regard to bioeffluents and exhaled air, compared to mixing or displacement ventilation alone (Melikov et al 2003).

2.3.3 PV in conjunction with UFAD system

Only few studies have explored the performance of PV in conjunction with UFAD. At the space under the table surface, the air velocity and temperature distribution was found significantly influenced by UFAD system, but at the head level, both the air velocity and temperature were instead significantly influenced by the PV system (Cho et al. 2001). Thus, the combined effect of PV and UFAD can achieve a better thermal environment around the occupants' workstation and the introducing of cooler PV air can increase the occupants' acceptability of temperature stratification created by UFAD (Cho et al 2001, Cermak and Melikov 2004, 2006). The IAQ performance of PV in conjunction with UFAD system also reveal that the inhaled air contaminant concentration and inhaled air temperature were independent of the UFAD air throw but was dependent on the type of PV ATD defined in Figure 2.3 (Cermak and Melikov, 2004). The RMP type of PV system was found with much lower inhaled air contaminant concentration than VDG.

A more detailed study of PV in combination with UFAD has been reported by Cermak (2004). The impact of the throw height of UFAD and the two type of PV air terminal (VDG and RMP) were investigated. The inhaled air quality was found substantially increased when PV was used. The RMP terminal was found more efficient in provide clean air in inhalation zone than VDG terminal. Regarding thermal comfort, the author mentioned that the use of a shorter throw may be associated with a draught risk and a larger vertical temperature difference between head and ankles. The draught risk could be decreased by increasing the throw height of UFAD with increased temperature. The use of round movable panel (RMP) PV terminal combined with UFAD was recommended by the author to provide excellent air quality and preferred thermal comfort for occupants.

In general, in the combined systems, the air flow near the occupant is affected by the interaction of thermal plume of human body, personalized ventilation flow, the thermal plume of other heat source near the occupants, the respiration flow of occupants and the ventilation flow of the surrounding space. The thermal plume of human body is formed by an upward free convection flow which is slow and laminar with a thin boundary layer at the lower parts of the body and becomes faster and turbulent with a thick boundary layer at the height of the head. The personalized ventilation flow is typically a free jet from the PV outlet. The velocity distribution in a non-isothermal jet is different from that in isothermal jet in the diffusion characteristics when buoyancy effect is taken into considered. The buoyancy effect increases when the temperature difference between PV air jet and the ambient air increases and decreases when the PV supply velocity increases (Melikov 2004).

Regardless of the airflow interaction, the inhaled air quality with personalized and mixing ventilation was higher or at least similar compared to mixing ventilation alone (Melikov et al. 2003). In the case of PV combined with displacement ventilation, the interaction caused mixing of the room air, an increase in the transport of bioeffluents and exhaled air between occupants and, at low flow rates of personalized air a decrease in the quality of the inhaled air compared to displacement ventilation alone (Melikov et al 2003). When the background ventilation flow is generated by UFAD system, the room temperature and contaminant distribution is dependent on the supply air flow of UFAD. When the supply air flow is with higher throw, the environment in the occupied zone is comparable to the mixing ventilation. Nevertheless, when it is with lower throw, the environment in the occupied zone is comparable to the displacement ventilation. At the occupant's breathing zone, the local air temperature, velocity and contaminant distribution were mainly affected by PV airflow (Cermak 2004).

2.4 Thermal Comfort Studies in non-uniform environments

In spaces served by upward flow ventilation systems such as DV and UFAD, the air temperature is normally stratified along the vertical height. If the gradient is sufficiently large, local discomfort can occur at the head and/or cold draught discomfort can occur at the feet, even the body as a whole is thermally neutral. For non-uniform environment, ASHRAE Standard 55 (2004) prescribes 3 ºC as the limit for the vertical air temperature difference between head and ankle level. ISO 7730 (2005) describes the stratification limit using three categories of decreasing quality: A<2 ºC, B<3 ºC, C<4 ºC. To obtain a percentage of dissatisfied due to draught (PD) less than 15%, the ISO Standard 7730 recommends a local mean air speed 0.25 m/s in summer.

Research on draught discomfort reveals that people are more sensitive to draught when their whole body thermal sensation is neutral or cooler (Fanger et al. 1988, Toftum 1994). At warmer whole body thermal sensation local air movement is desirable. Present standards (ASHRAE 55 2004, ISO 7730, 2005) recommend elevated velocity under individual control of each occupant in order to obtain thermal comfort at warm environment. Most of previous draught research was conducted in temperate zone. In the draught research conducted in hot and humid climate (Tanabe and Kimura, 1994; De Dear and Fountain, 1994), it was found that people usually prefer relatively high air velocity in air-conditioned environment. Recent study on local discomfort which is caused by draught perception in a temperature stratified space was conducted by Yu et al. (2005) with displacement ventilation system. The risk of draught complaints was found with a cold environment (20 °C at 0.6 m height) and the complaint due to insufficient air movement was found with a warm environment (26 °C at 0.6 m height). It was also reported that subjects would prefer lower air movement when the overall thermal sensation was cold and would prefer higher air movement when the overall thermal sensation was warm. The research on draught in UFAD system is very limited. The draught complaints were found increases with the decrease of UFAD supply air temperature (Matsunawa et al. 1995, Leite and Tribess, 2006).

Relationship between local and overall thermal sensation and comfort

Local thermal sensations are found to be different for different body segments (Arens et al. 2006a). The head is perceived as warmer and feet perceived as colder than the rest of the body. In a non-uniform thermal environment, the whole body thermal sensation and comfort were found to be affected by the sensations and comfort of local body segments. The subjects' overall thermal sensation was found closely following the local sensation which was furthest from neutral, and the overall thermal comfort of occupants was found closely following the most uncomfortable local body parts. The dominant segments found by most of the studies were almost consistent with each other. Head part was normally accounted as the most important part for upper body and feet was found more dominant for lower body parts (Zhang et al 2004, Arens et al 2006a, b, Cheong et al 2007).

The findings indicate that in a stratified environment served by displacement ventilation or UFAD system, the unacceptable warm sensation at head and unacceptable cold sensation at feet might be inevitable. When the overall thermal sensation is close to neutral, slightly warm thermal sensation is preferred at the lower body parts and slightly cool is preferred at the upper body parts. Slightly cool local thermal sensation at the body parts is preferred at warm overall thermal sensation and slightly warm local thermal sensation is preferred at slightly cool overall thermal sensation (Cheong et al., 2007). It was also reported that it was more difficult to achieve thermal comfort at the lower body parts than at the upper body parts in a space with DV (Cheong et al. 2007).

By individually cooling or heating the subject's local body parts to help remove some level of whole body thermal stress, the higher vote for overall comfort perception can be achieved (Zhang et al. 2005, Arens et al. 2006b). In Arens et al (2006b), by cooling the breathing air in a warm ambient environment (served by mixing ventilation), (T_{room}=29 °C, T_{supply}=23 °C), the overall sensation declined from warm to neutral, while the breathing zone sensation declined from neutral to cool. Both the corresponding overall and breathing zone comfort increased greatly. In an environment served by displacement ventilation system, when the head comfort is improved by adding an air movement at head level, the overall thermal comfort is also increased (Zhang et al. 2005).

The effect of individual control on thermal comfort

The air movement and temperature in a space required in present standards (ISO 7730 2005, ASHRAE 55 2004) are based on average values for a large group of occupants. However, there are large differences among people with regard to preferred indoor environment. The occupants' preferences to the air movement may differ by more than four times (Melikov et al. 1994, Toftum et al. 2002).

Individual control of the microenvironment at each workplace will make it possible for occupants to achieve their preferred environments. The human response and satisfaction was found to be significantly improved with the microenvironment generated by an Individually Controlled System (ICS) (Melikov et al. 1998, Knudsen and Melikov 2005, Kaczmarczyk et al. 2006, Melikov and Knudsen 2007). In Kaczmarczyk et al (2006), the subjects were found actively using the opportunity to change the airflow rate and to adjust the airflow direction by changing the position of the air terminal device. They also found that the airflow towards the face was preferred to the airflow towards the abdomen. Except the "headset" terminal at higher room air temperature of 26 °C, with the systems studied in this study, individual control allowed the subjects to maintain thermal neutrality.

Moreover, by providing occupants with individual control, the satisfaction with the indoor environment could be increased psychologically. A field study reported by Bauman et al. (1998) revealed that it is more important for occupants to be able to control their local environment than it is to actually make a large number of adjustments.

2.5 Justification of the study

The potential of UFAD system in providing better thermal comfort and higher inhaled air quality than mixing ventilation was already discussed. Its superior performance in offering full flexibility in changes to office layout by re-locating the outlets to suit any new workstation layout was recognized. However, those benefits cannot always be achieved coincidently. Two major draw backs were identified from studies on UFAD.

- "Cold feet" and draught at lower space of occupied zone
- "Warm head"- which is associated with the vertical temperature gradient

Moreover, the climatic condition is another barrier for adopting the UFAD, when the dehumidification demand is crucial especially in hot and humid climate.

Cold feet

As already discussed the "cool feet" problem in rooms ventilated with UFAD systems is related to the temperature of the supplied air and the high velocity near the air terminal devices. Figure 2.7 summarizes the supply air temperature reported in laboratory and field studies on the physical environment in rooms with UFAD. These studies have generally concluded that high risk of draught at the feet exists at the lower range of the supplied air temperature.

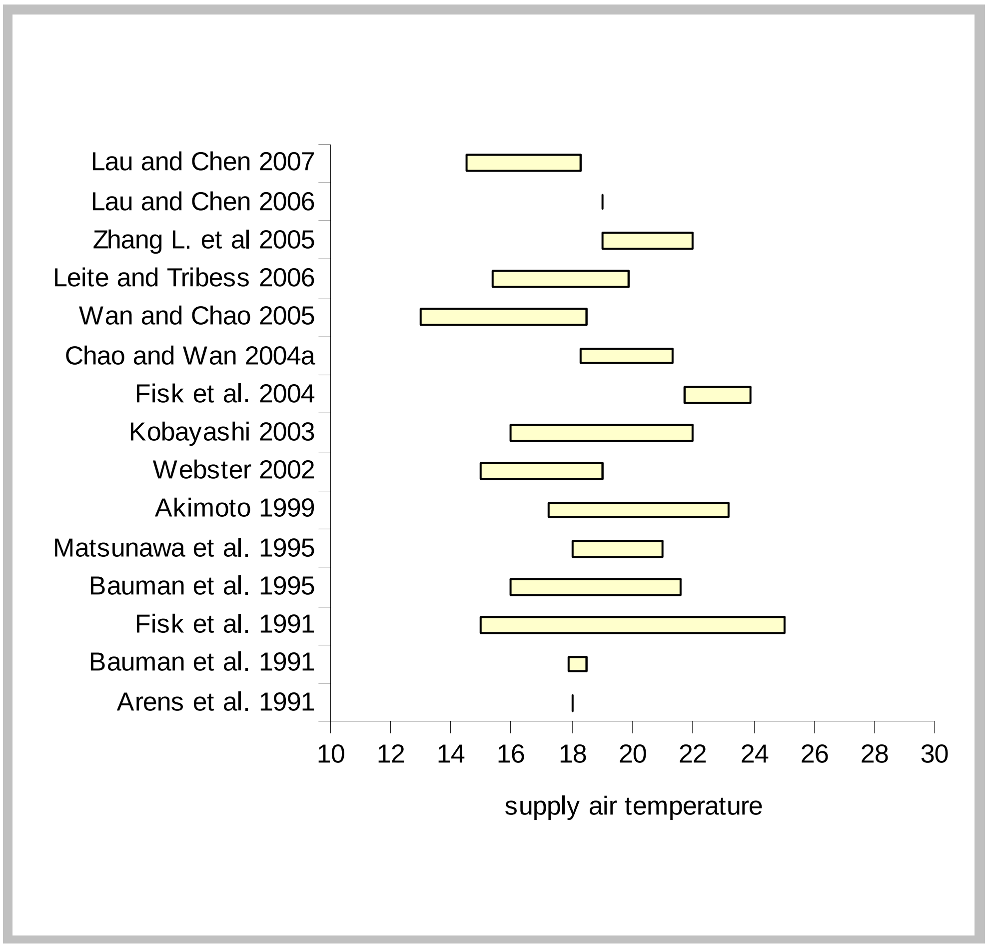


Figure 2.7 UFAD Supply air temperature range in Laboratory/Simulation studies (the unit of temperature is °C).

Higher DR and PPD have always been reported near the floor supply diffuser due to the low supply air temperature and high air movement (Bauman et al 1991, 1995, Matsunawa et al. 1995, Sekhar and Ching 2001, Kobayashi 2003, Chao and Wan 2004a, Leite and Tribess 2006, Lau and Chen 2007). Leite and Tribees (2006) found that with a UFAD system, at cool room temperature (t_{room}=21 °C) higher PPD were reported, and the corresponding supply air temperature with this cool room air temperature was 15.4 °C. Fifty five percent of subjects reported they could feel draught in this environment.

Warm head

The upward air flow pattern and warmer supply air temperature are the most important characteristic of UFAD system compared with CSMV system. Most of the possible energy performance advantages of UFAD and DV systems over CSMV system are related to these two characteristics. However, the stratification and warmer supply air temperature may result in complaints of uncomfortable warm thermal sensation of the head by occupants. As shown in Figure 2.8 when a warmer supply air temperature is adopted (>19 °C), the temperature at the head level for seated office occupants may rise above the range of upper comfort limit (ASHRAE 55, 2004). The dashed line outside the figure is a deduction from the author's current result which aims to show the effect of warmer supply air temperature if it is even higher than that adopted in the referred study. This may become unacceptable to occupants. In non-uniform environment cooler thermal sensation at the head has been reported as preferable by people (Zhang et al. 2005, Arens et al. 2006, and Cheong et al. 2007).

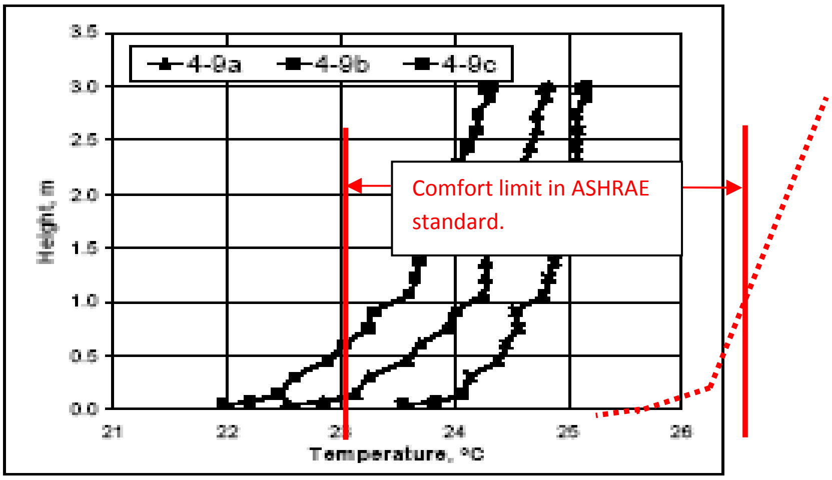


Figure 2.8 Stratification profile under different supply air temperature (4-9a:15.8 °C, 4-9b: 17.4 °C, 4-9c: 19.3 °C with room air flow at 2.7 L/s/m^2), (Source Webster 2002a).

Thus, the solution for the "cold feet" problem with UFAD by increasing the supply air temperature leads to the problem of "warm head". In this study, the use of PV in conjunction with UFAD is proposed for solving this inherent inconsistency. It is hypothesized that personalized flow under individual control of occupant will cool the head region and will solve the "warm head" dissatisfaction problem while the UFAD with warmer supply air will work without generating the "cold feet" discomfort.

The focus of most of previous studies on UFAD based on physical measurements has been placed on the effect of supply air flow and heat load location and density. The supply air temperature had rarely been studied as a controlled parameter. Moreover, there is limited data reported about the performance of UFAD in open plan offices with evenly distributed quick mixing type of diffuser. Most of the available laboratory documents are in the area of localized (TAM) or displacement type of UFAD. Human response to the environment generated by DV or MV has been studied. However, the ventilation flow served by UFAD is different from DV and MV which can result in different air flow around the occupants. Only limited data has been found in people's thermal comfort in the non-uniform environment served by UFAD-PV. Most of the human subject research has been conducted in temperate climatic conditions and almost no data on the response of tropically acclimatized occupants exists.

Human response to PV in conjunction with UFAD has not been studied in depth. The performance of this system combination with regard to the hypotheses defined above needs to be examined.

Dehumidification

The humidity control is one of the major concerns for UFAD system. The warmer supply air temperature of UFAD system demands for a warmer chilled water temperature. Loftness (2002) and Bauman (2003) have made a comprehensive review of UFAD system and draw conclusion that if a higher cooling coil temperature is used to produce warmer supply air temperature need in UFAD system, the cooling coil's capacity to dehumidify will be reduced.

In hot and humid climates, the dehumidification of the outdoor air supplied by the HVAC system is more crucial than in temperate climates with regard to energy use (Yau 2007). This is even more important and challenging with Personalized Ventilation (PV) system that aims to provide clean outdoor air directly to the breathing zone. In this case, additional energy for reheating might become necessary to provide personalized air with acceptable temperature and humidity.

Although humidity control can be achieved by maintaining the conventional cooling coil temperature to dry out the incoming outside air and use the method of bypass of the warmer return air to reheat the supply air, in hot and humid climate, the effectiveness of this control strategy is difficult to predict. More flexible and energy efficient strategies need to be explored. For example, dehumidifying heat pipes is one of the optimal options to enable an air conditioning unit to dehumidify better and still efficiently cool the air in hot and humid climate.

By incorporating a heat-pipe unit into the Air Handling Unit (AHU) for the PV system, the energy used to pre-cool and reheat the outdoor air could be saved (http://www.eere.energy.gov; Yau. 2007, 2008; Sekhar and Chong 2007). This will also enable some of the more challenging conditions of indoor temperature and humidity to be achieved in an energy efficient manner.

Chapter 3 Objectives and Hypotheses

3.1 Objectives

The objectives of this Ph.D. study are to evaluate the performance of PV in conjunction with UFAD with regard to thermal comfort and AQ (air quality) and to assess the energy efficiency potential of UFAD-PV over conventional mixing ventilation system. Based on the results of two pilot studies conducted to explore the characteristic of UFAD system (Pilot study I) and the feasibility of UFAD-PV (Pilot study II) the following specific objectives of the study were defined:

(1) Objective evaluation of the thermal comfort and AQ provided by the UFAD-PV system over a range of operating conditions in a hot and humid climate, especially with regard to the thermal environment near the human body, local ventilation effectiveness and inhaled temperature and draft rating (at foot and head level).

(2) Human response (including thermal comfort and perceived air quality) to the environment obtained with UFAD-PV system over a range of operating conditions in a hot and humid climate. Parametric emphasis of human response studies include perceived air quality (PAQ), local and whole-body air movement perception and acceptability, local thermal sensation and whole body thermal comfort and sensation.

(3) Evaluation of the energy saving potential of UFAD-PV system compared with conventional mixing ventilation system with emphasis being placed on the heat removal effectiveness and the energy saving from an energy recovery unit, the heat pipe.

3.2 Hypothesis

The following hypotheses are formulated, based on which the objectives of this UFAD-PV study are established:

- PV air can reduce the uncomfortable “warm head” sensation and can increase the acceptability of PAQ by providing cool and fresh air at the facial level in environment served by UFAD with warmer supply air temperature;
- The warmer supply air temperature of UFAD can reduce the risk of local discomfort due to “cold feet”;
- The reduced local thermal discomfort will change the overall thermal sensation and improve overall thermal comfort.
- Integrating heat pipes with a conventional cooling coil enables the warmer supply air temperature of PV system without compromising dehumidification levels and leads to energy conservation.

The expected performance of UFAD-PV system is shown in Figure 3.1 (a, b, c). In UFAD-PV system, the cold and fresh PV air and warmer UFAD supply air is expected to prevent the cold draught at feet level (Figure 3.1a) and “warm head” problem associated with the warmer UFAD supply air temperature (Figure 3.1b). This would create an acceptable thermal condition in the occupied zone resulting in clean air and a cooler sensation at the head level (Figure 3.1c).

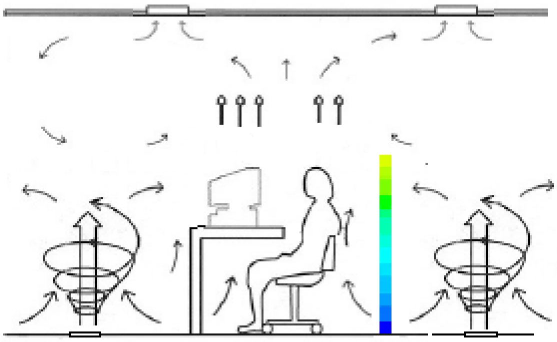


Figure 3.1a Schematic of UFAD with cooler supply air temperature causing “cold feet” (red: warm; blue: cold, green: slightly cool ~neutral.)

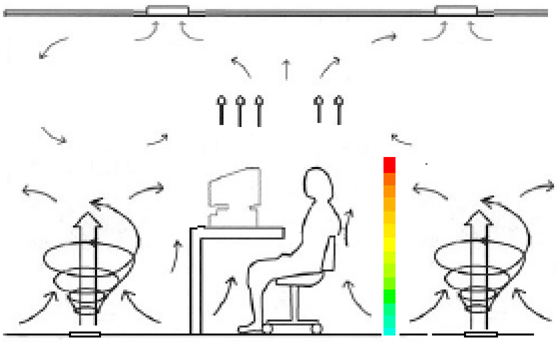


Figure 3.1b Schematic of UFAD with warmer supply air temperature causing “warm head” (red: warm; blue: cold, green: slightly cool ~neutral.)

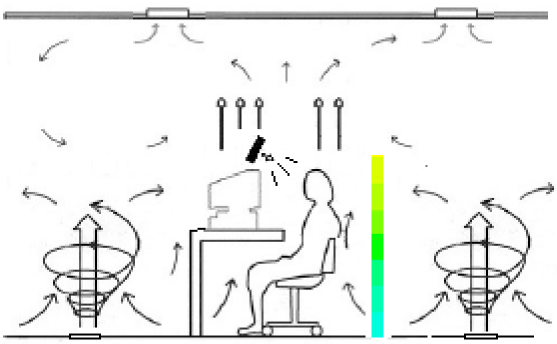


Figure 3.1c Schematic of UFAD-PV with warmer UFAD supply air temperature and cool and clean PV air, resulting in cool head and clean inhaled air (red: warm; blue: cold, green: slightly cool ~neutral.)

Chapter 4 Preliminary Studies

4.1 Introduction

The preliminary research comprised 2 pilot studies. Pilot study I compared the performance of CSMV system with UFAD system by using thermal manikin in a field environmental chamber. It was found that UFAD system created non-uniform environment with higher air velocity and higher risk of draught discomfort at lower space in comparison with CSMV. In Pilot study II, the feasibility of using PV air at the head level when the space is served by UFAD was investigated by using CFD simulation. It was found that the use of PV air affects the temperature, velocity and fresh air distribution at the occupant's breathing zone.

4.2 Pilot Study I – Comparison of UFAD and CSMV

In this study, the performances of UFAD and CSMV system were compared in the field environmental chamber at the National University of Singapore with a breathing thermal manikin.

4.2.1 Methods of Pilot Study I

Set-up of experiment

The measurements were carried out in the field environmental chamber FEC1 (11 m x 7 m x 2.7 m). The layout of the chamber is shown in Figure 4.1. There are 8 workstations place in the chamber and each of the workstation was equipped with one set of desk-top personal computer. A breathing thermal manikin (big black square, Figure 4.1) and two human beings (2 small black squares in Figure 4.1) were involved to simulate occupant in a commercial office building. The internal heat sources in the chamber were composed of lightings, 3 people and 8 set of computer towers and monitors (Figure 4.1 and

Table 2).Two systems, CSMV and UFAD were installed in the chamber. In CSMV operation mode, the conditioned air was supplied into the FEC through six 0.6 m×0.6 m ceiling supply diffusers and the return air was drawn through six 0.6 m×0.6 m ceiling return grilles. In UFAD operation mode, the conditioned air was supplied through 36 evenly distributed Φ0.2 m floor mounted swirl diffusers (connected with raised floor plenum) and the return air was drawn through the same return grille as CSMV. Air temperature and relative humidity (RH) inside the chamber were maintained at the set-point value by the Building Automation System (BAS).

Measurements

The room air temperature distribution, the surface temperatures and heat loss from different segments of the manikin were measured and were used to compare the two air distribution modes with regard to the thermal environment generated and to evaluate its impact on occupants' thermal comfort. The inhaled air temperature of the manikin was measured and used to evaluate the efficiency of the two air distribution modes in delivering cool air to the breathing zone. The inhaled air temperature was measured by a digital thermometer -Fluke 54 II (accuracy: 0.05% ± 0.03 °C) with a bead probe thermocouple mounted at the manikin's nose. The positioning of the thermal manikin and the air temperature and velocity measurement locations in the chamber are shown in Figure 4.1. Air temperatures and velocity were measured at 0.1 m, 0.6 m, 1.1 m and 1.7 m by 12 omnidirectional transducers (accuracy in velocity ±0.01 m/s, accuracy in temperature ±0.5 °C). The mean radiant temperatures were measured by using globe thermometer as well. The results show that mean radiant temperatures are equal to the air temperature, and thus the value presented in the text is also representative of operative temperature. As the under floor air was supplied through three separate compartments of the plenum, the measuring locations were allocated as A, B and C (Figure 4.1) within the occupancy zone. The heat source as defined above and their location was the same in all the experimental cases.

Experimental conditions

The thermal manikin was exposed to three different environmental conditions which were provided for CSMV and UFAD system respectively (Table 4.1). The internal heat sources are shown in Table 4.2.

Table 4.1 Experimental conditions

Experiments No.	Space set point temperature T_{set}(°C)	Space relative humidity RH%	Air distribution mode	Supply air flow rate (L/s)	Supply air temperature (°C)
1	20	60	CSMV	330	12.5
2	20	60	UFAD	900	12.7
3	23	60	CSMV	100	15.7
4	23	60	UFAD	140	16.8
5	26	50	CSMV	20	15.9
6	26	50	UFAD	20	17.3

Table 4.2 Internal thermal sources (Pilot Study I)

Heat source and location	Value (W)
Lighting:	
fluorescent (above occupied zone)	50 x 22
People: (sensible + latent)	
Seated	110 x 3
Office equipment and machinery:	
personal computer, desktop type	75 x 8
monitor, no shelf directly above	70 x 8
Total	∑=1663

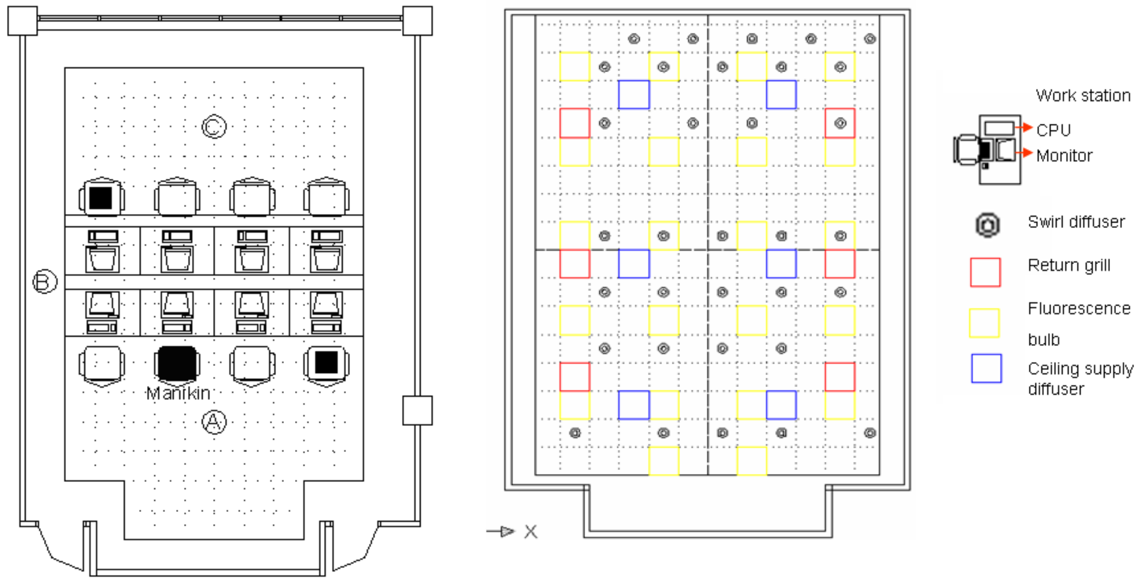


Figure 4.1 Lay out of FEC1. (A, B, C are the locations where the room air temperature, velocity and draught rating were detected. Each location has 4 vertical test points at 0.1 m, 0.6 m, 1.1 m and 1.7 m level respectively. The two black squares represent the positions of two human beings in this chamber)

4.2.2 Results and discussion of Pilot Study I

The averaged temperature and velocity profiles and the histogram of DR (Draught rating) are shown in Figure 4.2 a, b and c. The skin temperature profiles of the manikin are shown in Figure 4.3.

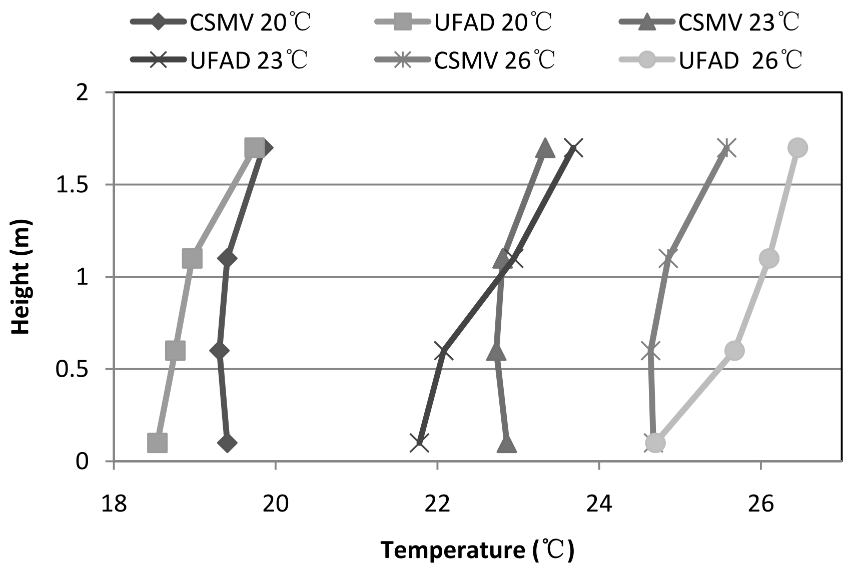


Figure 4.2a Temperature Profile (Pilot Study I)

The results in Figure 4.2a show that the vertical air temperature distribution is almost unchanged when the CSMV system was in operation. At 1.7 m level, the temperature is slightly (less than 1 °C) higher than at the lower heights of the room. Compared with CSMV system, temperature gradient could be apparently detected when the UFAD system was in operation (Figure 4.2a). The vertical temperature differences between 0.1m and 1.7 m for the experimental Cases 2, 4 and 6 are 1.2 °C, 1.9 °C and 1.8 °C respectively. The vertical temperature differences between 0.1 m and 1.1 m in Case 4 and 6 exceed 1°C.

The inhaled air temperatures with UFAD and CSMV systems are comparable and cooler when the room air temperature was in the cooler range (20 °C and 23 °C, Table 4.3). However, with warmer room air condition (26 °C, Table 4.3), although the UFAD system delivers the cold supply air directly to the occupied zone, the air temperature is warmer (more than 1 °C higher) than the CSMV system when the air reaches the breathing level.

Table 4.3 Inhaled air temperature

Room air temperature (°C)	CSMV	UFAD
20	20.5	20.2
23	23.8	23.7
26	25.8	27.1

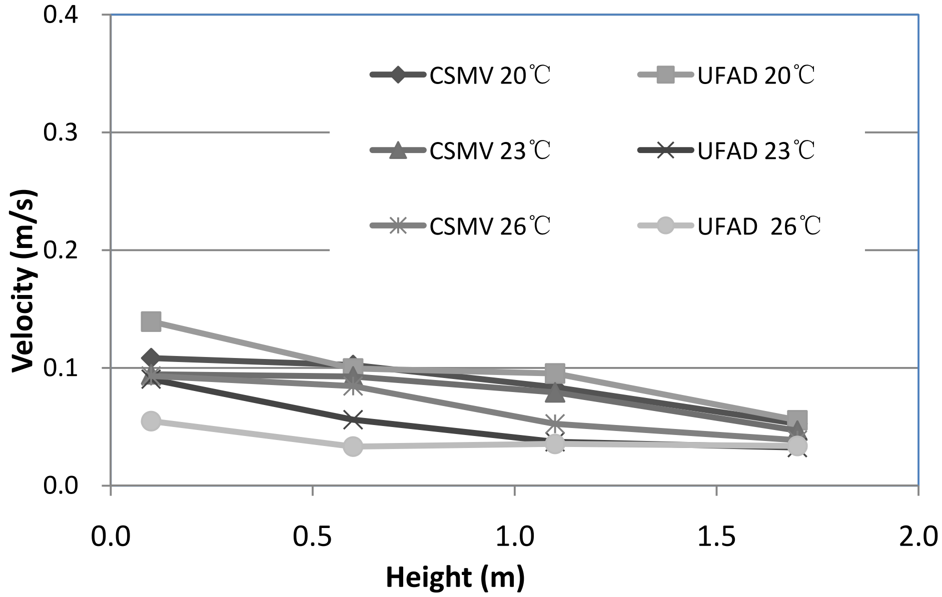


Figure 4.2b Velocity Profile (Pilot Study I)

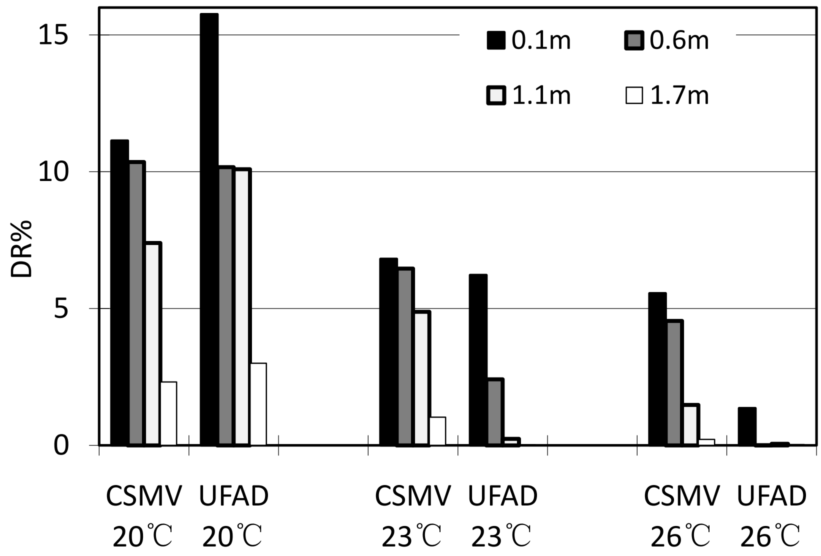


Figure 4.2c Draught Rating (Pilot Study I)

The average air velocity at four heights (0.1 m, 0.6 m, 1.1 m, 1.7 m) are shown in Figure 4.2b. In all cases, the highest air velocity occurred at the lower zone of the room. The draught rating model, developed by Fanger et al. (1988), was used to predict percentage of dissatisfied due to draught discomfort caused by the air terminal device of the UFAD and the CSMV systems. As expected, the highest risk of draught was identified at the lowest room air temperature of

20 °C and at the low heights where the highest air velocity occurred (see Figure 4.2b).

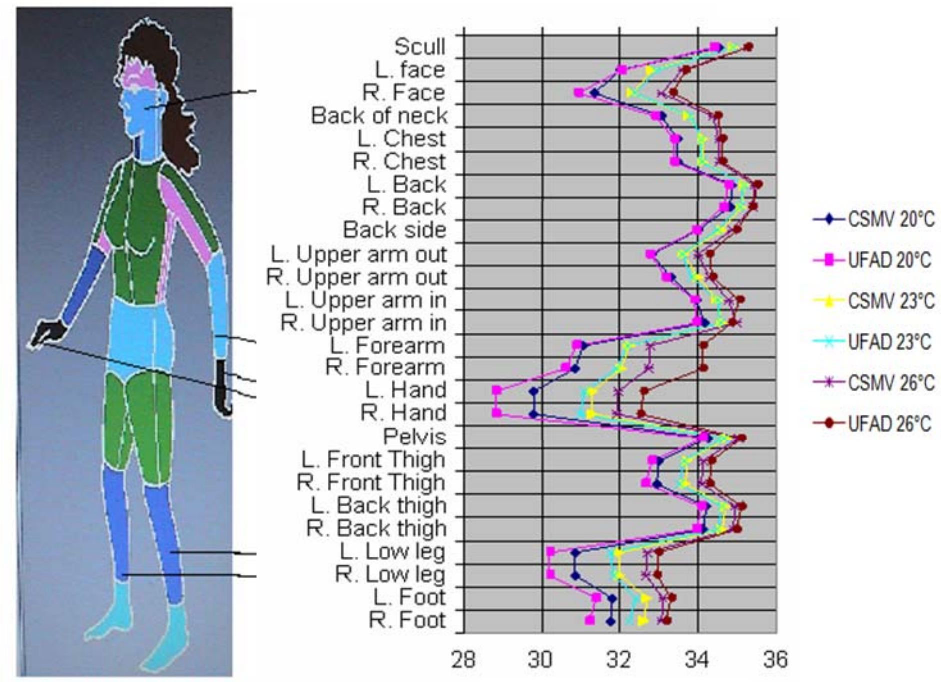


Figure 4.3 Manikin Surface Temperatures (°C)

By comparing the manikin's surface temperature in pairs of CSMV and UFAD under the same set point conditions (Figure 4.3), it is obvious that the manikin is more "sensitive" to the UFAD system when the environment is inclined to warm (26 °C) or cool (20 °C). In the warm ambient environment, the surface temperatures of manikin are warmer with UFAD, while in cool ambient environment, the manikin's surface temperatures are cooler with UFAD than with CSMV. The surface temperature profiles overlap at most of the covered body parts but separate at the uncovered body parts and are steeper when UFAD was in operation. Under the neutral condition (23 °C), the surface temperature profiles overlap at most body parts, only slightly separate at lower limb level (about 1 °C).

The key findings of Pilot study I can be summarised as follows:

1) Non-uniform thermal conditions occur when the UFAD system was in operation, i.e. relatively high temperature at head level and lower temperature at low heights. This suggests that the “cold feet” and “warm head” problem are inevitable when UFAD system is used;
2) Although comparable inhaled air temperatures were found with CSMV and with UFAD at cooler UFAD supply air temperatures, the inhaled air temperature with UFAD system is significantly higher than CSMV system when warmer UFAD supply air temperature is used. Therefore, an improvement of perceived air quality cannot be expected with UFAD system due to the impact of the warmer inhaled air temperature.
3) The manikin’s surface temperature is more “sensitive” to the environment served by UFAD system than that of CSMV system, which indicates the opportunity to provide thermal comfort condition in the immediate vicinity of occupants by UFAD system. By changing the UFAD supply air temperature to a warmer range, it is expected that the cold draught at lower body parts can be reduced and the “warm head” is expected to be eliminated by using cold PV air at facial level.

4.3 Pilot Study II – Feasibility of Using PV in UFAD

The feasibility of using PV air at the head level when the space is served by UFAD was investigated by using CFD simulation. The CFD simulation results were also used to test the hypothesis that PV air can reduce the uncomfortable "warm head" sensation and can increase the acceptance of inhaled air quality by providing cold and fresh air at the facial level in an environment served by UFAD with warmer supply air temperature which will reduce the risk of local draught discomfort at the lower body parts.

4.3.1 Methods of Pilot Study II

The geometry of the simulated model closely approximated the actual field environmental chamber. The configuration of 8 human bodies and computers were simplified by using block shape elements (Figure 4.4). The swirl diffusers were presented by annular outlet with both axial and tangential air flow direction which is shown in Figure 4.5 and Table 4.2.

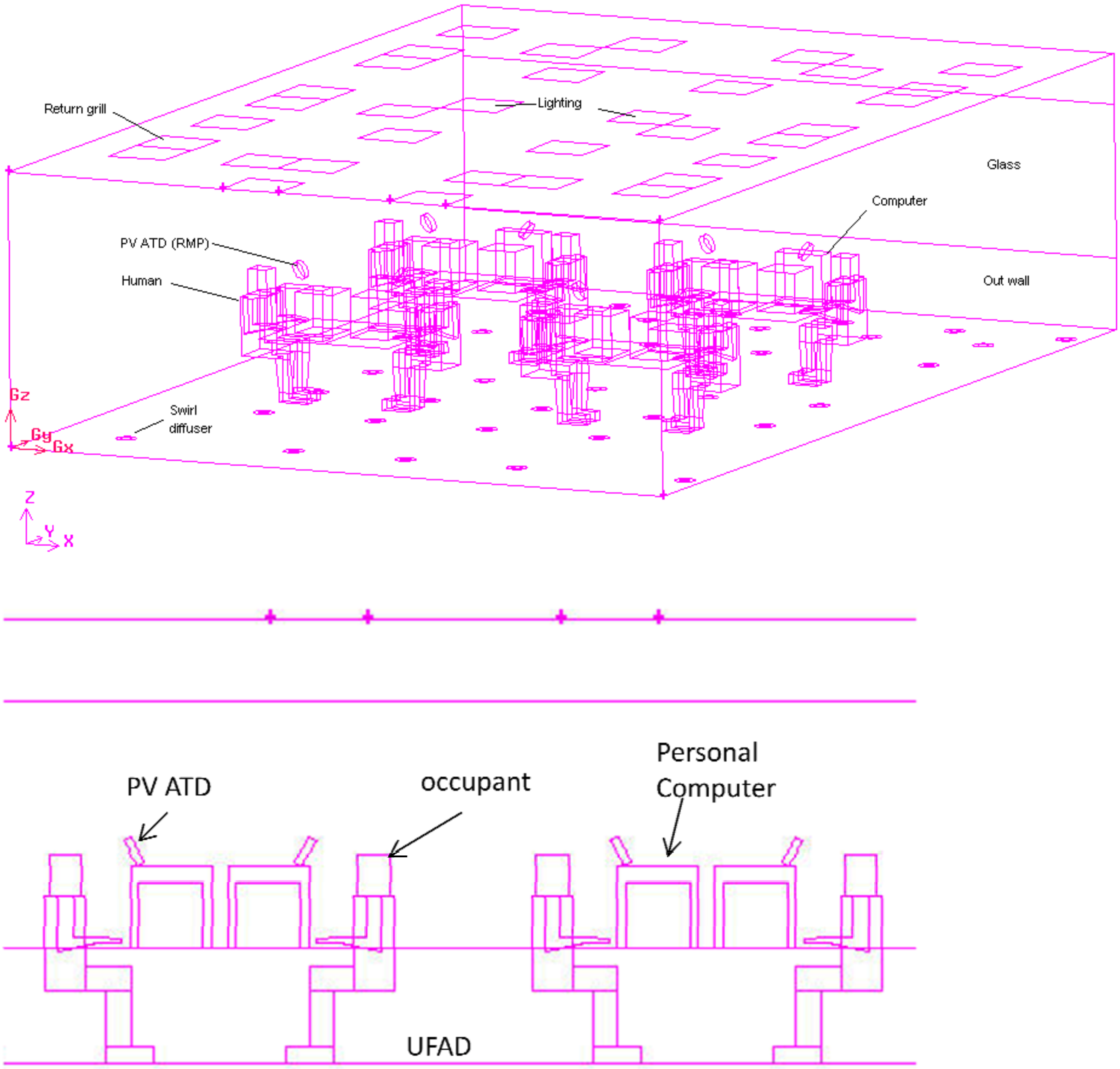


Figure 4.4 Geometry of CFD model

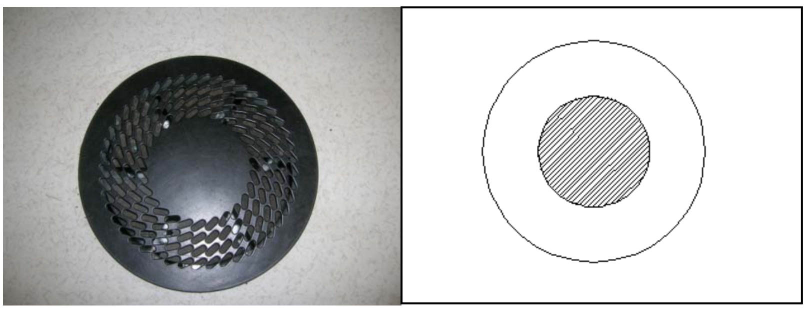


Figure 4.5 Floor mounted swirl diffuser (left: real shape, right: simulation configuration)

As large gradient of the solution variables (air temperature, velocity and fraction of fresh air) might occur near the boundaries, such as supply diffusers, human bodies and computers, non-uniform grids were utilized. The coupled continuity equation and momentum equations, energy equation and transportation equation were solved to obtain velocity, temperature and species distribution of several parameters. The SIMPLE algorithm (semi-implicit method for pressure-linked equations, Patankar. 1980) was employed in this simulation to resolve the coupling between pressure and velocity. The upward free convection flow around manikin/subject body caused by buoyancy force was simulated by adopting Boussinesq assumption and the full buoyancy effect was considered in viscosity model. Species transportation equation was activated and fresh air was set as the minor species. As a result, distribution of fresh air percentage can be obtained. To account for turbulence flow, the standard k-ε model was applied in this study. Sensitivity analysis was conducted to obtain grid independent and accurate solutions.

A simplified model for the swirl air supply diffuser was used in the simulation with a local swirl axial direction momentum and a tangential direction momentum. Eight PV ATDs were represented by round panel PV terminal-185 mm circular shaped velocity outlet with velocity normal to boundary. The centre of PV terminal surface was located at 1.3 m above the floor and 0.3 m in front of human face. The angle between the normal line of PV terminal and human face is 30° (Figure 4.4). The return grilles were represented by 6 square shaped pressure outlets.

Table 4.4 Boundary conditions for supply diffusers and exhaust grilles

Surfaces	Direction Specification		Air flow	Boundary Type
UFAD Supply 1-33	Axial component factor	Tangential Component factor	Velocity (m/s)	Velocity inlet
	0.5	0.5		
PV inlet 1-8	Normal to boundary		Velocity (m/s)	Velocity inlet
Return grille 1-6	Normal to boundary			Pressure Outlet

Table 4.5 Internal thermal load (Pilot Study II)

Heat source and location	Value (W)
Lighting:	
fluorescent (attached at ceiling)	1188
People: (sensible + latent)	
8 Seated	880
Office equipment and machinery:	
personal computer, desktop type	600
monitor, no shelf directly above	560
Total	∑=3228

Table 4.6 Perimeter surface temperature

Perimeter Surface	temperature (K)
Internal wall	Adiabatic
External wall	303
Glass	303
Ceiling	Adiabatic
floor	UFAD supply air temperature

The boundary conditions of the supply diffusers and exhaust outlets are listed in Table 4.4. Other boundary conditions such as internal heat load and perimeter surfaces (wall, ceiling, floor and glass) are described in Tables 4.5~4.6. The UFAD supply air is marked with 10 % of clean air, and when steady state is achieved, the percentage of clean air is distributed evenly along the vertical height. In order to make the UFAD-PV system more optimal and flexible, parametric study was designed. The simulated cases are listed in Table 4.7. The simulated cases were used to compare the performance of the

UFAD with/without PV and to detect the effect of UFAD supply air temperature and volume as well as the effect of PV supply air temperature on the microenvironment at the workstation (Table 4.8).

Table 4.7 Different simulation cases

Case No.	UFAD			PV		
	Supply air temperature t_{supply} (°C)	Supply air volume (m^3/h)	Mass fraction of outdoor fresh air (%)	Supply air temperature t_p (°C)	Supply air volume (L/s/person)	Mass fraction of outdoor fresh air (%)
Case 1	21.7	913	10	-	-	-
Case 2	21.7	913	0	20	10	100
Case 3	22	1600	10	-	-	-
Case 4	22	1600	0	20	10	100
Case 5	22	1600	0	16	10	100
Case 6	20	1600	10	-	-	-
Case 7	20	1600	0	20	10	100
Case 8	18	1600	10	-	-	-
Case 9	18	1600	0	20	10	100
Case 10	22	3200	10	-	-	-

Table 4.8 Effects of PV and UFAD operation parameters on microenvironment at the workstation.

Performance concern	Case No.
The comparison of UFAD and UFAD-PV	Case 1 and Case2
	Case 3 and Case 4
	Case 6 and Case 7
	Case 8 and Case 9
The effect of PV supply air temperature	Case 4 and Case 5
The effect of UFAD supply air temperature with UFAD alone	Case 3, 6 and 8
The effect of UFAD supply air temperature when used with UFAD-PV	Case 4, 7 and 9
The effect of UFAD supply air volume when used with UFAD alone (with warmer UFAD supply air temperature)	Case 1, 3 and 10
The effect of UFAD supply air volume when used with UFAD-PV operation (with warmer UFAD supply air temperature)	Case 4 and Case2

4.3.2 Results and discussion of Pilot Study II

Figures 4.6 to 4.8 show some of the simulation results. The symbol “X” is the distance (in m) from human face. Symbol “Centre” is the centre line of the room.

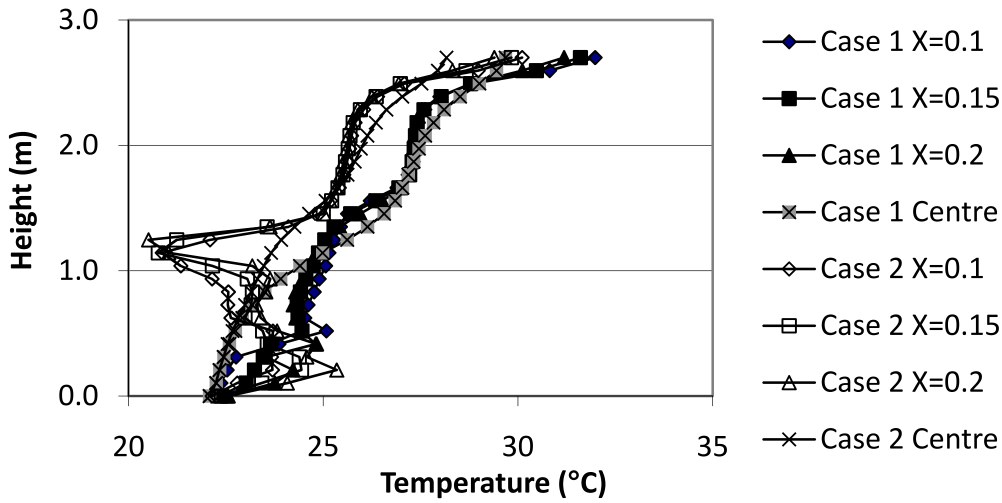


Figure 4.6 Effect of PV air on air temperature (°C) distribution compared with UFAD

The cooling effect of PV air decays along the distance from PV ATD to human face. When comparing between cases with UFAD alone and UFAD-PV (Figure 4.6 and Figure 4.9) it can be seen that the air temperature decreased by PV air along the horizontal distance to human face increases with the increase of distance X at the breathing zone.

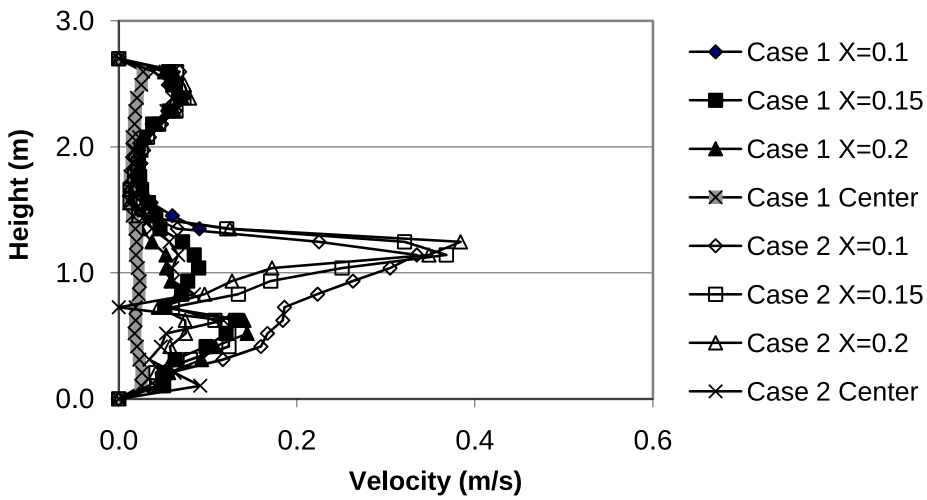


Figure 4.7 Effect of PV air on air velocity distribution compared with UFAD

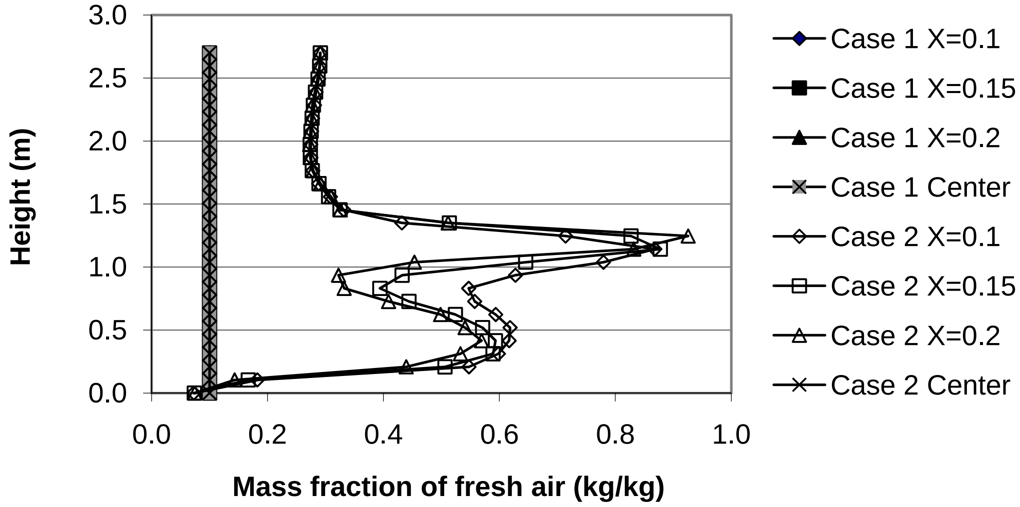


Figure 4.8 Effect of PV air on fresh air distribution compared with UFAD

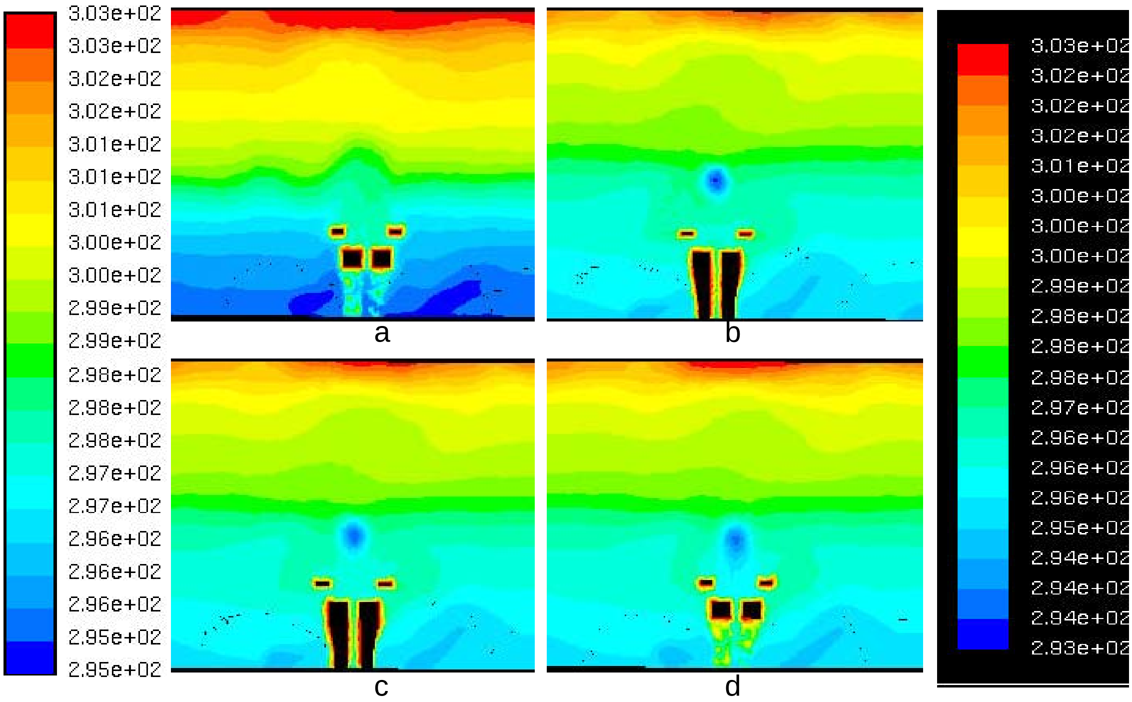


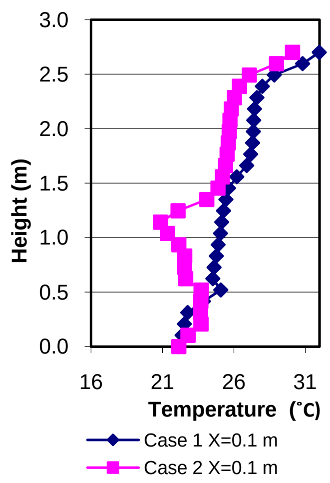
Figure 4.9 Filled contour of Temperatures (cut from one workstation) a: UFAD alone (0.1 m to human face); b~d: UFAD-PV, (b: 0.2 m to human face, c: 0.15 m to human face, d: 0.1 m to human face), the unit in this figure is "K". The left temperature scale is for "a" and the right temperature scale is for "b-d"

Figure 4.9 shows the contour of temperatures at 0.1 m distance from human face in Case1 (U22) and 0.1~0.2 m distance to human face in Case 2 (U22 PV20-10).

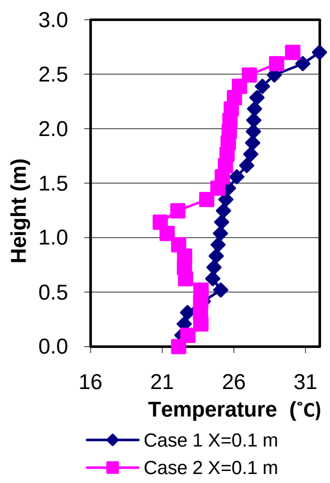
In Figures 4.10, 4.11 and 4.12 the profiles of temperature, velocity and mass fraction of fresh air are respectively given at 0.1 m in front of human face (X=0.1) and are given in pairs or in groups of corresponding operating parameters to enable comparison and analysis. The figure's labels, according to parametric variation, are listed in Table 4.9. These profiles give the information about the parametric variation on temperature, velocity and fresh air distribution near human body. The units for the profile are: °C for temperature, m/s for velocity.

PV air can apparently affect the air temperature near occupants at the breathing level. The comparison of the temperature profiles (Figure 4.10, Case 1 and Case 2; Case 3 and Case 4; Case 3 and Case 5; Case 6 and Case 7; Case 8 and Case 9) shows that the use of PV together with UFAD always makes the air temperature at breathing level (1.1 m) cooler than cases using UFAD alone. Warmer PV supply air temperature (20 °C) provide warmer environment at the breathing zone than cooler PV supply air temperature (16 °C) (Figure 4.10, Case 4 vs. Case 5). With the same UFAD flow rate, the temperature profiles for Case 3, 6 and 8 in Figure 4.10 show that the shape of the temperature profiles do not change at different UFAD supply air temperatures (18 °C, 20 °C and 22 °C for Cases 3, 6 and 8 respectively). They only move to warmer or cooler side according to the UFAD supply air temperature. This finding is in accordance with former studies (Webster et al. 2002a, 2002b). The air temperatures at the lower space near the human body were found changed with the change of UFAD supply air temperature and the breathing zones are almost unchanged with the same PV air supply condition (Figure 4.10 Cases 4, 7, 9). In cases with UFAD alone, the vertical temperature stratification decreased with the increase of UFAD supply air volume (Figure 4.10 Cases 1, 3, 10 with 913 m^3/h, 1600 m^3/h, 3200 m^3/h respectively), which is consistent with other studies involving stratification (Bauman 1995, Webster et al. 2002a, 2002b). When combined with the PV system, different UFAD supply air volume (913 m^3/h and 1600 m^3/h) do not apparently affect the performance of PV air in the occupied zone. Although the temperature stratifications increase with decrease of supply air volume, the temperatures in the breathing zone are not apparently different at different UFAD supply air volume (Case 2 and Case 4 in Figure 4.10).

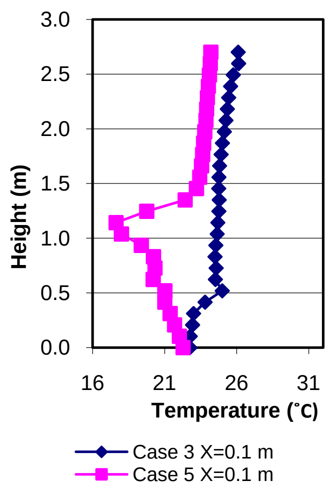
(1) Temperature Profiles



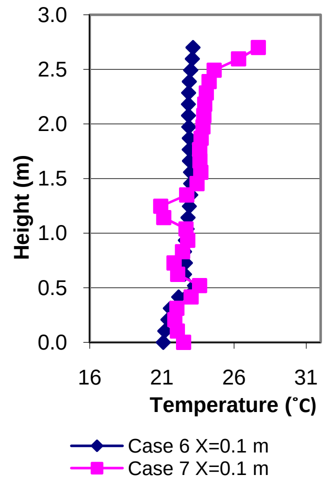
Case 1 and Case 2



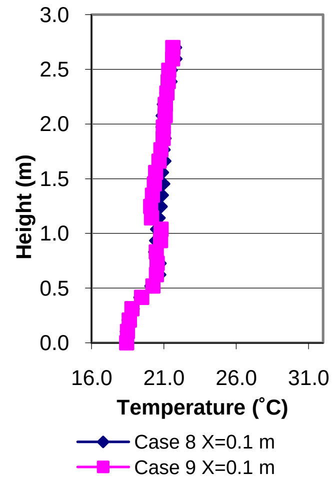
Case 3 and Case 4



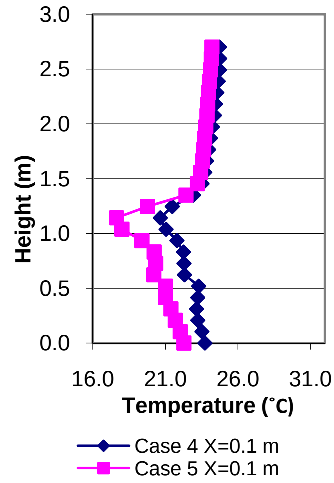
Case 3 and Case 5



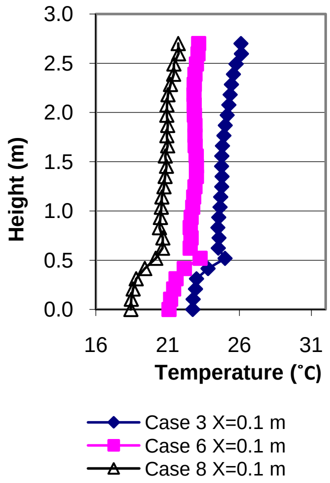
Case 6 and Case7



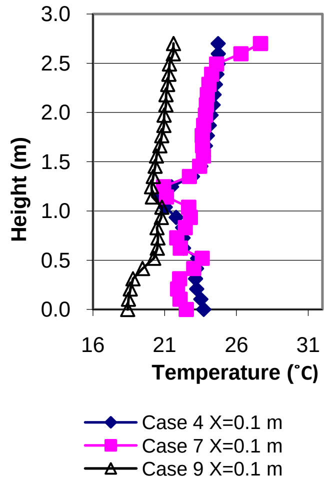
Case 8 and Case 9



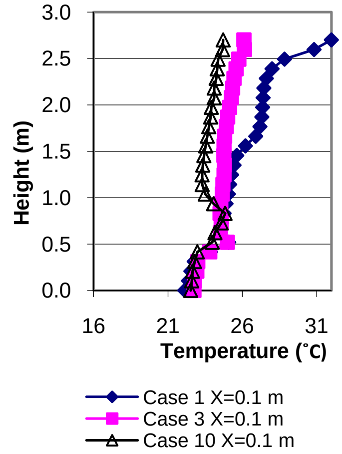
Case 4 and Case 5



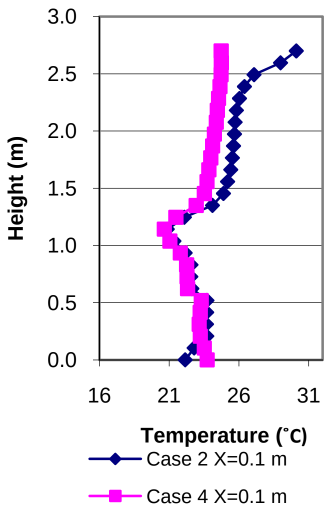
Case 3, 6 and 8



Case 4,7 and 9



Case 1, 3 and 10



Case 2 and Case 4

Figure 4.10 Temperature profiles

(2) Velocity Profiles

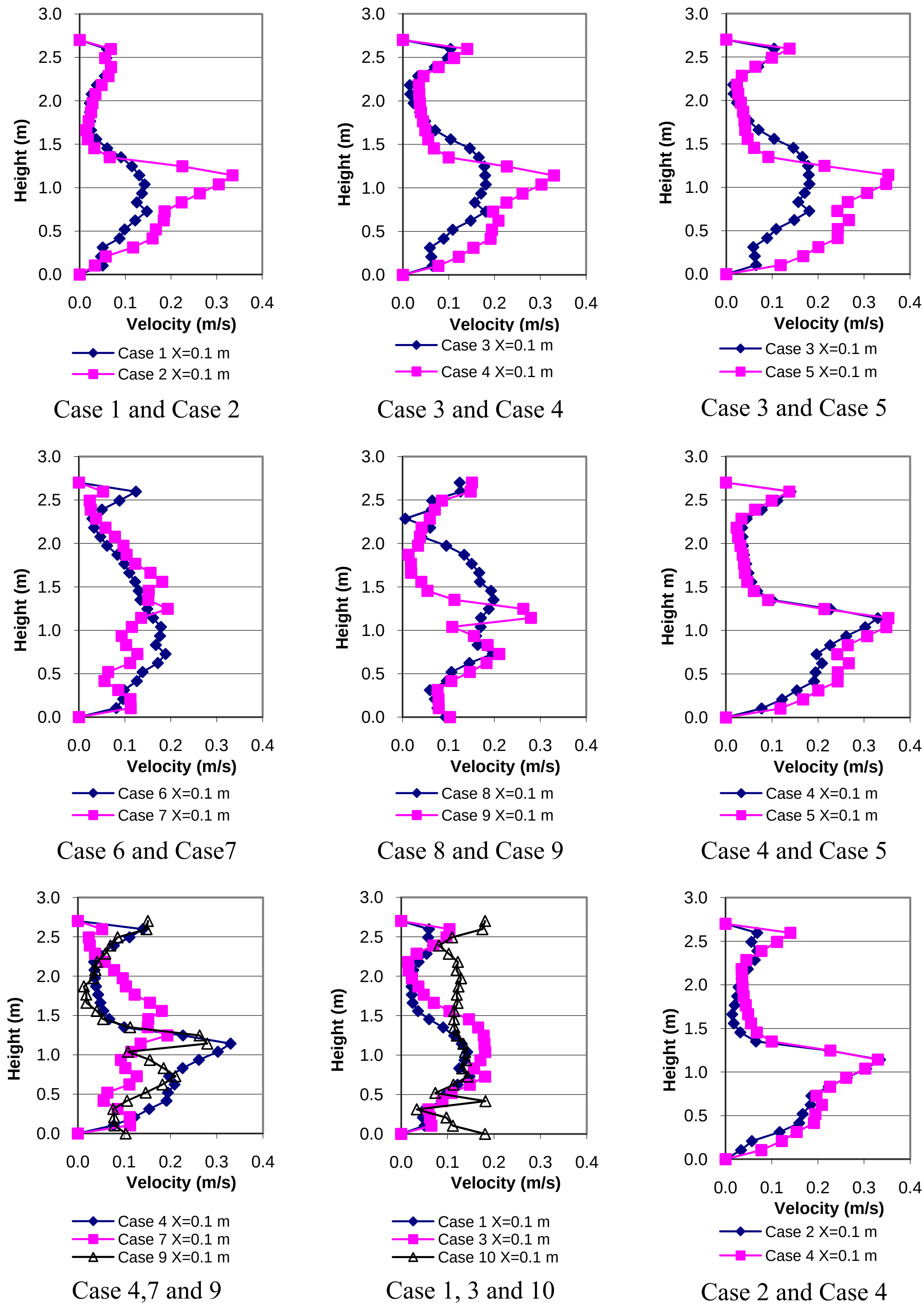
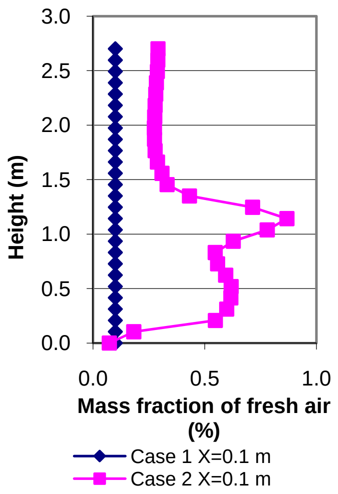


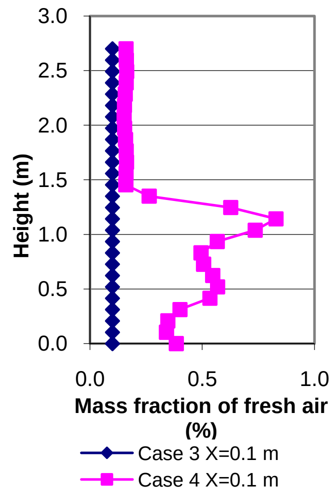
Figure 4.11 Velocity profiles (values at centre line of human body, X=0.1m distance to human face)

The velocities at the breathing level are obviously increased by introducing PV air motion at the breathing level (Figure 4.11, Case 1 and Case 2; Case 3 and Case 4; Case 3 and Case 5; Case 6 and Case 7; Case 8 and Case 9) when compared with the cases using UFAD alone. According to Case 4 and Case 5 in Figure 4.11, slightly higher velocities at occupied zone were found with the cooler PV supply air temperature. When combining PV with UFAD, the velocities at breathing zone were slightly different at different UFAD supply air temperatures, despite the PV supply condition being identical for those cases (Cases 4, 7, and 9 in Figure 4.11). The velocities at breathing zone decrease with the decrease of UFAD supply air temperature. This indicates that the temperature difference between the PV air and the ambient air might have certain effect on the PV air distribution at the breathing zone. With greater supply air volume 3200 m^3/s (Case 10, floor diffuser outlet velocity =1.45 m/s), the velocity at the lower part near human body is higher than that at Case 1, and Case 3. All the velocities at the occupied zone are lower than 0.2 m/s (Cases 1, 3 and 10 in Figure 4.11). The velocity profiles at the breathing zone were observed not affected by the change of UFAD supply air volume when PV system was also applied (Case 2 and Case 4 in Figure 4.11).

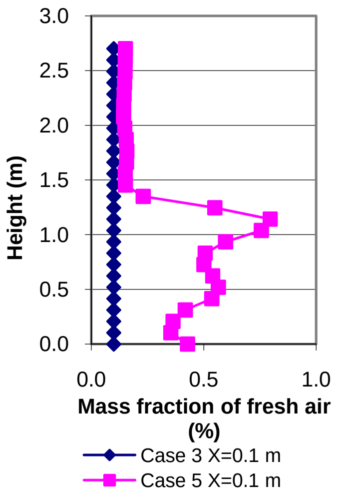
(3) Mass fraction of fresh air profiles



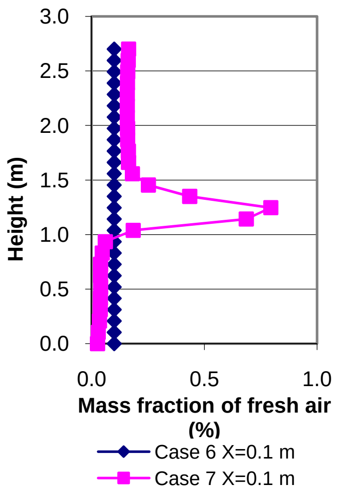
Case 1 and Case 2



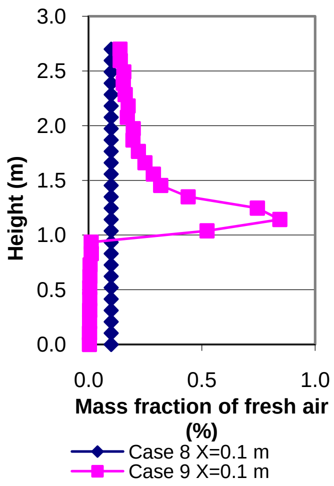
Case 3 and Case 4



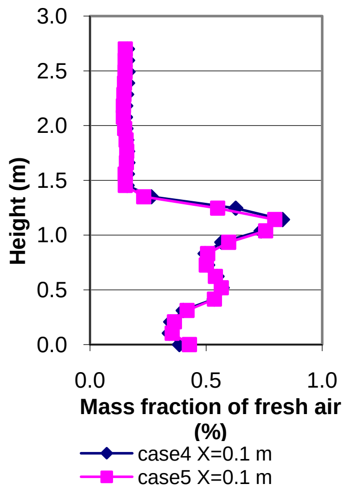
Case 3 and Case 5



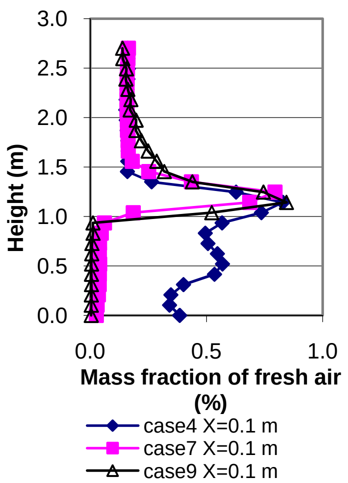
Case 6 and Case7



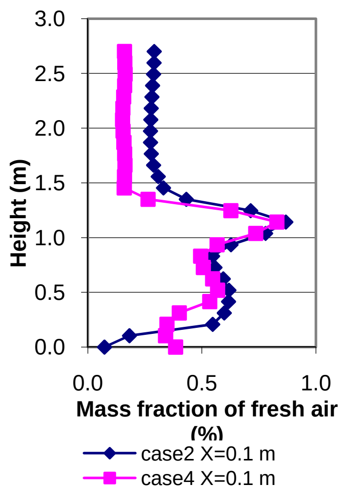
Case 8 and Case 9



Case 4 and Case 5



Case 4,7 and 9



Case 2 and Case 4

Figure 4.12 Mass fraction of fresh air (values at centre line of human body, X=0.1m distance to human face)

The mass fractions of fresh air which is marked by species air are also dramatically increased by providing 100% fresh air at PV ATD (Figure 4.12, Case 1 and Case 2; Case 3 and Case 4; Case3 and Case 5; Case 6 and Case 7; Case 8 and Case 9). The change of PV supply air temperature does not change the mass fraction of fresh air significantly (Figure 4.12, Case 4 and Case 5). In cases with the same PV supply condition, same UFAD supply air volume but different UFAD supply air temperature (Case 4,7 and 9), the mass fraction of fresh air at breathing zone are similar at breathing zone. However, the different levels of UFAD supply air volumes were not affect the PV air distribution in the breathing zone (Figure 4.12, Case 2 and Case 4).

To illustrate the effect of PV air to the breathing area (1.0~1.4 m) and to the whole occupied zone (0.1~1.7 m) near the human body (X=0.1 m), the air temperature of the air is analyzed by t-test (2tailed, independent) among the pair of cases which use UFAD only and use UFAD-PV (Table 4.9). The numbers indicating significant difference are marked by Bold.

Table 4.9 Statistical analysis of the effect of PV air on the environment near human body

	Breathing area (1.0~1.4m)		Whole occupied zone (0.1~1.7m)	
Pair of case	t	P	t	P
Case 1 and Case 2	**-5.5**	**0.0001**	**-0.3**	**0.0047**
Case 3 and Case 4	**-8.3**	**0.0000**	**-4.9**	**0.0011**
Case 3 and Case 5	**-6.2**	**0.0000**	**-6.8**	**0.0000**
Case 6 and Case 7	-1.8	0.1166	0.2	0.8584
Case 8 and Case 9	-1.4	0.2005	-0.5	0.6195
Case 4 and Case 5	**-2.33**	**0.0480**	**-3.5**	**0.0016**
Case 2 and Case 4	-0.75	0.4745	-1.1	0.2700

The PMV, PPD at 0.6 m height (gravity centre of sitting human body) and DR (at 0.3 m and 0.1 m height) near human body (at 0.1 m horizontal distance to human face) for each case are listed in Table 4.10. When the velocity is lower than 0.1 m/s, the calculation will adopt 0.1 m/s as the air velocity. The mean radiant temperature (MRT) is assumed to be equal to air temperature and the relative humidity (RH) is assumed to be 50%. Occupants' activity level is assumed to be sedentary posture with 1.0 met and clothing level is assumed to be 0.50 clo, which is defined as the ASHRAE Standard 55 (2004) summer clothing level. The two vertical heights correspond to the height of low leg (0.3 m) and foot (0.1 m). The numbers indicating Draught Risk are marked by bold.

Table 4.10 PMV, PPD and DR

Case no.	PMV	PPD (%)	DR (%)	
	0.6 m	0.6 m	0.3 m	0.1 m
Case 1	-0.5	12	12	13
Case 2	-1.0	33	14	12
Case 3	-0.5	12	12	12
Case 4	-1.1	34	**18**	12
Case 5	-1.8	59	**28**	**16**
Case 6	-1.1	29	14	14
Case 7	-1.1	31	13	14
Case 8	-1.9	72	**17**	**17**
Case 9	-2.1	79	**17**	**17**
Case 10	-0.7	15	12	14

By using PV air, the thermal sensation votes (PMV) (Table 4.10) are always inclined to cooler sensation. For Case 1 and Case 2, Case 3 and Case4, Case 3 and Case 5, Case 6 and Case 7 (Table 4.9), the PV supply air temperatures are lower than ambient air temperature. Hence, the cooler sensations are caused by the combined effect of cooler air temperature and higher air motion introduced by PV air. For Case 8 and Case 9, the supply air temperatures of PV are comparable to air temperatures with UFAD and the cooler sensation is mainly affected by the higher air movement.

The change in PV supply air temperature significantly changes the temperature near the human body at both the breathing zone (0.9~1.4 m) and in the space away from the workstation (0.1~1.7 m) (Table 4.9 Case 4 and Case 5). The lower PMV are detected with cooler PV supply air temperature from Table 4.10. According to Case 4 and Case 5 in Figure 4.11 and 4.12 respectively, the profiles of velocity and mass fraction of fresh air are not apparently affected by the change of PV supply air temperature

Cooler UFAD supply air temperature causes the cooler sensation. The UFAD supply air volume for Case 3, 6 and 8 is 1600 m^3/h, and accordingly, the supply air velocity at floor diffuser is 0.72 m/s. Higher DR (17%) is found at the lower part near human body when the UFAD supply air temperature is 18°C. This indicates that when the supply air velocity is higher (e.g. 0.72 m/s), the higher supply air temperature (>18 °C) should be used to avoid draught discomfort.

When combining PV with UFAD, the lower parts near human body are mainly affected by the UFAD supply condition and the breathing zones are mainly affected by PV air (Table 4.10). The DR at lower parts near human body is 12% at t_{supply}=22°C, and is 17% at t_{supply}=18°C. The result is similar to that of Cho et al. (2001). With greater supply air volume 3200 m^3/s (floor diffuser outlet velocity =1.45 m/s) and warmer UFAD supply air temperature (22 °C), the DR at 0.3 m and 0.1 m near human body are relatively low (in range of 12~14%) in Table 4.10. It indicates that with warmer supply air temperature, the draught risk at lower body can be avoided even with higher supply air volume (diffuser outlet velocity).

4.3.3 Conclusions of Pilot Study II

The results of the Pilot study II can be summarised as follows:

UFAD-PV system can decrease the uncomfortable sensation as “warm head” and is not likely to cause cold draft when the warmer UFAD supply air temperature (20 and 22 ˚C) and cooler PV supply air temperature (20 ˚C) were used. This is consistent with former physical/ subjective studies in PV combined with mixing/displacement ventilation (Melikov et al. 2002, Melikov et al. 2003, Melikov 2004, Kaczmarczyk et al. 2004, 2006, Cermak et al. 2006, Sekhar et al. 2003a, 2005, Gong 2004, Yang et al. 2003) However, this study is based on simplified body shape of occupants, thus the velocity distributed around the human body might be different with the actual measurements. Further physical measurement and subjective responses with real human beings are needed.

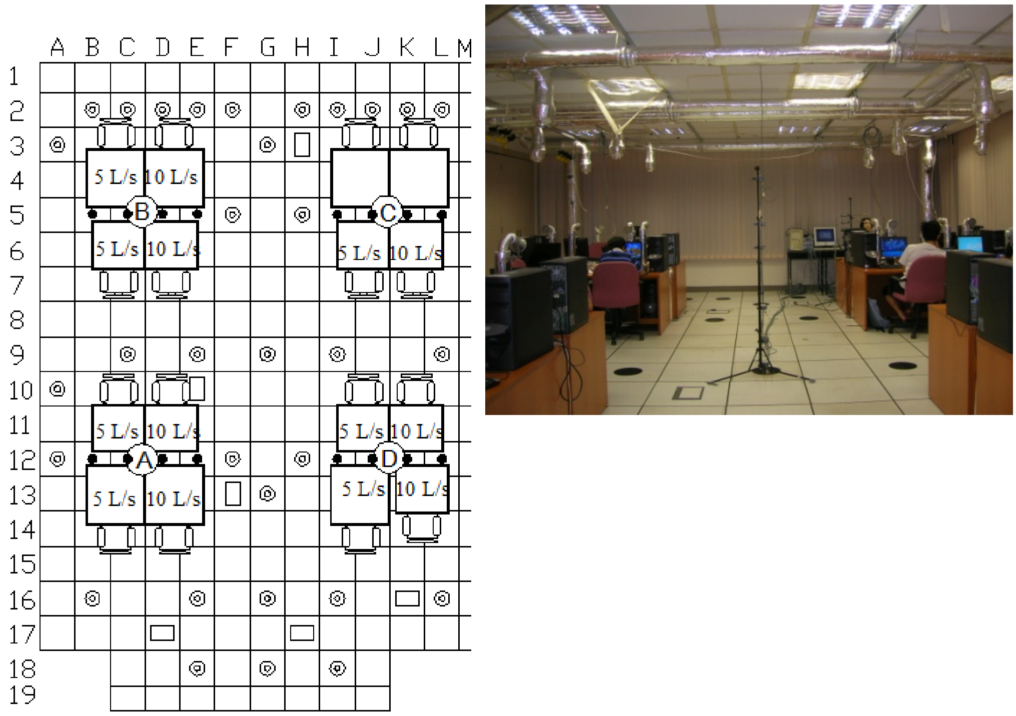
Chapter 5 Manikin and Human Subject Study-Methods

Objective measurements and subjective assessments were employed in this research to investigate the thermal and IAQ performance of UFAD-PV and to assess the acceptability of the UFAD-PV system by tropically acclimatized subjects. A breathing thermal manikin was employed for the objective measurements. Temperature and velocity parameters were measured as well. Subjective responses were collected by means of a questionnaire survey. In the questionnaire survey, primary data based on a sample were collected, and inferences were made on the population.

5.1 Experimental set up

5.1.1 Chamber

The experiments were conducted in a field environmental chamber (FEC2) at the National University of Singapore. The chamber has 11.0 x 7.8 x 2.6 m clear space and under-floor plenums with 0.4 m height. The FEC has an east-facing wall (top-wall in Figure 5.1) consisting of large glass panels, which are attached with solar block film and furnished with internal blinds to reduce heat conduction and solar radiation. The layout of the chamber, which simulates a typical office environment, is shown in Figure 5.1. Twenty one 50 W (0.6 m x 0.6 m) fluorescent lighting fixtures were used in this chamber to mock up a typical open plan office. There were 16 workstations in this chamber. Each workstation was equipped with a Personal computer (PC), a desk-mounted PV air terminal device and an upholstered chair with a backrest.

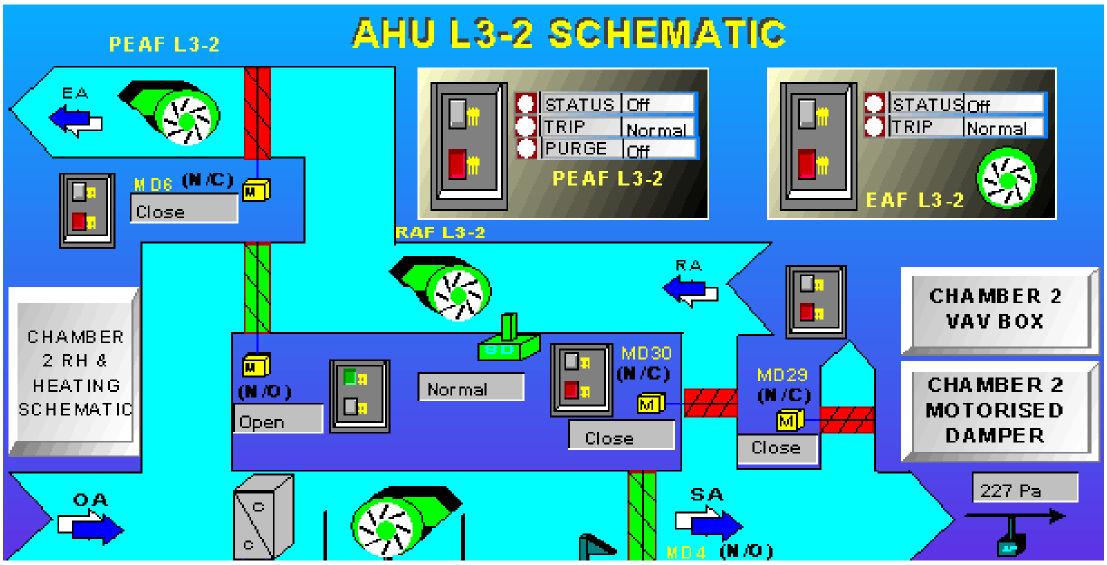


a) FEC layout **b) An experimental session in the FEC**

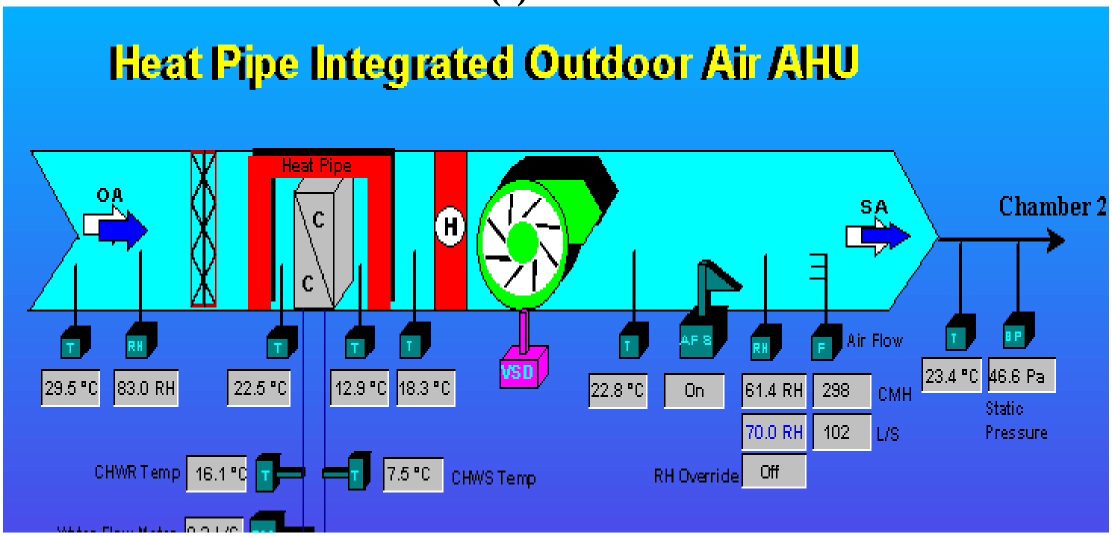
Figure 5.1 Layout of the experimental chamber

5.1.2 HVAC systems

In this research, the background total volume air and the personalized air were served by different HVAC systems. The total volume ventilation systems involved were ceiling supply mixing ventilation system and under-floor air distribution (UFAD) system. The personalized air ventilation system was served by a separate HVAC system which delivered 100% conditioned outdoor air directly to each workstation. The PV and the UFAD systems operated together. The thermal load of the space was removed by conditioned re-circulated air supplied by the UFAD. The reference cases, the UFAD and the mixing ventilation, were operated alone. The AHU for PV, named PAHU, served the PV system only (Figure 5.2b). It had a heat pipe integrated with the conventional cooling coil (Figure 5.2 b).



(a)



(b)

Figure 5.2 Schematic diagrams of AHU - (a) total volume ventilation system (b) PV system

5.1.2.1 Mixing ventilation system

The mixing ventilation system supplied the conditioned air through 6 ceiling diffusers which were distributed evenly in the ceiling of the chamber (Figure 4.1). The supply diffusers were 0.6 m x 0.6 m rectangular perforated panels. The room air left the room through 6 evenly distributed ceiling mounted return grilles. The return grilles were 0.6 m x 0.6 m rectangular panels.

5.1.2.2 UFAD System

The under floor air distribution system delivered the conditioned air through 3 under floor plenums and floor mounted circular shaped diffusers to the room. The number of diffusers was different in the studied cases: 24 in the cases with UFAD supply air temperature at 22 ˚C and 18 in the cases with UFAD supply air temperature at 18 ˚C. The air flow rates entering each plenum were kept identical by adjusting the 3 dampers. The conditioned air coming from the AHU was directed to each plenum compartment through 3 VAV boxes. Each of the VAV box served one plenum. The opening ratio of the VAV boxes was automatically controlled by BAS system to maintain the room air temperature and humidity at the desired level. Moreover, the number of floor diffusers on the floor panel of each plenum was the same. Thus, the air flow rate through each diffuser was same across the whole floor panel. Figure 5.3 shows the layout of the workstation and diffusers that were open under different UFAD supply temperatures. In Figure 5.3, UV22 refers to the experimental cases with 22 °C UFAD supply air temperature and UV18 to the experimental cases with 18 °C UFAD supply air temperature. The floor diffuser used in this study is shown in Figure 5.4. The performance of the floor diffuser was tested with 20 L/s discharge rate. In each experiment, the floor diffuser discharge rate was kept constant at 20 L/s. The results of the measurements are presented in Figure 5.5. The velocities at each point were measured by omnidirectional transducers (Table 5.2).

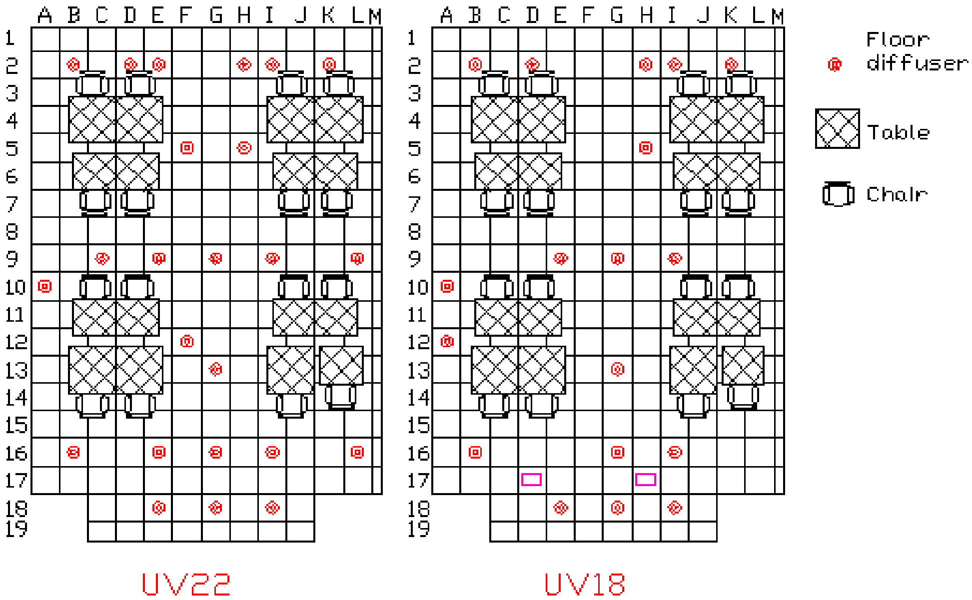


Figure 5.3 Layout of workstation and UFAD diffusers on the floor (UV22: UFAD supply air temperature at 22 ˚C, UV18: UFAD supply air temperature at 18 ˚C)

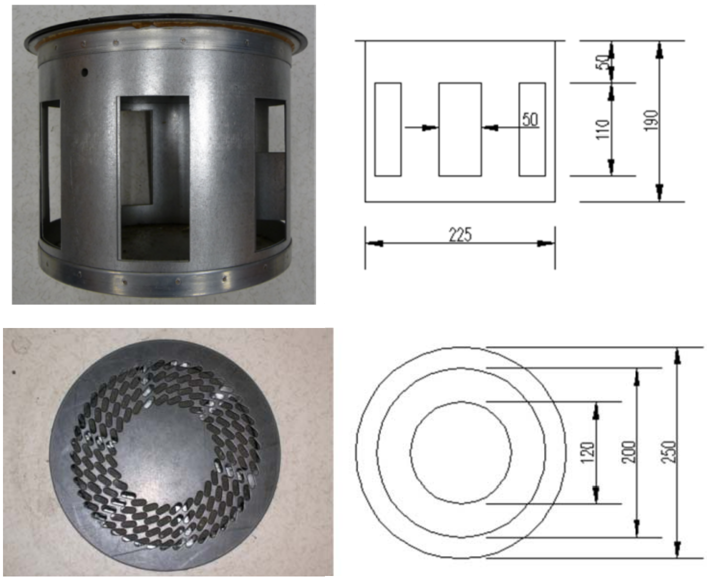


Figure 5.4 Floor diffuser (unit mm)

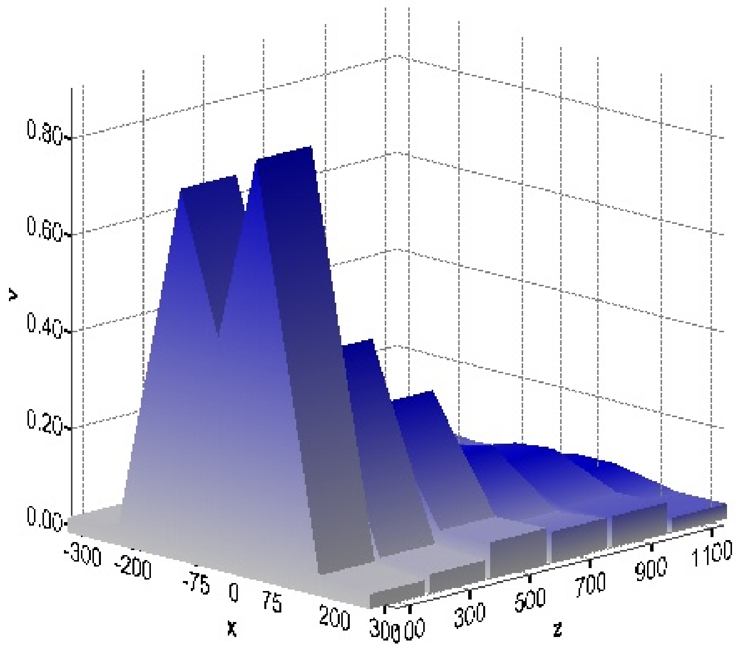


Figure 5.5 Velocity profiles of UFAD diffuser with 20 L/s air volume flow rate. (V: velocity (m/s); X: radius from center of the diffuser on horizontal plane (mm); Z: vertical height from the floor (mm).)

5.1.2.3 Personalized ventilation system

The personalized ventilation system used in this study is shown in Figure 5.6. The PV ducts were concealed under the floor panels. Each workstation was equipped with one PV-ATD. The 16 workstations were divided into 8 groups. Each group has one workstation with 5 L/s PV air flow rate and the other one with 10 L/s (for example, Figure 5.1 workstation 4B-C and 4D-E). The flow rates for each PV duct were balanced by adjusting the dampers installed on each duct.

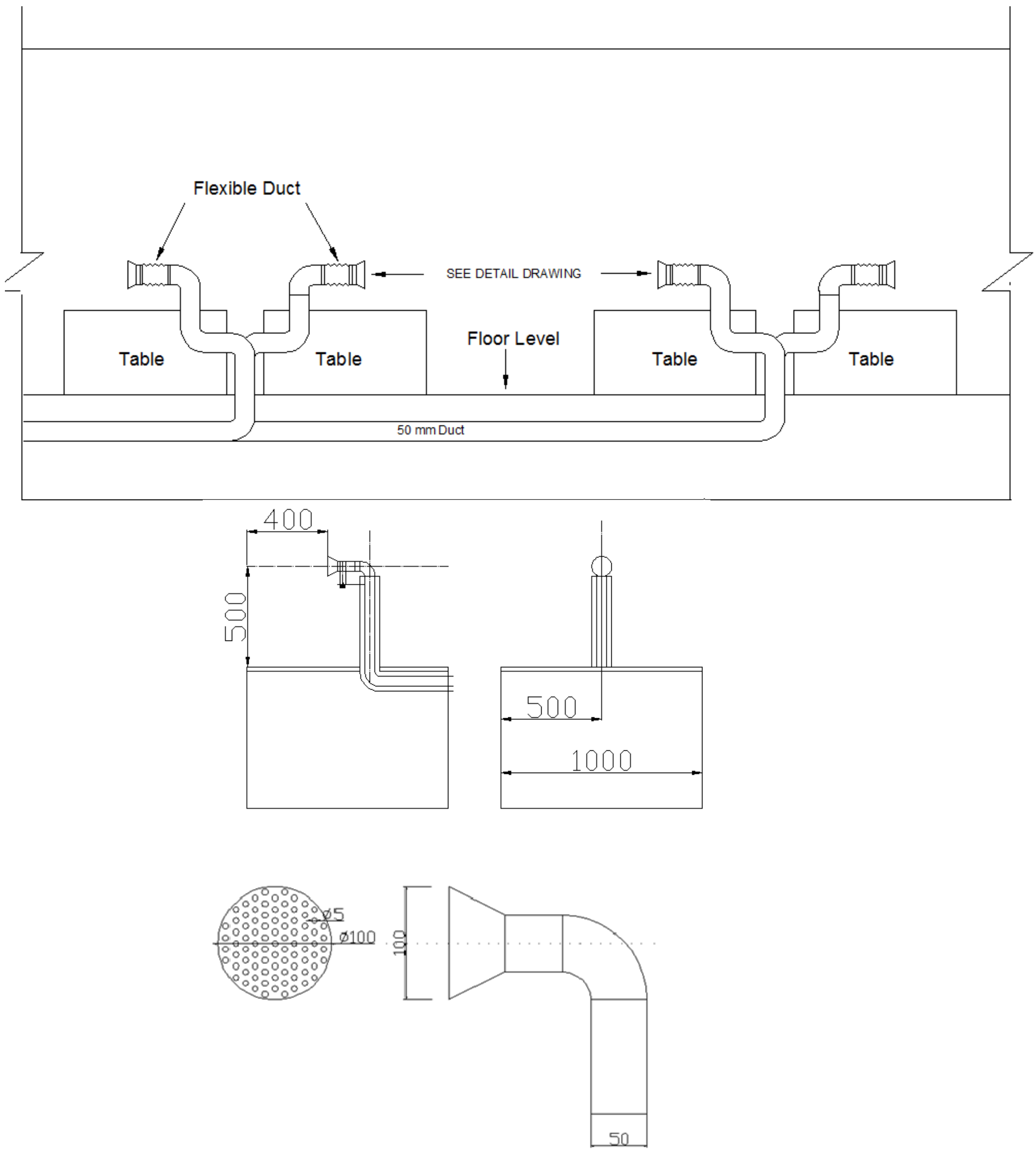


Figure 5.6 Personalized air ventilation system (unit in mm)

The air terminal device of PV used in this study is shown in Figure 5.6. The outlet of the ATD is a Φ100mm perforated panel with 50% free area ratio. A perforated flow equalizer with Φ50mm was installed inside the conical shaped cap of the ATD. The ATD was tested with 10 L/s and 5 L/s air flow rate and the air velocities were measured at the center line with 250 mm distance from the ATD outlet is 0.7 m/s and 0.3 m/s respectively.

5.2 Experimental conditions

The experimental conditions for the overall research project, including the physical and human response measurements involved different combinations of UFAD supply air temperature (22 ˚C and 18 ˚C) and PV supply air temperature (22 ˚C and 26 ˚C) as well as 3 experiments at reference conditions without PV, i.e. UFAD with supply air temperature at 22 ˚C and 18 ˚C and mixing ventilation with ceiling supply air diffuser. In Table 5.1, the eight experimental conditions are listed (the air temperature kept in the room, the air temperature supplied from the UFAD system, the PV air temperature, the PV supply flow rate and the total ventilation flow supplied to the room). During all the experiments, the air temperature /RH at four points (A, B, C and D in Figure 5.1a) at 1.3 m height of the room was used as a target temperature/RH and was controlled at 26 ˚C/ 50%±5%. The RH level of PV air was monitored but not controlled. The operating conditions were controlled by a building automation system (BAS). To keep the room air temperature at 26 ˚C at 1.3 m height, the supply flow rates were different according to different UFAD supply air temperature (480 L/s with 22 ˚C and 360 L/s with 18 ˚C). The supply flow rate of ceiling supply mixing ventilation was 750 L/s.

Table 5.1 Experimental Conditions

System Type	Exp. Condition (Session no.)	Temperature (˚C)			PV flow rate (L/s)	Total volume ventilation system flow rate (L/s)	RH (%) ambient	RH (%) PV air
		t_{room}	t_{supply}	t_p				
Mixing	C	26	16	-	-	750	49	-
UFAD	UV22	26	22	-	-	480	57	-
UFAD+PV	22-26-5	26	22	26	5	480	52	51
UFAD+PV	22-26-10	26	22	26	10	480	52	51
UFAD+PV	22-22-5	26	22	22	5	480	54	63
UFAD+PV	22-22-10	26	22	22	10	480	54	63
UFAD	UV18	26	18	-	-	360	45	-
UFAD+PV	18-26-5	26	18	26	5	360	45	49
UFAD+PV	18-26-10	26	18	26	10	360	45	49
UFAD+PV	18-22-5	26	18	22	5	360	46	66
UFAD+PV	18-22-10	26	18	22	10	360	46	66

(“C” refers to the conventional CSMV)

In Table 5.1, the four experiments with PV and three reference cases are listed. The combinations studied are defined as follows: first the air temperature supplied from the UFAD system, followed by the PV air temperature and finally the PV air flow rate (eg. 18-26-10).

When the UFAD supply air temperature was 22 °C, 24 floor diffusers were opened. With 18 °C UFAD supply air temperature, the supply air volume flow rate of the UFAD system was less than that with 22 °C supply air temperature. In order to keep the air flow rate through each floor diffuser at the same level, the number of open diffusers was reduced to 18 when 18 °C UFAD supply air temperature was used (Figure 5.3).

5.3 Objective measurements

5.3.1 Room air temperature/ velocity/ DR distribution

Air temperature, mean velocity and DR and were measured at a point (G10 in Figure 5.1a) in the occupied zone as well as at one work station (J4 in Figure 5.1a) simultaneously with the subjective measurement for 2.5 hours. Temperature of inhaled air was also measured near the manikin's mouth (3 ~5 cm). Tracer gas measurements for each of the eight UFAD-PV experimental conditions were conducted at the conclusion of the human response measurements. The parameters that were measured, the corresponding locations and the measuring instruments used are listed in Table 5.2 and 5.3. The air temperature, mean velocity and DR in the occupied zone were measured at heights of 0.1 m, 0.3 m, 0.6 m, 1.1 m, 1.3 m and 1.7 m using the omni-directional transducer. At the work station, these parameters were measured near the manikin at heights of 0.1 m, 0.2 m, 0.6 m, 1.0 m, 1.1 m, 1.2 m, 1.3 m and 1.4 m using the omni-directional transducer. The profiles of the mean value of those parameters along vertical height from floor to ceiling are analyzed. Moreover, in order to identify the mixing pattern close to the work station at floor level, the air temperature at the floor surface which is recorded by the sensors of BAS system are incorporated when analyzing the temperature profile close to the work station. The inhaled air temperature was measured in the beginning, middle and end of the 2.5 hours duration of the experiments and the average value was used in the analysis.

Table 5.2 Details of thermal comfort and IAQ parameters measured

Measured Parameter	Units	Name of Instrument	Location (Figure 5.1)
Floor supply air temperature (Ts)	°C	HOBO data logger	Floor diffuser
Floor supply air velocity	°C	Omni-directional transducer	Floor diffuser
PV supply air velocity	m/s	Air flow anemometer	Each PV outlet
Return air temperature (Te)	°C	HOBO data logger	return grille K4
Room air temperature	°C	Thermal anemometer with omnidirectional transducer	G10, at 0.1, 0.3, 0.6, 1.1, 1.3 and 1.7m (Figure 5.1)
Velocity	m/s		
Draft Rating (DR)	%		
Local temperature,	°C	Thermal anemometer with omnidirectional transducer	Near the manikin J4 (0.1, 0.2, 0.3, 0.6, 1.1, 1.2,1.3, 1.4m height)
Turbulence intensity			
Draft Rating (DR)	%		
Inhaled air temperature	°C	digital thermometer - Fluke 54 II	
Concentration SF_6	ppm	Photo-acoustic spectrometer multi-gas analyzer (INNOVA)	1.3m height of G10, D5, D12, return grille level of K4 and manikin's mouth (J4)

Table 5.3 Accuracy of instruments

Name of equipment	Time intervals of data collection	Accuracy
Omni-directional transducer	60 seconds	V~±0.01m/s, T~±0.5℃
HOBO data logger	60 seconds	V~0.03±5%m/s, T~±0.4℃
Air flow anemometer	--	0.1±3%m/s
INNOVA		±2%
Digital thermometer -Fluke 54 II	60 seconds	0.05%±0.03%)

5.3.2 Manikin based equivalent temperature

The thermal manikin measurements formed an integral part of the physical measurements. During the experiment, a thermal manikin was placed in front of a workstation in sedentary posture to simulate a human-being with typical summer clothing (0.7 clo). The manikin was located at workstation J4 (Figure 1a) and operated with both thermal and breathing mode. The operating parameters of the manikin are listed in Table 5.4. The body of the manikin is divided into 26 segments. The surface temperature and heat flux for each of the body segments was recorded every 1 minute. The "manikin-based equivalent temperature" (ISO Standard 14502-2 2004) was as the index to determine the effects of the thermal environment on the body cooling.

Table 5.4 Manikin operating conditions during experiment

Parameters/ condition		Value/ description
Posture		Seated
Thermal operation		Comfort
Clothing		0.7 clo. (undergarments, T-shirt, pants and slipper)
respiration	Inhalation	Through mouth 2.5 s/ breathing
	Exhalation	Through nose 2.5 s/ breathing, 34 °C exhale air temperature
	Break	1.0 s/breathing
	frequency	10 times/min.
	pulmonary ventilation volume	6 L/min.

The control system of the manikin is based on correlation between skin temperature (t_s) and dry heat loss (Q_t) of an average human body according to Fanger's comfort equation:

$$t_s = 36.4 - 0.054 \cdot Q_t \qquad \text{(Eq. 5.1)}$$

Where t_s is the skin temperature, °C,

Q_t is sensible heat loss, W/m^2,

36.4 is the deep body temperature, °C,

0.054 is thermal resistance offset of the skin temperature control system, K.m^2/W.)

The equivalent temperature has been found to be a useful tool to determine the effects of local air movement and radiant asymmetry, while measured air temperatures and velocities provided less detailed explanations. The equivalent temperature (formerly equivalent homogenous temperature) is defined as "The uniform temperature of the imaginary enclosure with air velocity equal to zero in which a person will exchange the same dry heat by radiation and convection as in the actual non-uniform environment" (ISO standard 14505 2004).

$$t_{eq} = 36.4 - C \cdot Q_t \qquad \text{(Eq.5.2)}$$

Where t_{eq}= the manikin-based equivalent temperature, °C,

36.4 = the deep body temperature, °C,

Q_t = the sensible heat loss, W/m^2,

C = constant dependent on clothing, body posture, chamber characteristics and thermal resistance offset of the skin surface temperature control system, K.m^2/W.

In the present study, the cooling effects of the non-uniform conditions created with the UFAD-PV systems were quantified by calculating the change in manikin-based equivalent temperature obtained in actual measurements with

PV from reference conditions (UFAD only) according to the following equation:

$$\Delta t_{eq} = t_{eq} - t^*_{eq} \text{ (Eq. 4.6)} \qquad \text{(Eq. 5.3)}$$

Where t_{eq} = manikin-based equivalent temperature in an actual environment, °C,

t^*_{eq} = manikin-based equivalent temperature in reference conditions, °C.

Before the experiment, calibration of the manikin was performed in the indoor environmental chamber. During the calibration, the indoor condition was kept as close to homogeneous as possible. The manikin was exposed in the chamber to a given air temperature, dressed and kept at sedentary posture as it was during subsequent actual experiments. The heat loss from the body segments was recorded. Under the homogeneous condition, the indoor air temperature was equal to the t_{eq}. Then the constant C values were calculated based on Eq.5.2.

5.3.3 Tracer gas measurements

Tracer gas (SF_6) measurements were performed to investigate the performance of the UFAD-PV system in terms of the ability to provide occupants with conditioned outdoor air. SF_6 was dosed at the location G10 (Figure 1a) at 1.3 m height until the concentration measured at 1.3 m height of G10, D5, D12, return grille level of K4 and manikin's mouth (J4) increased to 100 ppm. The manikin was set with both thermal and breathing mode (Table 5.4). The 100% outdoor air supplied by the personalized ventilation system was kept free of SF_6, which was continuously sampled at above mentioned locations inside the environmental chamber by Infra-red photo-acoustic spectrometer multi-gas sampler and analyzer. The results of tracer gas concentration measurement were used to analyze the performance of the system with regard to inhaled air quality. Two indices as defined below were calculated: personal exposure effectiveness (PEE) and Personal exposure index (PEI).

The PEE index expresses the percentage of personalized air in inhaled air. It is derived from the following equation (Melikov et al., 2002):

$$\mathbf{PEE} = \frac{C_{R,SF6} - C_{I,SF6}}{C_{R,SF6} - C_{PV,SF6}} \qquad \text{(Eq. 5.4)}$$

Where $C_{R,\,SF6}$ = SF_6 concentration of the tracer gas in the exhaust/return air (ppm),

$C_{PV,\,SF6}$ = SF_6 concentration of the tracer gas in personalized air (ppm),

$C_{I,\,SF6}$ = SF_6 concentration of the tracer gas in the inhaled air (ppm).

The concentrations are average values taken over concentration measurement curves when steady-state conditions were reached. This index is equal to one if the inhaled air consists of 100% of the personalized air and equal to zero if no personalized air is inhaled.

The Personal Exposure Index (PEI), also called pollutant removal efficiency, is the effectiveness of an air distribution system in removing internally generated pollutants from the ventilated space. It can be expressed either as an average or overall relative effectiveness for the whole occupied zone or as a local relative effectiveness. The local ventilation effectiveness for the removal of pollutants, ε_V, also called the PEI, is expressed as (Awbi, 2003):

$$\mathbf{PEI} = \frac{C_R - C_{\infty}}{C_I - C_{\infty}} \qquad \text{(Eq.5.5)}$$

Where C_R = contaminant concentration in the exhaust/return air (ppm),

C_I = contaminant concentration in the inhaled air of a person (ppm)

C_∞ = contaminant concentration in the outdoor supply air (ppm).

5.3.4 Energy analysis

The temperature effectiveness shows how effectively the excessive heat is removed from the room. This index was used in this study for evaluation of heat removal effectiveness.

Temperature effectiveness (Heat removal effectiveness)

The temperature effectiveness (Etheridge and Sandberg, 1996) is defined as:

$$\varepsilon_t = (t_{ex} - t_0)/(t_{oz} - t_0) \qquad \text{(Eq. 5.6)}$$

where t_{ex} and t_0 are exhaust and supply air temperatures, and t_{oz} is the average occupied zone temperature.

Energy saving ratio (heat pipe)

The energy saving potential of integrating heat pipe in the PAHU is represented by the energy saving ratio (ε_{HP}) which was defined as the ratio of the energy saving from free cooling heat recovery to the total energy input of the PAHU.

$$\varepsilon_{HP} = \frac{1.184\, m_a[(h1' - h2') + (h4' - h3')]}{1.184\, m_a[(h1 - h2) + (h3 - h2)]} \qquad \text{(Eq5.7)}$$

Where m_a= the air mass flow rate (kg/s)

h_1= enthalpy of the outdoor air before entering the cooling coil (without heat pipe) (kJ/kg)

h_2= enthalpy of the air after the cooling coil (without heat pipe) (kJ/kg)

h_3= enthalpy of the air after the heater (without heat pipe) (kJ/kg)

h_1'= enthalpy of the outdoor air before entering the evaporator of the heat pipe (kJ/kg)

h_2' = enthalpy of the air before entering the cooling coil (kJ/kg)

h_3' = enthalpy of the air after the cooling coil (kJ/kg)

h_4' = enthalpy of the air after the condenser of the heat pipe (kJ/kg)

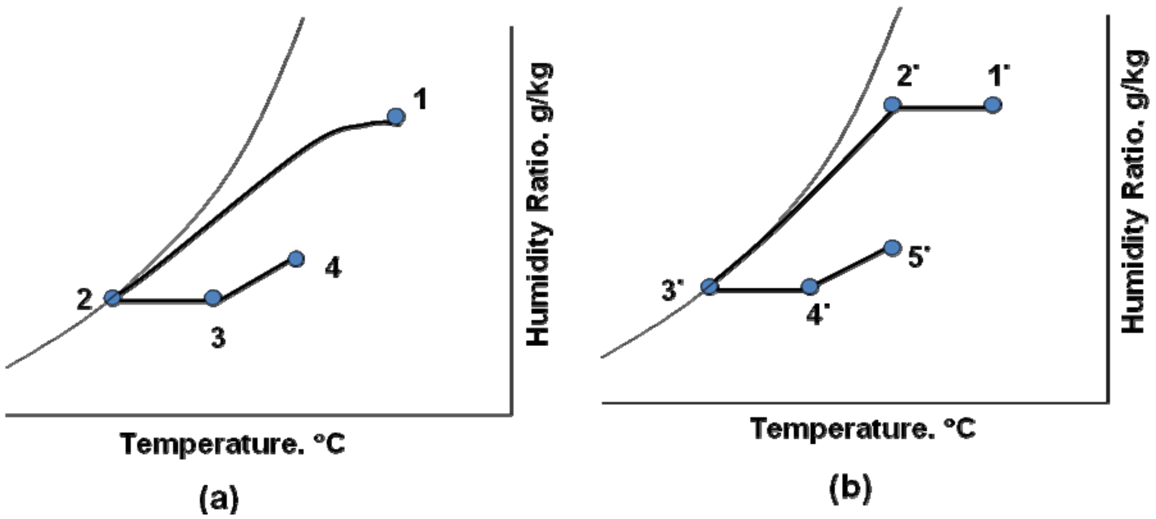


Figure 5.7 Psychrometric analysis of Heat Pipe (a) without heat pipe; (b) with heat pipe (Source: Sekhar and Chong, 2007)

As shown in Figure 5.7a, when the outdoor air passes through the cooling coil, the status of the air changes from 1 to 2. In order to create a warmer supply air temperature for UFAD system to create certain level of room condition (4), reheating is necessary (2 to 3). Reheating is not an attractive option owing to its energy penalty and is also, typically, not permitted in most codes and standards in hot and humid climates, including Singapore (CP13, 1999). When the heat pipe is integrated with the conventional AHU (Figure 5.7b), the energy saving could be expected from the pre-cooling (1' to 2') and reheating (3' to 4'), which is an entirely passive process and requires no additional primary energy.

5.4 Subjective survey

The physical measurements to characterize the IAQ and thermal comfort provided by the UFAD-PV system were accompanied with human response measurements involving university students as subjects. These experiments were conducted by a strict adherence to experimental design and protocol that complied with the requirements of the Institutional Review Board (IRB) of the university.

5.4.1 Subjects

Thirty tropically acclimatized subjects, 15 males and 15 females, were divided into 4 groups (Table 5.5) and were asked to wear typical summer clothing (0.6~0.7 clo.). Their average age was 22. Their average height was 1.67m and average weight is 55.7 kg (Appendix 2). Two of the groups, Group1 and 2, consisted of 7 subjects only (Group 1 – 4 females and 3 males, Group 2 – 3 females and 4 males). When these groups participated in the experiments the thermal manikin was used to replace the last member of the group and to collect the objective measurements discussed above. In this way more accurate comparison of human responses with thermal manikin based equivalent temperature was achieved.

Table 5.5 Subjects' groups

Group	Number of Female	Number of Male
1	4	3
2	3	4
3	4	4
4	4	4

The subjects were recruited based on the following criteria: having been exposed to local tropical climate for more than 6 months, familiarity with a PC, impartiality to the chamber in which the study were carried out, and absence of chronic diseases, asthma, allergy and hay-fever, etc. Subjects were instructed to have normal meals before arrival at the thermal chamber. No intake of alcohol was allowed 24 hours prior to each experiment. The duration of each experiment was 2.5 hours. During the experiments, subjects were asked to be dressed in typical office attire to simulate an office environment (about 0.6~0.7clo.). Subjects were restricted to only deskbound activities. During the experiments, they were not allowed to eat anything. They could drink only plain water. Subjects were randomly exposed to different test conditions on different days and were kept blind to the test conditions to avoid biased results.

5.4.2 Questionnaires

A computerized questionnaire survey was used to obtain the responses from the various groups of subjects in several series of experimental conditions. During the experiments, the subjects responded to questionnaires on the thermal sensation for the whole body and body parts (ASHRAE seven point thermal sensation scale: cold = -3, cool = -2, slightly cool = -1, neutral = 0, slightly warm = 1, warm = 2, hot = +3), whether they felt any air movement at any of the body segments, how they felt the air movement at each body part (scale categories and weights were adopted on a diagram of human body: +3 Much too air movement; +2 Too breezy; +1 Slightly breezy; 0 Just right; -1 Slightly still; -2 Too still; -3 Much too still), the acceptability for air movement at different body parts (face, neck, chest, shoulder and upper arm, lower arm and hands, back and lower body) was voted on linear visual scales with end point coded as 0 (very unacceptable) and 100 (very acceptable), with an interval in between 50 (just unacceptable) and 50 (just acceptable) for assessment of air movement acceptability. Subjects were also asked to indicate their preferred change for air movement of different body parts. Detailed questionnaires are shown in Appendix 1.

5.4.3 Procedures

Each experimental session proceeded as follows:

i. Subjects arrived at the chamber 30 minute prior to the commencement of the experiment. They were seated in the control room and briefed about the procedure. During this period, as they acclimatized to the environment, they started answering some questions which inquired about their personal particulars and the type of clothes they were wearing.

ii. Every 15 minutes thereafter, subjects completed a questionnaire on their thermal sensation for different parts of the body, thermal comfort acceptability and air movement detection and acceptability as well as SBS. After the acclimatization period, these subjects entered the chamber and started to answer the questions. In the first 15 mins they were asked to sit at the workstations with 5 L/s PV flow rate.

iii. After the first 15 mins, the subjects were given the opportunity to change to the adjacent workstation with 10 L/s PV flow rate.

iv. After the second 15 mins, the subjects were given the opportunity to change back to the workstation they stayed in the first 15 mins. They were also allowed to stay in the workstation they were seated currently.

v. After the third 15 mins, the subject must stay in the workstation which they finally chose and answer the questionnaire every 15 mins.

5.4.4 Data analyses

Only data for the last 15 minutes of each experiment were used for analysis; it is believed that subjects would have acclimatized after they were exposed to the environment for about 3 hours. Microsoft Excel's Analysis ToolPak and statistical software SPSS (Version 11.5) was used to analyze the results obtained from the questionnaires. Shapiro-Wilk Test was performed to test whether the samples came from normal population. This test indicates whether parametric or non-parametric tests will be appropriate for statistical analysis of the data. When the test shows that the samples are normally distributed, parametric tests such as Paired T-test is used to determine whether there are any significant differences between different cases. If not, non-parametric tests, such as Wilcoxon test, were used. The correlations between subjective responses and physical parameters were analyzed using linear correlations by two tailed Pearson test. The overall descriptive statistic analysis of all subjective responses for the last 15 mins is listed in Appendix 3.

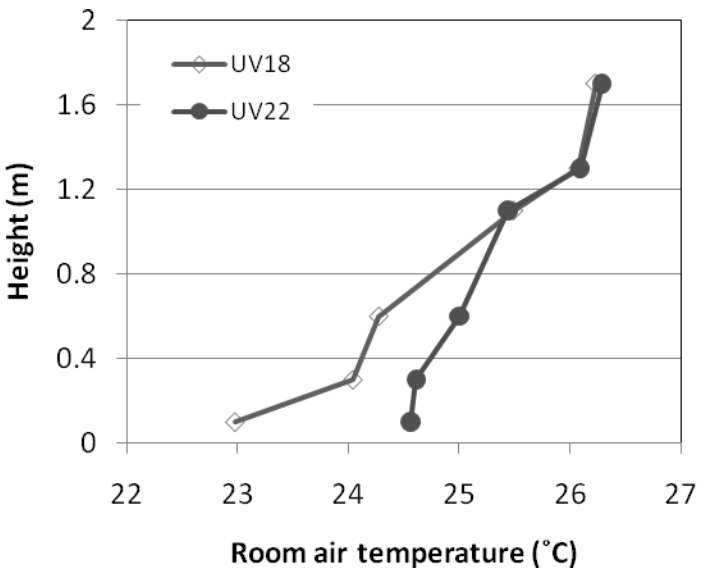
Chapter 6 Manikin and Human Subject Study – Results: Effect of UFAD Supply Air Temperature

The effect of warmer UFAD supply air temperature is analyzed in this chapter. Both the objective parameters and human responses are discussed. The results of the manikin measurements reveal that the warmer UFAD supply air temperature can result in a warmer thermal environment in the lower space of the occupied zone. Subjective responses also showed that the warmer thermal environment created by the warmer UFAD supply air temperature has a positive effect on the thermal sensation and acceptance of air movement at feet level. The warmer UFAD supply air temperature was proven to effectively prevent cold draft at feet level as expected. However, the performance of the UFAD system with warmer supply air temperature might be abated when compared with that of conventional ceiling supply system regarding the warmer sensation of whole body and the unpleasant sensation at facial part. Thus, the motivation for exploring the UFAD-PV system is discussed based on the effect of the warmer UFAD supply air temperature on the human responses for whole body and head level.

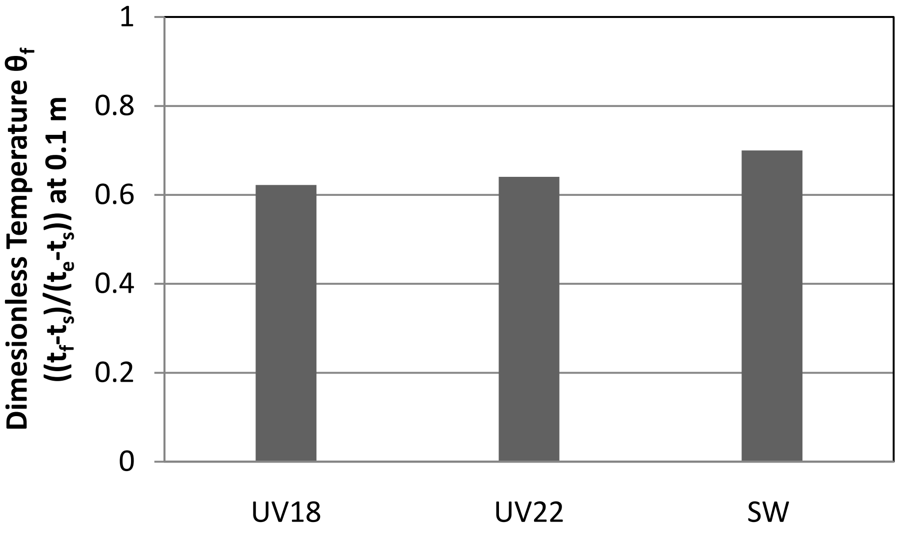
6.1 Room air temperature/velocity/DR distribution

Vertical temperature distribution at the centre of the room

The vertical room air temperature distribution at the centre of the room is presented in Figure 6.1a.



(a)



(b)

Figure 6.1 Room air temperature distribution at the centre of the room, (a): Vertical room air temperature (b): θ_f ,Dimensionless Temperature at 0.1 m (SW, from Webster et al. 2002a)

From the data collected at the centre of the room, it can be concluded that the room air temperature stratified along the vertical height of the space. However, the profiles measured with the two UFAD supply air temperatures, UV18 (18 °C) and UV22 (22 °C) differ at the lower part of the space. This is in contrast to the observations made by Webster et al (2002a) (Figure 2.8) that increase of the air temperature only moves the vertical temperature curves parallel to each other. In the current study, the temperatures at the upper heights tend to converge and be close to the room air temperature at 1.3 m height, which is maintained at 26 °C. As expected, lower temperature exists when temperature of the supply air is 18 °C. As the room air temperature is controlled at 26 °C at 1.3 m, above the height of the controlled points (1.3 m), the temperature profiles at the center of the room are almost overlapped for the two cases. The warmer UFAD supply air temperature results in warmer room air temperature especially at the lower part of the space. The air temperature measured at 0.1m at the centre of the room is 23 ˚C in case UV18 and 24.6 ˚C in case UV22. Although the difference between the two profiles decreases with the increase of the vertical height, the room air temperature in case UV22 was always at warmer side than case UV18. The temperature profile slope of UV22 is steeper than that of UV18. This is due to the lower air volume flow rate (360 L/s) associated with the 18 ˚C supply air temperature.

The dimensionless temperature near the floor (Bauman et al. 2003) is defined as

$$\theta_f = \frac{t_f - t_s}{t_e - t_s} \qquad \text{(Eq. 6.1)}$$

where t_f, t_s and t_e stand for the air temperature near the floor, at the supply, and at the exhaust, respectively.

In this research, with the cooler supply air temperature (18 °C), the dimensionless temperature θ_f (Bauman et al. 2003) at 0.1 m is 0.63 and is 0.65 with the warmer supply air temperature (22 °C) (Figure 6.1b). Although the supply air flow rates of the UFAD system were different according to different supply air temperature, the dimensionless temperatures of the UFAD system were almost equal to each other for the two cases (UV18 and UV22). This result shows that the dimensionless temperature near the floor was almost constant regardless of the airflow rates. This is consistent with the results of former researchers. Experimental data for both swirl and variable-area floor diffusers taken from Webster et al (2002a) (Figure 6.1b, SW) reveals that the dimensionless temperature near the floor remain close to constant level of 0.7 over a fairly wide range of airflow rates.

Vertical room air temperature distribution (close to the manikin)

The vertical room air temperature distribution close to the manikin is presented in Figure 6.2.

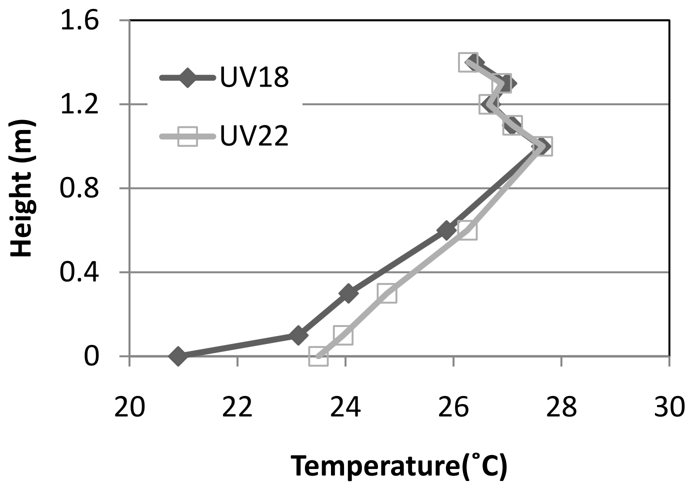
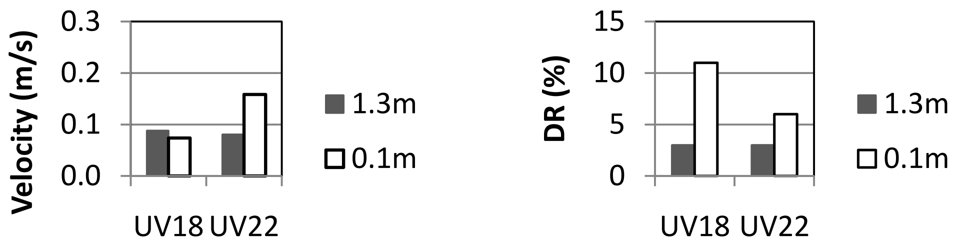


Figure 6.2 Vertical room air temperature distributions close to the manikin (The temperature at height "0" refers to the temperature of floor surface)

In the region close to the floor surface and lower body parts of the manikin (0.1~0.6 m), the room air temperatures are also warmer with the warmer UFAD supply air temperature (UV22). The vertical temperature gradients are larger in the space close to the thermal manikin than those in the centre of the room. At the ankle level (0.1 m), the room air temperatures were 22.7 ˚C in case UV18 and 24.2 ˚C in case UV22 which are close to those measured at the centre of the room. However, at the breathing zone (1.1 m), the measured temperature increases to 27.1˚C for both of the cases which were about 2 degrees higher than that at the centre of the room (25.5 ˚C, Figure 6.1). This might due to the closer distance between the measuring points and the heat source (manikin and personal computer), which has a thicker boundary layer when the height increases. The convection flow generated in this region result in higher level of temperature gradient and warmer temperature at breathing zone than in the space away from the workstation.

Room air velocity and Draft Rating distribution

The air velocity measured in the space close to the manikin is shown in Figure 6.3.



(a) (b)

Figure 6.3 Measurements close to the manikin - (a) Room air velocities (b) DR distribution

At the 1.3 m height (occupant's head level), the air velocities in both cases, UV18 and UV22, are similar and lower than 0.1 m/s. This is observed even with the higher UFAD air flow rate supplied in the case with warmer UFAD supply temperature (UV22). After being fully mixed with the room air, the air velocities are always reduced to almost still condition at a certain height. Above this height, the air velocity distributions are not affected by the supply air flow rate of the UFAD system. At the ankle level, the air velocity is higher with the warmer UFAD supply air temperature (UV22) (Figure 6.3a, 0.1 m) than that with the cooler UFAD supply air temperature (UV18). This is consistent with the higher supply air flow rate, which is associated with the warmer UFAD supply air temperature. In the space close to the floor, the air velocity distributions are affected by the UFAD supply air flow rate.

Similar to the air velocity distribution, the draught ratings are comparable for the two cases (UV18 and UV22) (Figure 6.3 b). The DR values determined at 1.3 m were quite close between the two cases with UFAD. However, at the ankle level (0.1 m), the DR distribution shows a different pattern than that of the velocity. When the warmer supply air temperature (UV22) was used, the DR is relatively lower. The warmer UFAD supply air temperature could compensate the effect of the higher air movement and result in a smaller DR even with a higher air velocity.

6.2 Manikin based equivalent temperature

The manikin based equivalent temperatures for UV18 and UV22 are presented in Figure 6.4.

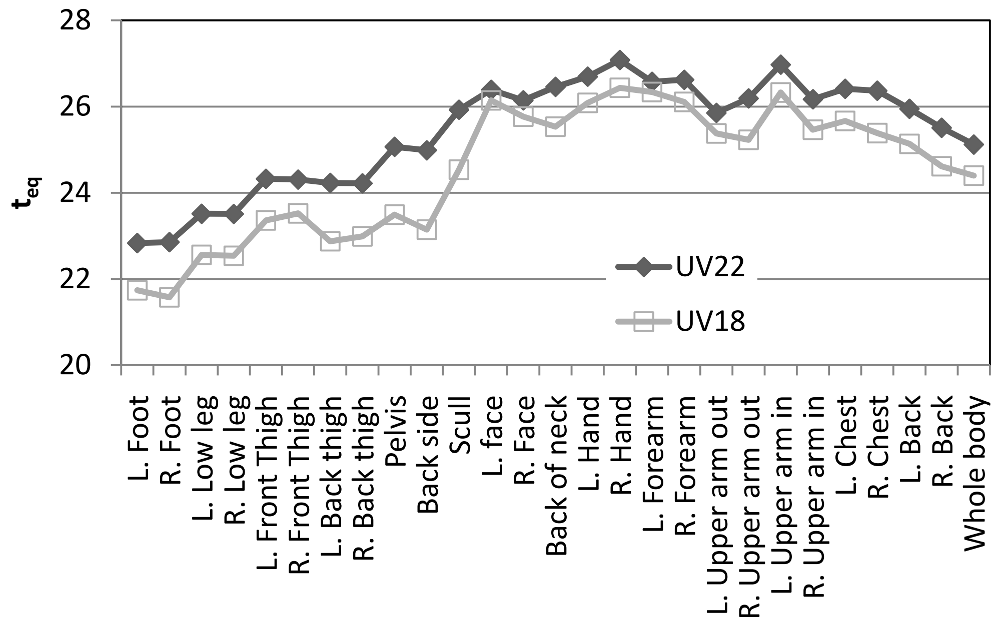


Figure 6.4 Manikin based equivalent temperature
($\Delta t_{eq,feet,\ 18\text{-}22}$= -1.2 ˚C, $\Delta t_{eq,whole\ body,\ 18\text{-}22}$= -0.7 ˚C, , $\Delta t_{eq,face,\ 18\text{-}22}$= -0.3 ˚C)

In case UV22, the t_{eq} at feet segment was 22.9 ˚C which is about 1.2 ˚C warmer than the t_{eq} at feet in case UV18. The difference of the t_{eq} at feet was about 1.2 ˚C ($\Delta t_{eq,face}$) between the two cases. At the facial part, the Δt_{eq} decreased to only 0.3 ˚C. When the Δt_{eq} of whole body is considered, the value is just between that at feet and face (0.7 ˚C).

The results in Figure 6.4 can be explained with the temperature and velocity distribution around the manikin. The air temperature at the lower parts of the room was always warmer with warmer UFAD supply air temperature. Moreover, the higher air movement associated with this warmer UFAD supply air temperature was not likely to cause an excessive heat loss through convection and higher level of DR as it was already discussed. In order to keep the same level of temperature at 1.3 m height in the room and remove the same amount of cooling load from the space, higher air flow rate of the UFAD system was demanded when the warmer supply temperature was used and vice versa. The air velocity measured close to the manikin's ankle level is higher with the warmer UFAD supply air temperature. However, the draft rating is not as high as the velocity when the warmer supply air temperature was used. This indicates that the warmer supply air temperature of UFAD has the ability to prevent cold draft even with a higher air velocity. The equivalent temperature at feet level also shows the same trend. Since both air velocity and air temperature have an impact on convective heat loss, the increase of velocity and temperature at the same time may lead to increase of the convection heat loss but it may also lead to decrease of convection heat loss when the temperature increase is high enough. Although the air movement close to the floor has certain effect on increasing the convective heat loss from the manikin's feet level, the case with warmer UFAD supply air temperature can reduce the heat loss of the lower body segments.

6.3 Subjective response

6.3.1 Thermal sensation at feet

Figure 6.5 compares the thermal sensation at the feet as reported by the subjects during the experiments at the two UFAD supply air temperatures. The average thermal sensation for the pool of 30 subjects is compared in the figure. The comparison shows that the increase of UFAD supply air temperature can result in a warmer thermal sensation at feet level. This effect of UFAD supply air temperature was found to be statistically significant (P=0.0012). The warmer supply air temperature can significantly reduce the cool sensation at feet. Moreover, the subjective responses on the thermal sensation at feet are consistent with the results of manikin based equivalent temperature, which is warmer in case UV22 than in case UV18 at feet. Both the manikin measurements and the subjective response indicated that the warmer UFAD supply air temperature (UV22) can improve the thermal comfort at the lower body part.

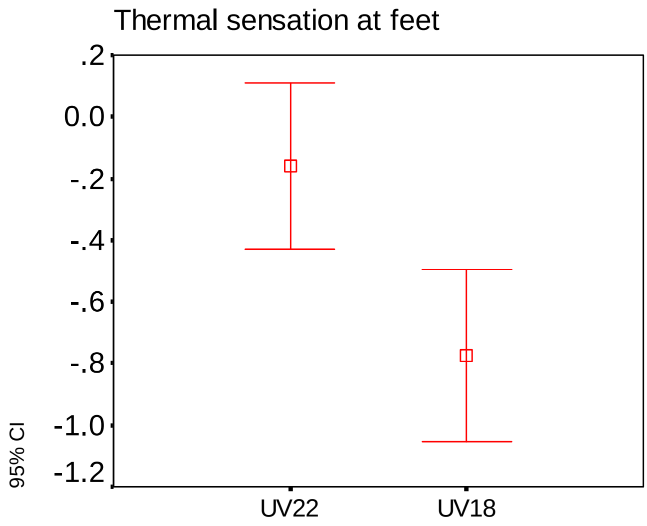


Figure 6.5 Thermal sensation at feet reported at UFAD supply air temperatures of 18 ˚C (UV18) and 22 ˚C (UV22) *Average thermal sensation reported by the 30 subjects is shown. The 95% confidential interval is identified*

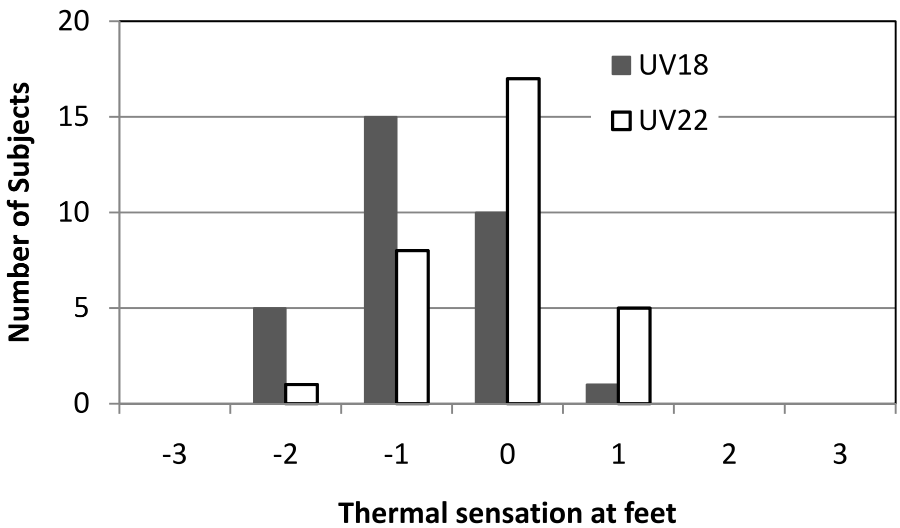


Figure 6.6 Distribution of the thermal sensation at feet as reported by the individual subjects participating in the experiment (*Thermal sensation scale: =-3 cold, =-2 cool, =-1 slightly cool, =0 neutral, =1 slightly warm, =2 warm, =+3 hot***)**

The thermal sensation is close to neutral (-0.2) in case UV22 and decreased to "slightly cool" (-0.8) in case UV18 (Figure 6.5). The same trend can also be found from the histogram chart in Figure 6.6, which shows the distribution of the thermal sensation vote of the subjects. The highest frequency of the thermal sensation vote changes from “-1, slightly cool” to “0, neutral” when the UFAD supply air temperature changes from 18 °C to 22 °C. In case UV18, fifty percent subjects felt “slightly cool” and 5 of the thirty subjects felt “cool” at the feet level. About one third of the subjects felt “neutral” and only one subject felt “slightly warm”. While in case UV22, the number of subjects who felt “slightly cool” at feet level was reduced to 7 and only one subject reported “cool” sensation. The number of subjects who felt “neutral” and “slightly warm” increased to 22 (17 for “neutral” and 5 for “slightly warm”). The results of statistical analysis of the effect of the two UFAD supply air temperatures are shown in Figure 6.7.

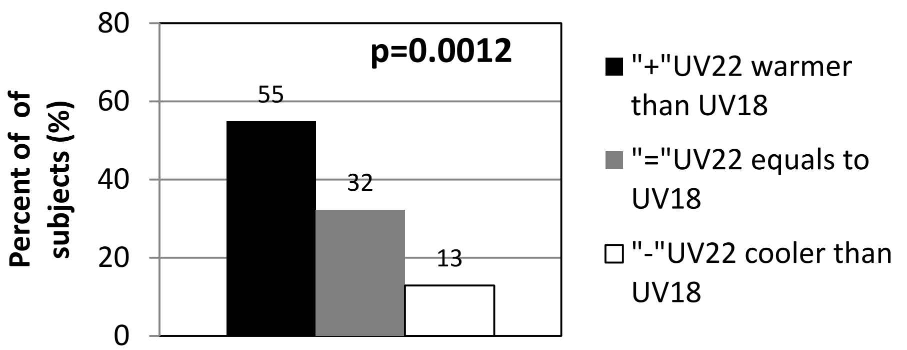


Figure 6.7 Comparison of thermal sensation at feet level in pair of UFAD supply air temperatures at 22 ˚C (UV22) and 18 ˚C (UV18) (Wilcoxon Signed Ranks Test, P-value =0.0012) *(“+”: subjects who vote for warmer thermal sensation at feet in case UV22 than in case UV18; “=”: subjects who vote for same thermal sensation at feet in case UV22 and UV18; “-“: subjects who vote for cooler thermal sensation at feet in case UV22 than in case UV18.)*

The significance of the effect of different UFAD supply air temperature on the thermal sensation at feet were analyzed by using Wilcoxon Signed Ranks Test between the two cases UV22 and UV18. The effect of warmer UFAD supply air temperature on bringing warmer thermal sensation at feet is significant (p=0.0012). The result shows that most of the subjects (55%) felt warmer at feet in case UV22 than in case UV18 (Figure 6.7). Few of them (13%) felt cooler at feet with 22°C UFAD supply air temperature than with 18 °C. Those who reported no difference between the two cases (UV22 and UV18) are about 32%.

6.3.2 Perception, acceptability and preference of air movement

(1) Perception of air movement

The average vote of the subjects for perception of air movement at feet is shown in Figure 6.8. The chart indicates that the subjects feel less breezy with the warmer UFAD supply air temperature. In this case (UV22), the mean value of perception of air movement at feet is in the range of "just right" (0) and "slightly still" (-1). The vote for perception of air movement increases with the decrease of UFAD supply air temperature (UV18) to a level in the range of "just right" (0) and "slightly breezy" (+1). It is evident that UV18 causes more breezy perception than UV22 at the feet level.

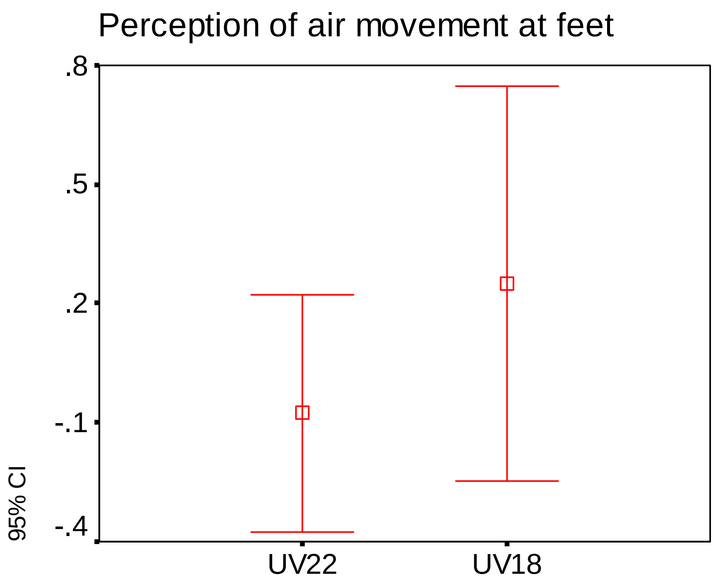


Figure 6.8 Mean values of Perception of air movement at feet (error bar with 95% confidential interval.)

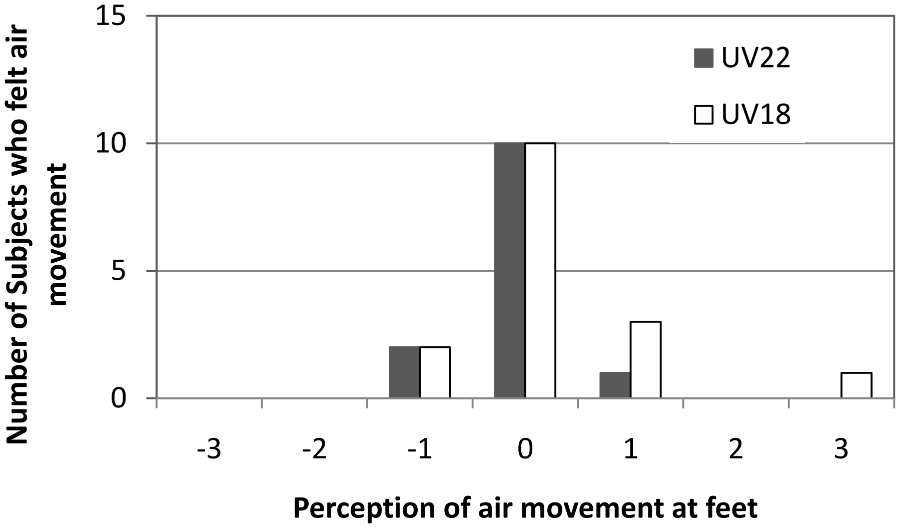


Figure 6.9 Number of subjects of each perception of air movement scale
(*Perception of air movement scale: +3 Much too air movement; +2 Too breezy; +1 Slightly breezy; 0 Just right; -1 Slightly still; -2 Too still; -3 Much too still, N no air movement*)

Figure 6.9 compares the perception of air movement at the feet as reported by the subjects during the experiments at the two UFAD supply air temperatures. The number of the subjects who reported that they did not feel any air movement increases from 15 with case UV18 to 18 with case UV22. Among those who felt the air movement, the number of subjects who felt "slightly breezy" and "much too air movement" are less in case UV22 than in case UV18. These changes of the counted numbers for perception of air movement scales between the two cases indicate that the subjects were less sensitive to the air movement at feet level with a warmer UFAD supply air temperature when compared with their responses to the cooler UFAD supply air temperature.

However, the distribution of the counted number for each perception of air movement scale seems similar for case UV22 and UV18 (Figure 6.9). To identify the effect of different UFAD supply air temperatures, the subjects' responses are analyzed in pairs for the two cases (UV22 and UV18). The results of the statistical analysis reveal that among those who felt the air movement, subjects' perception of air movement were not significantly different between the two cases (P=0.206 >0.05). The majority of the subjects (61%) have the same perception of air movement between the two cases UV22 and UV18 (Figure 6.10). The subjects who felt more "breezy" with the cooler UFAD supply air temperature were about 28% (Figure 6.10 "-"). There are still 11% of the subjects who felt more "breezy" with the warmer UFAD supply air temperature (Figure 6.10 "+").

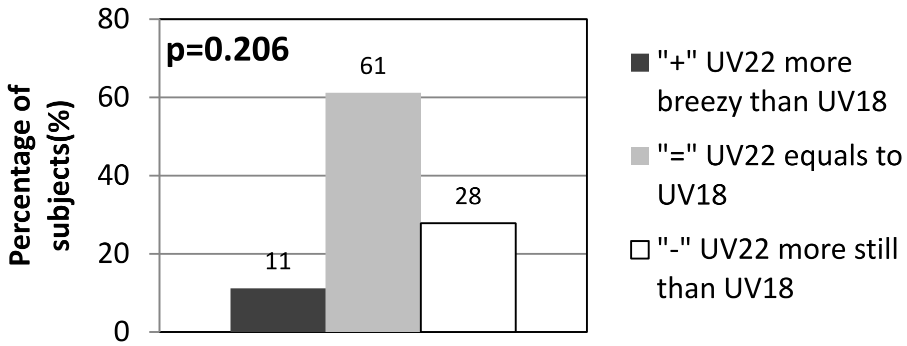


Figure 6.10 Comparison of perception of air movement at feet level in pair of UFAD supply air temperature at 22˚C (UV22) and 18˚C (UV18) (Wilcoxon Signed Ranks Test, p-value =0.206>0.05) *("+": subjects who perceived more breezy air movement at feet in case UV22 than in case UV18; "=": subjects who perceived same perception of air movement at feet in case UV22 and UV18; "-": subjects who perceived more still air movement at feet in case UV22 than in case UV18).*

(2) Acceptability of air movement (feet)

The perception of air movement results identifies that the percentage of subjects who felt the air movement at feet more "still" at supply air temperature of 22 ˚C (UV22) was 28% and higher than the percent of subjects who felt the air movement at the feet as more "breezy". However, the above results cannot ascertain whether this effect of warmer UFAD supply air temperature causing a more "still" perception at feet is negative or positive for the occupants. Therefore, the acceptability of air movement at feet level was analyzed between the cases UV22 and UV18. The results are shown in Figure 6.11 and Figure 6.12.

The percentage of subjects who felt unacceptable was significantly higher when the cooler UFAD supply air temperature was used. In case UV18, the percentage of subjects who reported unacceptable air movement at feet level was about 16%. As the results in Figure 6.11 show, when the warmer UFAD supply air temperature was used (UV22), a lower percentage of subjects felt the air movement at feet level was unacceptable (6.5%). Thus, the positive effect of the warmer UFAD supply air temperature was apparent. At the feet level, the more "still" perception of the air movement was not necessarily causing unacceptable air movement at feet level. The air movement at feet level was more acceptable for most of the subjects when the warmer UFAD supply air temperature was used.

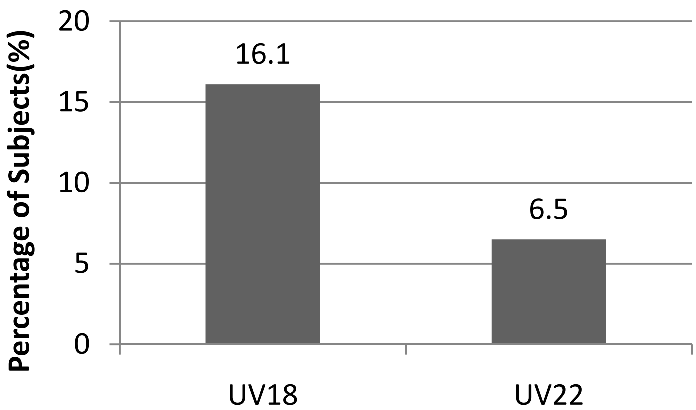


Figure 6.11 Percentage of subjects who felt air movement at feet unacceptable

Moreover, the positive effect of warmer UFAD supply air temperature on the subjects' acceptability of air movement at feet level was confirmed by the statistical analysis. The acceptability of air movement at feet is significantly improved by using warmer UFAD supply air temperature (p=0.035, Figure

6.12). In Figure 6.12, thirty five percent of subjects felt more acceptable to the air movement at feet with 22˚C UFAD supply air temperature than with 18 ˚C. Fifty five percent of them felt no difference on the acceptability of the air movement at feet between the two UFAD supply air temperatures. Only 10% of the subjects reported that they were less satisfied with the air movement at feet in case UV22 than in case UV18.

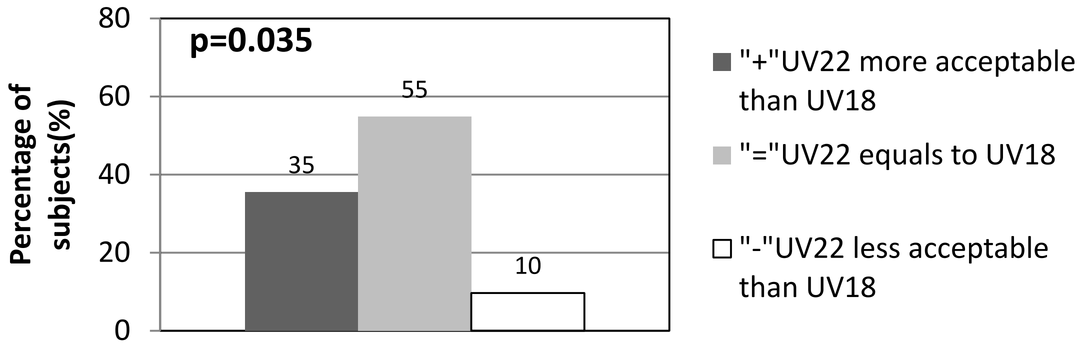


Figure 6.12 Comparison of acceptability of air movement at feet level in pair of UFAD supply air temperature at 22˚C (UV22) and 18˚C (UV18) (Wilcoxon Signed Ranks Test, p-value =0.035) *("+": subjects who felt the air movement at feet in case UV22 more acceptable than in case UV18; "=": subjects who felt the same acceptability for the air movement at feet in case UV22 and UV18; "-": subjects who felt the air movement at feet in case UV22 less acceptable than in case UV18)*

(3) Preference for air movement(feet)

In addition to rating the acceptability of air movement, the subjects were also required to answer the question about their preference for change of air movement. The scale categories for the preference of change of air movement were: (1) more air movement, (0) no change of air movement and (-1) less air movement.

The results in Figure 6.13 show that majority of subjects are satisfied with the air movement at feet and did not like to make any changes. In both the cases, UFAD supply air temperature of 18 ˚C and of 22 ˚C, more than fifty percent of the subjects preferred "no change" ("0") for the air movement at the feet. In the case with warmer UFAD supply air temperature (UV22), less subjects preferred less air movement at feet and more subjects prefer more air movement when compared with the responses at the cooler UFAD supply air temperature (UV18). In case UV22, the percentage of subjects who preferred “more air movement” (“1”) was 36%, which is higher than with the cooler UFAD supply air temperature (21%). Moreover, the percentage of subjects who preferred “less air movement” (“-1”) decreased from 11% (in case UV18) to 7% (in case UV22) with the increase of UFAD supply air temperature.

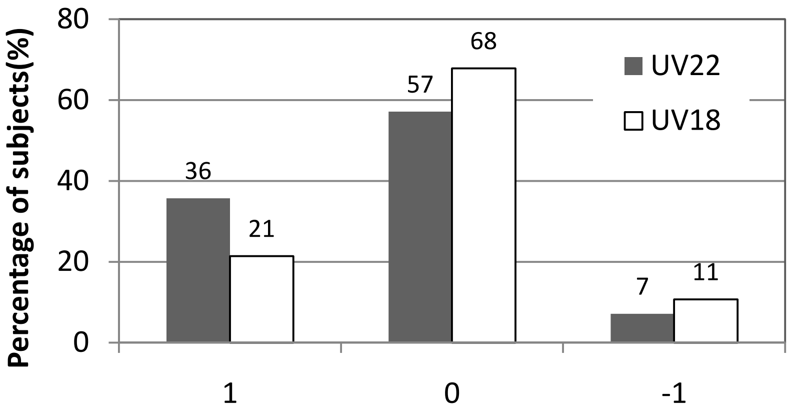


Figure 6.13 Preference for air movement at feet *(“1”: more air movement, “0”: no change, “-1”: less air movement*)

The results of statistical analysis (Figure 6.14) show that at feet level, majority of the subjects (74%) report no difference on their preference for air movement between case UV18 and UV22. The difference between the two cases (UV18 and UV22) is not statistically significant (Figure 6.14, p=0.157). This result indicates that the effect of changing the UFAD supply air temperature from 18 °C to 22 °C is not significant in changing the preference for air movement. Although the actual air movement is higher with the warmer UFAD supply air temperature, occupants are not likely to be annoyed by excessive air movement at feet level. This result is consistent with that of manikin equivalent temperature at feet segments. Although the higher level of air velocity could increase the convection heat loss, with the warmer air temperature, the heat loss is lower.

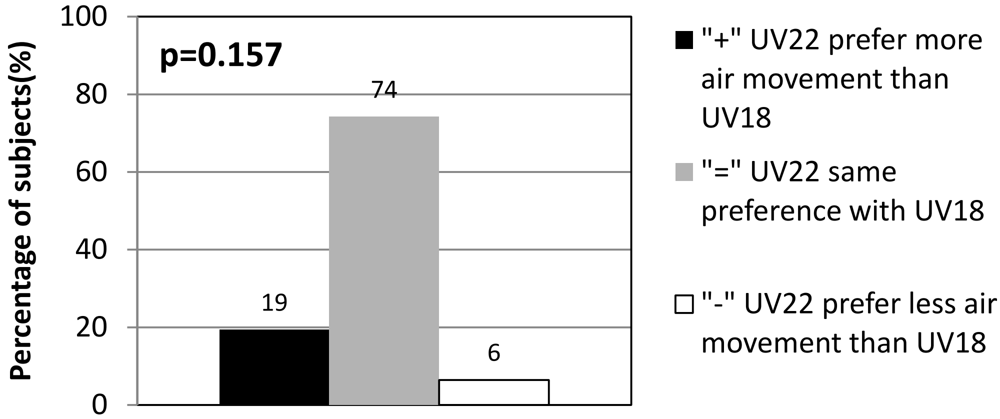


Figure 6.14 Comparison of preference for air movement at feet level in pair of UV22 and UV18, (Wilcoxon Signed Ranks Test, p-value =0.157) the preference for air movement at feet level is NOT significantly different between UV22 and UV18) *("+": subjects who prefer to have more air movement at feet in case UV22 than in case UV18; "=": subjects who have the same preference for the air movement at feet in case UV22 and UV18; "-": subjects who prefer to have less air movement at feet in case UV22 than in case UV18)*

The lowest acceptability of air movement at the feet level is reported by the subjects who preferred less air movement ("-1") as it can be seen from the results shown in Figure 6.15. However, the preference for more air movement at feet level ("1") does not cause unacceptable feeling of the air movement at feet. The subjects who preferred "no change" ("0") of the air movement are most satisfied with the current air movement and reported the highest acceptability. It is only slightly higher than the acceptability of air movement reported by the subjects who preferred more air movement.

This relationship between the acceptability of air movement and preference at feet level indicates that the subjects are most likely to feel the air movement unacceptable when they are annoyed by the unpleasant air movement at feet level and are willing to change to less air movement.

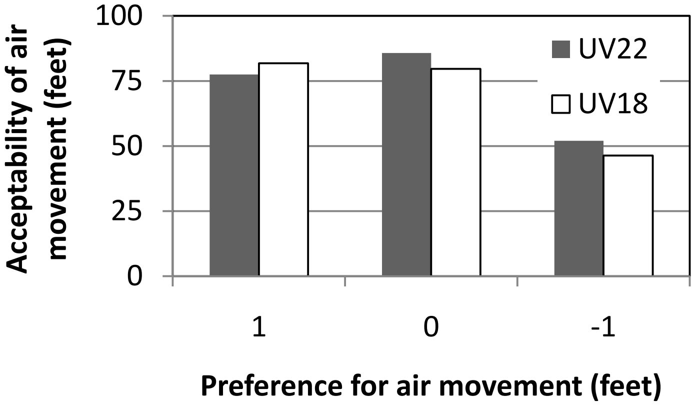


Figure 6.15 Preference for air movement and acceptability at feet
(*Preference for air movement at feet "1": more air movement, "0": no change, "-1" less air movement; Acceptability of air movement at feet (Y-axis) 0~50-: very unacceptable ~just unacceptable, 50-~50+: just unacceptable ~just acceptable, 50+~100: just acceptable to very acceptable*)

Despite the air velocity at feet level being higher with warmer UFAD supply air temperature, more occupants reported that they did not feel the air movement in case UV22 than in case UV18 (Figure 6.9). At feet level, t_{eq} (Figure 6.4) and thermal sensation (Figure 6.5) increase with the increase of UFAD supply air temperature. However, the DR at feet (0.1) show negative trends when UFAD supply air temperature increased (Figure 6.3), which indicates that when the DR is reduced, the subjects will feel warmer at feet region. Moreover, when the subjects feel warmer thermal sensation at feet, they also reported that they feel more acceptable of the air movement at feet and unwilling to change (Figure 6.11 and Figure 6.13). These results are in accordance with the study of local thermal sensation and comfort reported by Cheong et al (2007). It was described in this report that lower body segments of calf and foot preferred slightly warm sensation.

6.3.3 Motivation for integrating Personalized Ventilation (PV) with UFAD

a) Whole body thermal sensation and comfort

Subjects' voting for their whole body thermal sensation to the three cases with total volume or mixing ventilation system (C: ceiling supply mixing ventilation, UV22, and UV18) are shown in Figure 6.16. The average value of subject's vote for the whole body thermal sensation shows that in the three cases, it ranges between "slightly cool" (-1) to "neutral" (0). Among the three cases, the mixing ventilation (MV) system is the one that received the relatively cooler sensation vote for the whole body. In the case with UFAD, the whole body thermal sensation is warmer than that of the MV system. The two UFAD supply air temperatures do not appear to cause an apparent difference regarding the whole body thermal sensation. The votes for whole body thermal sensation are slightly warmer in case UV22 than that in case UV18 and more close to "neutral".

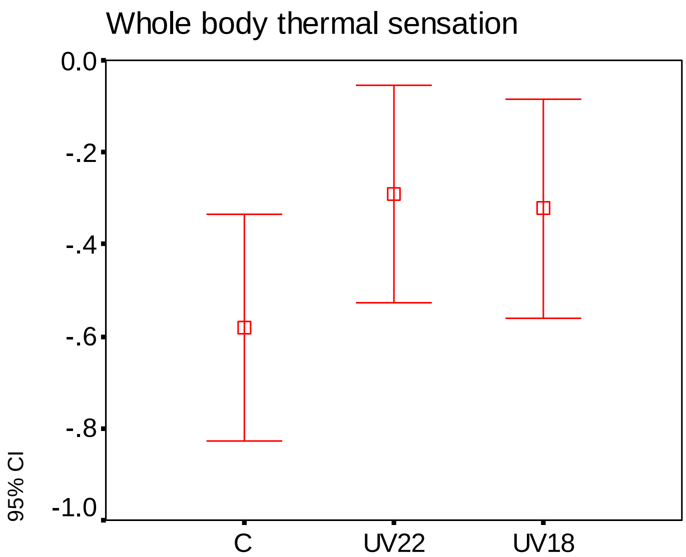


Figure 6.16 Whole body thermal sensation (*Thermal sensation scale: =-3 cold, =-2 cool, =-1 slightly cool, =0 neutral, =1 slightly warm, =2 warm, =+3 hot*)

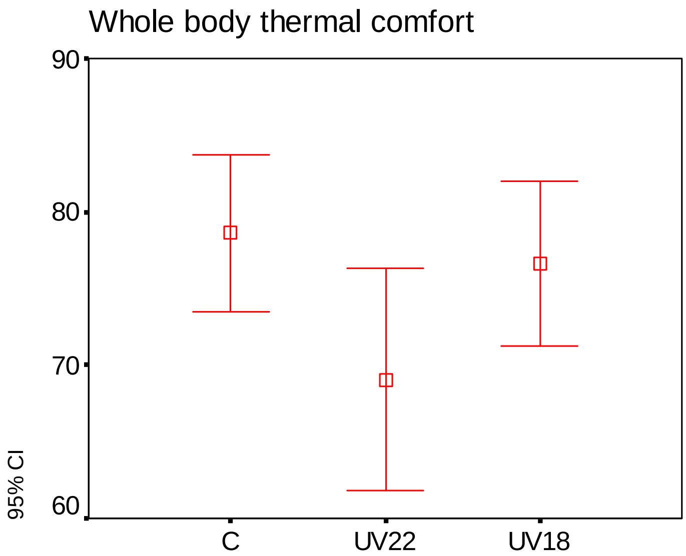


Figure 6.17 Whole body thermal comfort acceptability (*0~50-: very unacceptable ~just unacceptable, 50-~50+: just unacceptable ~just acceptable, 50+~100: just acceptable to very acceptable***)**

However, these close to "neutral" thermal sensation values do not necessarily result in higher rating of the whole body thermal comfort. In contrast, the more close to "slightly cool" whole body thermal sensation values are more likely to cause a higher level of whole body thermal comfort. In Figure 6.17, the highest rating of the whole body thermal comfort acceptability is achieved when MV system was used (case C). The lowest value of the whole body thermal comfort acceptability is found in case UV22. When integrating the result of subjects' responses to the whole body thermal sensation and whole body thermal comfort, the conclusion that the tropically acclimatized occupants would prefer relatively cooler sensation can be drawn.

b) Thermal sensation (face)

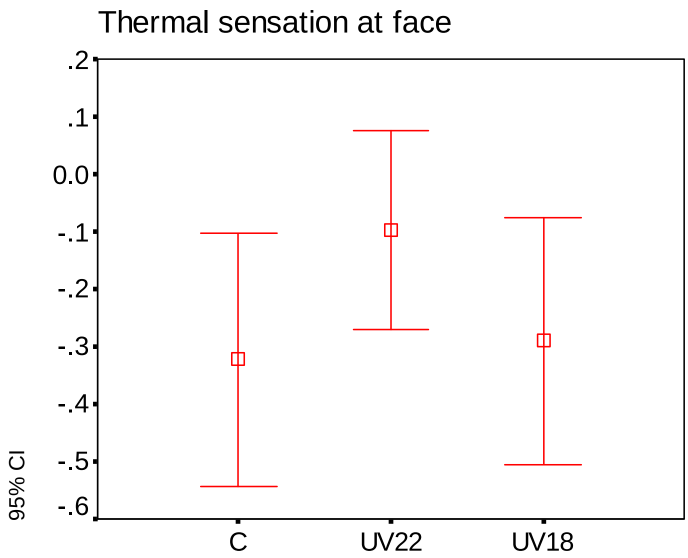


Figure 6.18 Thermal sensation at face (*Thermal sensation scale: =-3 cold, =-2 cool, =-1 slightly cool, =0 neutral, =1 slightly warm, =2 warm, =+3 hot***)**

Among the three cases, the average thermal sensation at face is the warmest in case UV22 (Figure 6.18). With the higher UFAD supply air temperature of 22 °C subjects felt warmer at the face than at supply air temperature of 18 °C (UV18) and the case with ceiling supply (C). However, when comparing the subjects' thermal sensation at face in pair of case UV22 and case C, majority of the subjects (Figure 6.19, 74%) reported the same thermal sensation at face in case UV22 and C. Moreover, about 23% of the subjects reported that they felt a warmer sensation at face in case UV22 than in case C. The statistical analysis shows that the difference of the subjects' vote for the thermal sensation at face between case UV22 and case C was significant (Figure 6.19, p=0.035). The UFAD with warmer supply air temperature lead to a significantly warmer sensation at face compared with conventional ceiling supply MV system.

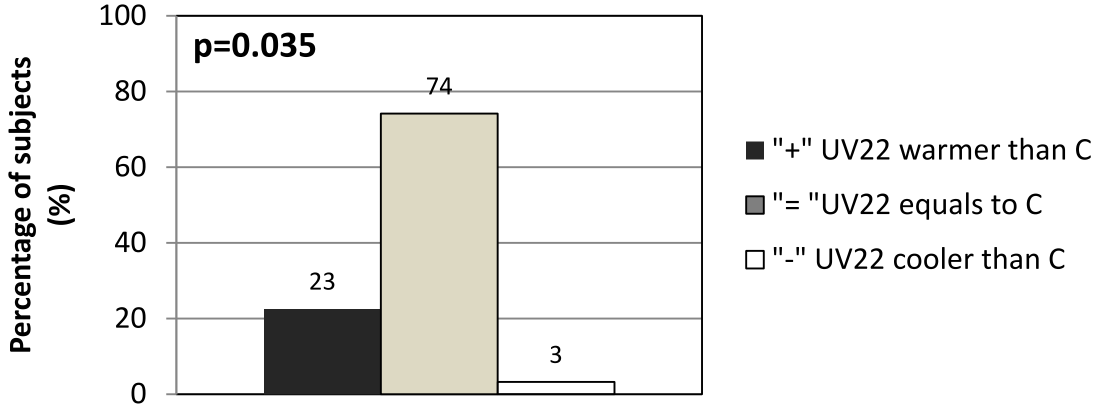


Figure 6.19 Comparison of thermal sensation at face in pair of UV22 and C (p=0.035) *"+": subjects who vote for warmer thermal sensation at face in case UV22 than in case C; "=": subjects who vote for same thermal sensation at face in case UV22 and C; "-": subjects who vote for cooler thermal sensation at face in case UV22 than in case C*

The warmer UFAD supply air temperature make the subjects experience the warmest thermal sensation and lowest thermal comfort for the whole body when compared among the three cases. Moreover, among the three cases, the average thermal sensation at face is highest and the number of subjects who prefer "more air movement" is the highest in case UV22 among the three cases. This is consistent with that reported by Arens et al. (2006a, 2006b), which found that the subjects were sensitive to a "warm head-region" sensation for their head part in warm environment and their overall thermal comfort was found closely following the most uncomfortable local body parts.

c) Acceptability of air movement and preference for change of air movement (face)

As already discussed, lower percentage of subjects felt the air movement at feet level as unacceptable when UFAD air was supplied at 22 °C than at 18 °C (Figure 6.11). However there are more subjects who reported that they felt the air movement at the face unacceptable in the case when the UFAD air was supplied at 22 °C than at 18 °C. At the feet level, the warmer thermal sensation and relatively "still" perception of air movement influenced by the warmer UFAD supply air temperature has a positive effect. However, at the facial part, the effect of the UFAD supply air temperature has a negative impact on the acceptability of the air movement. In Figure 6.20, the percentages of subjects who felt the air movement at the face unacceptable are compared for the three cases: C, UV22 and UV18. Only 10% of the subjects found the air movement at the face as unacceptable when mixing ventilation was applied. In the case with UFAD (UV18) this percentage of subjects reporting the air movement as unacceptable is only slightly higher, 13%. However, when the UFAD air was supplied with at 22 °C the percentage of subjects who found the air movement unacceptable increase to 26%, i.e. almost twice as high as in the case UV18.

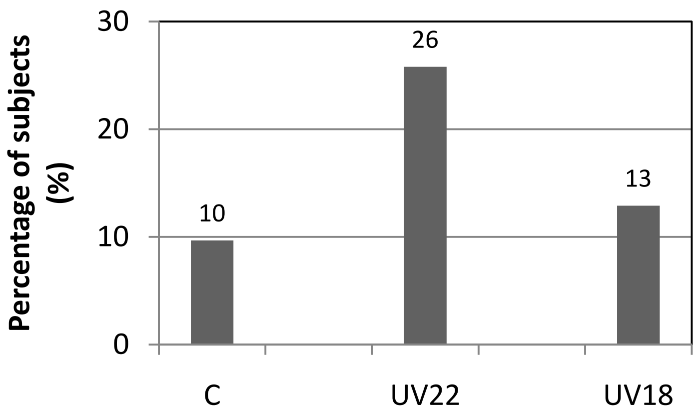


Figure 6.20 Percentage of subjects who felt air movement at facial part unacceptable

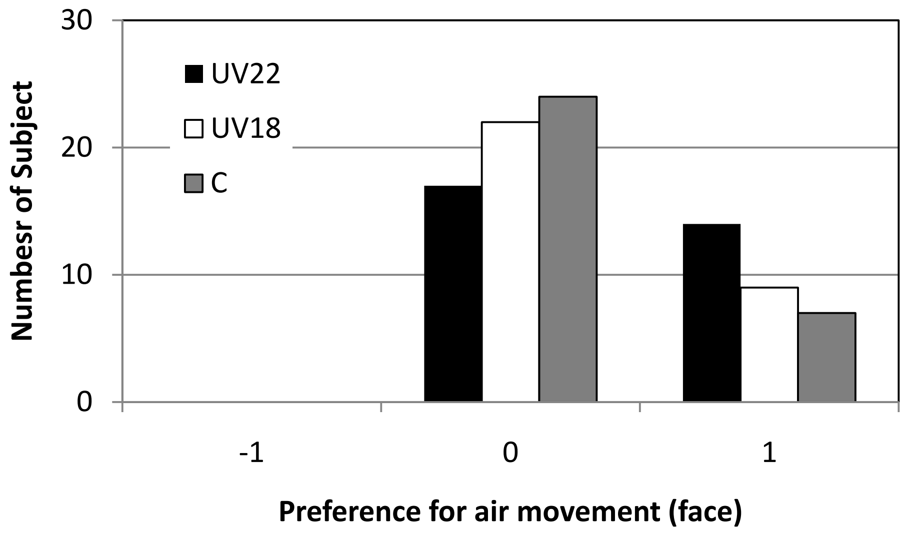


Figure 6.21 Preference of preference for air movement at face (*Preference for air movement at face: "1"= more air movement, "0"= no change, "-1"= less air movement***)**

When analysing the subjects' preference for change of air movement, it can also be found that with the warmer UFAD, more people were not satisfied with the current air movement they were experiencing. The results in Figure 6.21 show that in case UV22, the number of subjects who prefer "no change" of the air movement is the lowest and the number of subjects who prefer "more air movement" is the highest among the three cases. In contrast to the results obtained for the feet, the subjects' perception of unacceptability of air movement at the facial region is more likely caused by insufficient air movement.

The warmer UFAD supply air temperature can apparently reduce the risk of unacceptable air movement at feet; however, it will increase the risk of unacceptable air movement at facial level. The results of the subjective survey show that occupants were more likely to be annoyed by the insufficient air movement and prefer higher air movement at facial part.

6.4 Effect of warmer UFAD supply air temperature - Key findings

- Subjective responses show that the warmer thermal environment created by the warmer UFAD supply air temperature has a positive effect on the thermal sensation and acceptance of air movement at feet level. It effectively prevented cold draft at feet level.
- The performance of the UFAD system with warmer supply air temperature might be abated when compared with that of conventional ceiling supply system regarding the warmer sensation of whole body and the unpleasant sensation at facial part.
- According to these comparative results between UFAD system with warmer supply air temperature and conventional ceiling supply system, the UFAD system with warmer supply air temperature has relatively low performance in providing enough air movement at facial part. By introducing personalized ventilation in the UFAD system, improved performance can be expected.

Chapter 7 Manikin and Human Subject Study – Results: Effect of PV

In this chapter, the performance characteristics of combining PV with UFAD are evaluated based on objective and subjective measurements. The use of PV provides cooler thermal sensation at face and improves the whole body thermal comfort and the acceptability of air movement in comparison with use of the UFAD or CSMV alone. By granting the occupants opportunity to choose the PV flow rate, more occupants could make themselves comfortable with the air movement. The measured inhaled air quality and perceived air quality are also improved by using PV.

7.1 Room air temperature /velocity/ DR distribution

Room air temperature distribution

The warmer UFAD supply air temperature results in warmer room air temperature especially at the lower part of the space. The air temperature measured at 0.1 m at the centre of the room is 23 ˚C in case UV18 and 24.6 ˚C in case UV22. (Figure 7.1) Due to the heat load distribution in the lower space, the gradients of the room air temperature are steeper at the lower space and rather gentle in the upper space (Figure 7.1). Moreover, with higher level of supply air volume (cases with UFAD supply air temperature 18 ˚C), the temperature profiles are steeper than those with 22 ˚C supply air temperature, especially close to the floor level. This result is consistent with previous studies on temperature stratification in rooms with UFAD (Webster et al., 2002, Akimoto et al. 1995). The temperature distribution at the centre of the room (Figure 7.1) reveals that in the region away from the workstation (i.e. in the centre of the chamber), the thermal environments are only affected by the operating condition of the ambient total volume ventilation system (i.e. UFAD or CSMV). The effect of PV system on the temperature distributions at the centre of the room is negligible.

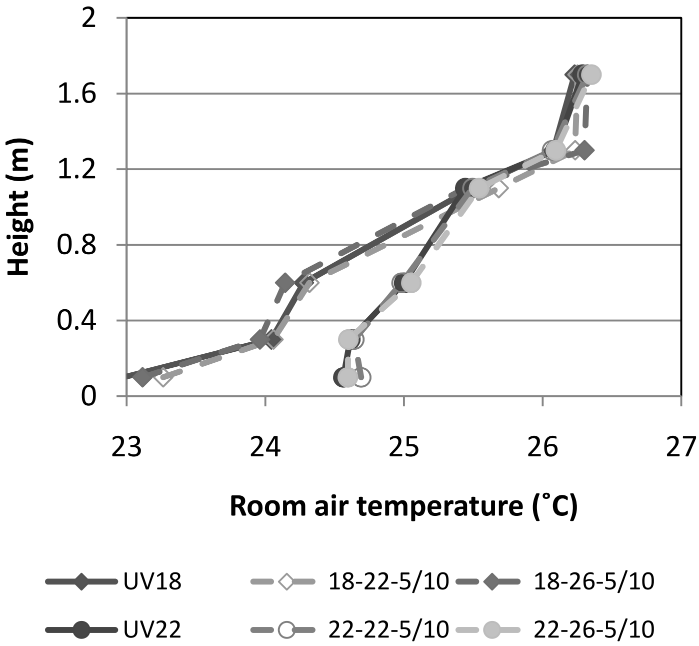


Figure7.1 Room air temperature distribution in the centre of the test chamber, far from the workstations with PV

The temperatures measured at the workstation where the manikin was placed are shown in Figure 7.2. In the region close to the workstation, the patterns of temperature distribution are different to those at the centre of the room. The furniture and human body obstruct the UFAD air discharged from the floor outlet and thus promote mixing which resulted in slightly cooler temperature at ankle level in the region close to the workstation than at the center of the room (Figure 7.2 and Figure 7.1, 0.1 m height). At the work-station (Figure 7.2), the temperature distribution pattern above the table surface is different to that under the table surface. The temperature increases continuously under the table surface but the rate of increase above the table surface is not as steep. It can be found from Figure 7.2 that in the space under the table, the temperature gradient between ankle level (0.1 m) and the “under surface” of the table (0.6 m) is about 3~4 ˚C in all experimental cases. The thermal flow generated by the heated manikin increases the temperature below the desk resulting to air temperature as high as 28 ˚C at 1 m height. This effect disappears above 1 m which results in negative vertical temperature gradient, i.e. decrease in the temperature. This is attributed to the thermal plume of the manikin being affected by the table surface and higher temperatures being observed immediately under and above the table surface. Moreover, in cases with UFAD-PV, at the space above the table surface, the conditions of the PV air show dominant effect on the thermal environment. There is no difference in the temperature profiles obtained with and without use of PV up to the height of 0.6 m above the floor. The use of the PV changes the vertical temperature distribution above 0.6 m. The vertical temperature distribution is affected by the parameters of the PV air flow. The temperature decreases and the vertical temperature profiles are more inclined to the cooler side when the PV air flow rate increases and its temperature decreases.

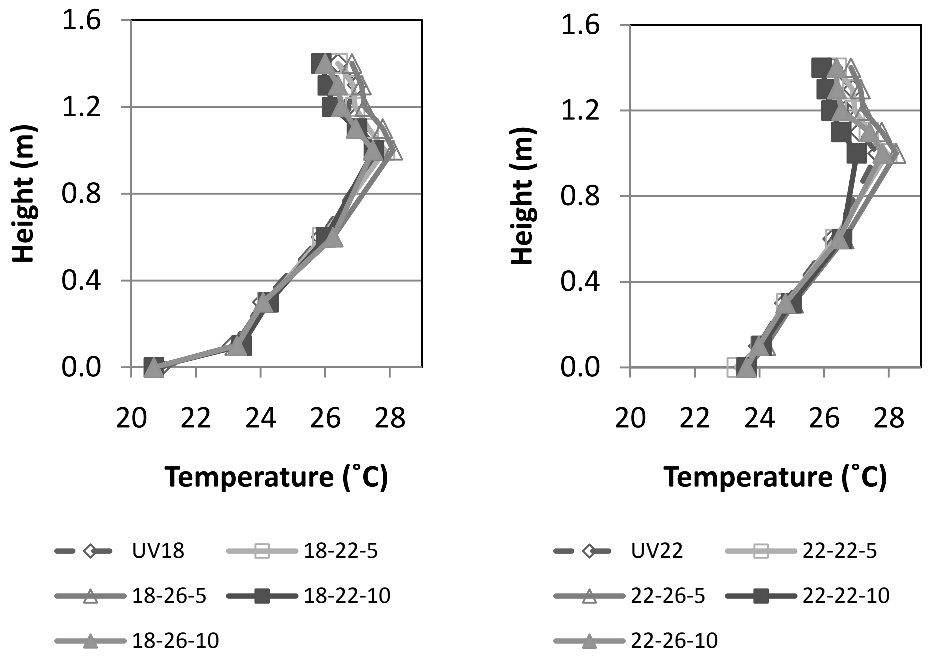


Figure 7.2 Room air temperature distribution (close to manikin) (left: UFAD supply air temperature 18 ˚C; right: UFAD supply air temperature 22 ˚C)

The temperature differences between the cases with UFAD-PV and UFAD alone at manikin's face level (1.3m) are compared in Figure 7.3. The PV supply air flow rate has strongest impact on the temperature distribution at the breathing zone followed by the temperature of the PV air. In Figure 7.3, variation in the temperature difference [$t_{(UFAD\text{-}PV)} - t_{UFAD}$] values between cases E and G (0.3 °C) is the variation due to change of the PV air temperature (26 °C and 22 °C) for the same UFAD supply air temperature of 22 °C and at the same PV flow rate of 10 L/s. This compares with the variation in [$t_{(UFAD\text{-}PV)} - t_{UFAD}$] values between cases A and E (0.75 °C), which is the variation due to PV flow rate (5 L/s and 10 Ls) at the same UFAD supply air temperature of 22 °C and the same PV temperature of 26 °C. It is thus seen that the variation in the temperature difference when the PV flow rate is changed (0.75 °C) is twice as much as that when the PV temperature is changed (0.3 °C).

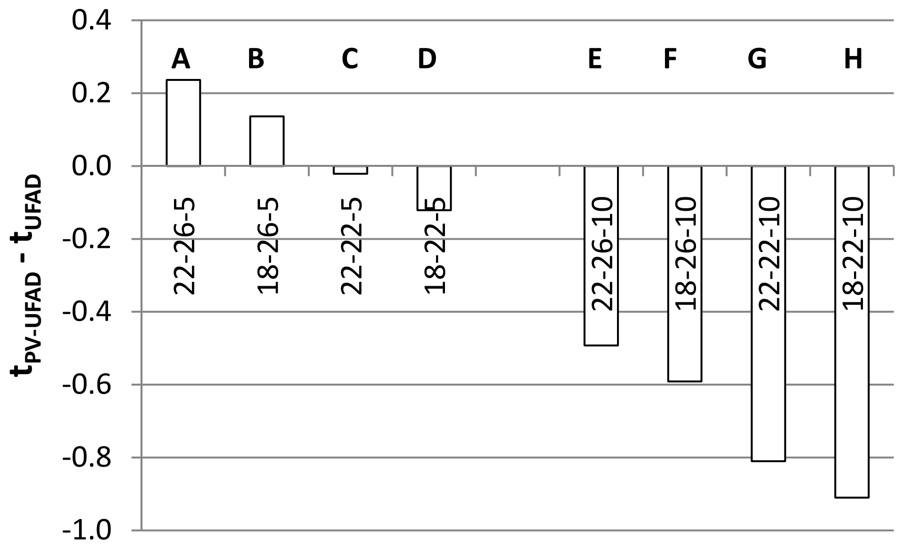


Figure 7.3 Difference in air temperatures between UFAD-PV and UFAD alone, measured at 1.3 m (manikin's face level)

Velocity distribution

The air velocities measured at the workstation at 1.3 m (breathing zone) and 0.1 m (ankle level) is presented in Figure 7.4. Higher PV air flow rate results in higher velocity at the facial part. When PV air flow rate is 10 L/s, the air velocities measured at 1.3 m height and 15 cm in front of the manikin are in the range of 0.6~0.7 m/s and do not change with the variation of PV or UFAD supply air temperatures (Figure 7.4, 18-22-10, 22-26-10, 18-26-10 and 22-26-10). The same trend can also be found among the cases with PV air flow rate at 5 L/s. With this lower PV flow rate, the air velocities measured close to the manikin are about 0.3 m/s, i.e. about half of that with 10 L/s PV air. In the space close to the floor (0.1 m), similar to the distribution of the air temperature, the UFAD operating conditions have the dominant influence on the velocity at ankle level and the effect of PV is negligible. The warmer UFAD supply air temperature (22 ˚C) always results in a higher level of velocity (0.1~0.2 m/s) at the ankle level than that with 18 ˚C (<0.1 m/s)

(Figure 7.4) due to the higher supply flow rate of UFAD system with warmer UFAD supply air temperature.

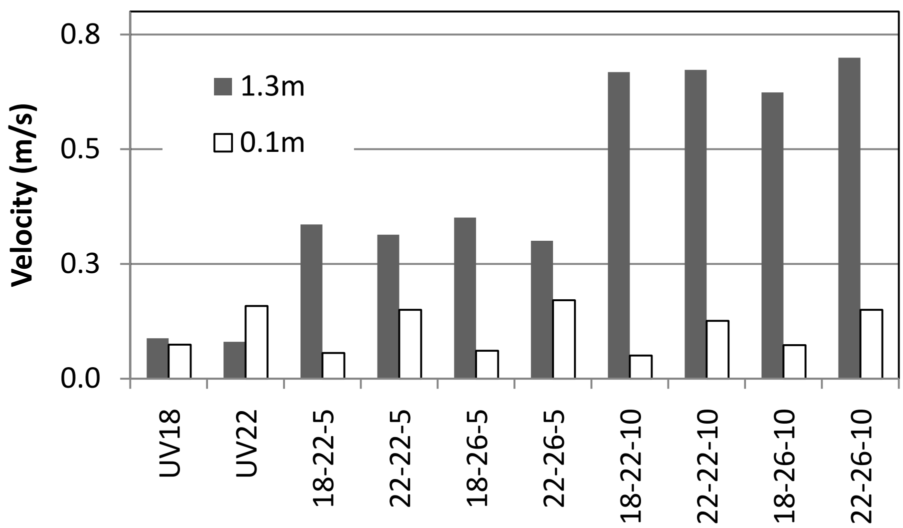


Figure 7.4 Velocities at 1.3 m and 0.1m

Draft rating (DR)

The draught rating at the workstation at 0.1 m (feet) is presented in Figure 7.5. In the space close to the floor (0.1 m), draft rating at the feet is quite low since the velocity is very low. The effect of the air temperature is stronger than the effect of the air velocity. The warmer UFAD supply air temperature of 22 ˚C always brings a lower value of DR at the feet than supply temperature of 18 ˚C (Figure 7.5). Although the velocities are higher with the warmer UFAD supply air temperature, the DRs at the feet are always lower with the warmer UFAD supply air temperature (only about 5%, Figure 7.5). This means that the effect of the air temperature is stronger than the effect of the air velocity.

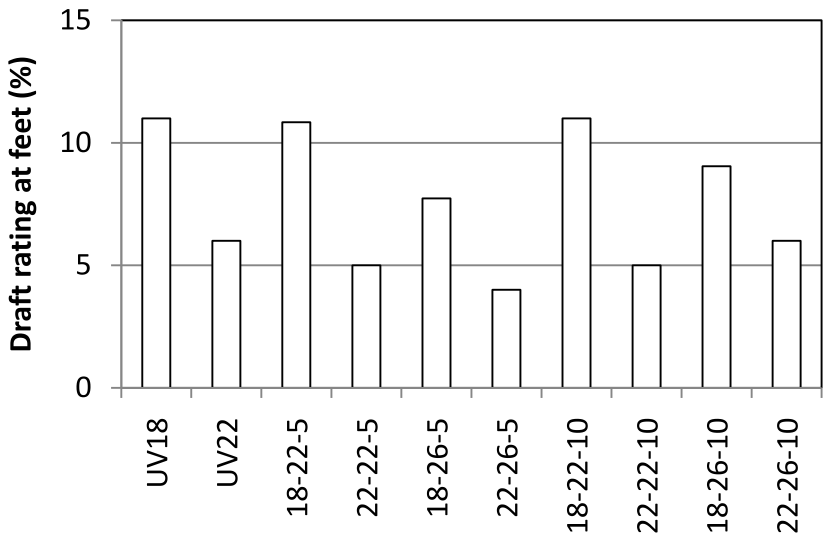


Figure 7.5 DR at 1.3 m height (15 cm in front of manikin)

The relationship between draught rating at feet and occupants' thermal sensation at feet is presented in Figure 7.6. The association between the predicted draft rating (DR) and subjects' local thermal sensation and air movement perception, acceptability and preference at the feet is analyzed. The relationship between DR and subjects' thermal sensation at feet is relatively stronger (Figure 7.6, $R^2 = 0.58$). A negative linear relationship between DR and thermal sensation at feet indicates that the warmer UFAD supply air temperature would result in lower DR and improved thermal sensation at feet.

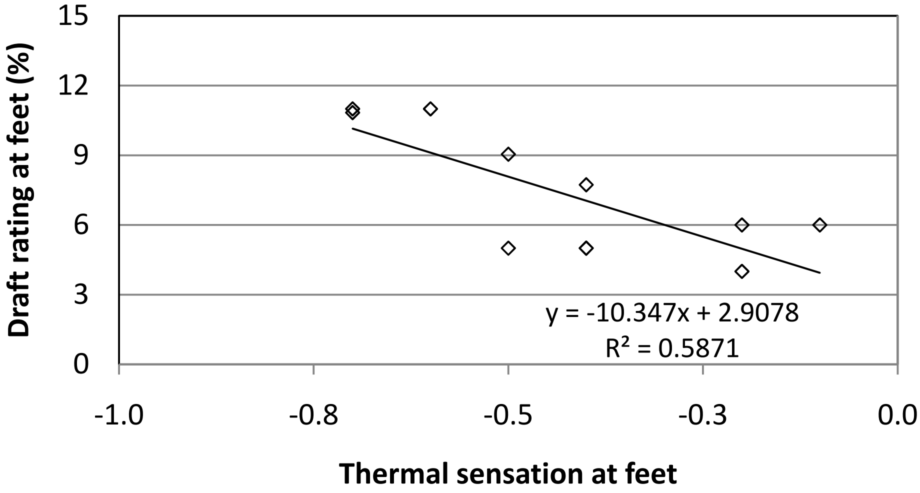


Figure 7.6 Draft rating (measured at 0.1 m height close to manikin feet) and its relationship with thermal sensation at feet (*Thermal sensation scale: -1 – slightly cool; 0 – neutral***)**

7.2 Manikin based equivalent temperature

The manikin based equivalent temperatures are shown in Figure 7.7. In the lower region, equivalent temperatures are differentiated according to different UFAD supply air temperatures, whilst, at the head region, such as scull, face and back of the neck, they are more influenced by PV air.

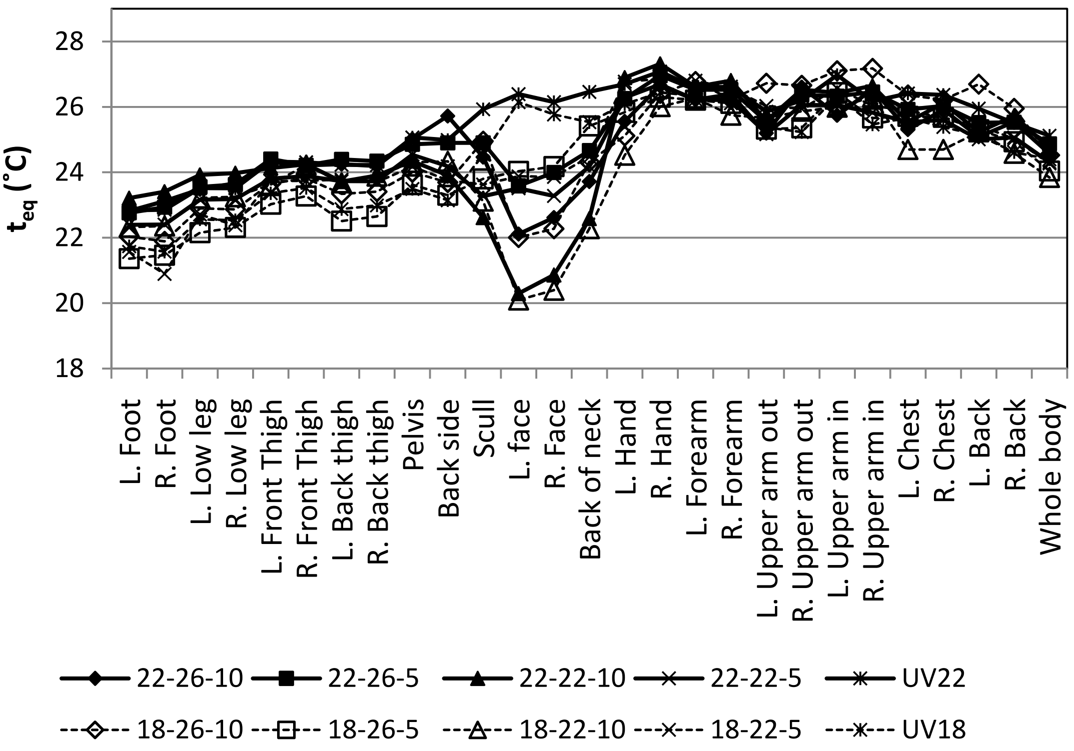


Figure 7.7 Manikin based equivalent temperature

To identify the effect of PV air, the difference between the manikin-based equivalent temperatures (Eq.5.3) in the cases with UFAD-PV and UFAD alone were used

The Δt_{eq} for each body segment as shown in Figures 7.8 and 7.9 are obtained from t_{eq} of cases that have the same UFAD supply air temperature for UFAD-PV system and UFAD system alone.

It can be observed from Figures 7.8 and 7.9 that the use of the PV decreases the manikin based equivalent temperature at the facial region by 2~6 ˚C. However, the changes of t_{eq} at other body segments are not apparent. The maximum change of t_{eq} at the head level are found in case 22-22-10 (Figure 7.8) and 18-22-10 (Figure 7.9) which are with cooler PV air temperature and higher PV air flow rate. The cooling effect of PV airflow supplied at 26 ˚C is lower (Figure 7.8 case 22-26-10 and Figure 7.9 case 18-26-10). When the PV air flow rate is 5 L/s, the values of Δt_{eq} are the smallest. Moreover, in cases with this lower PV air flow rate, the effect of the PV air temperature are not apparent as it was in cases with higher PV air flow rate (Figure 7.8 case 22-22-5 vs. case 22-26-5 and Figure 7.9 case 18-22-5 vs 18-26-5).

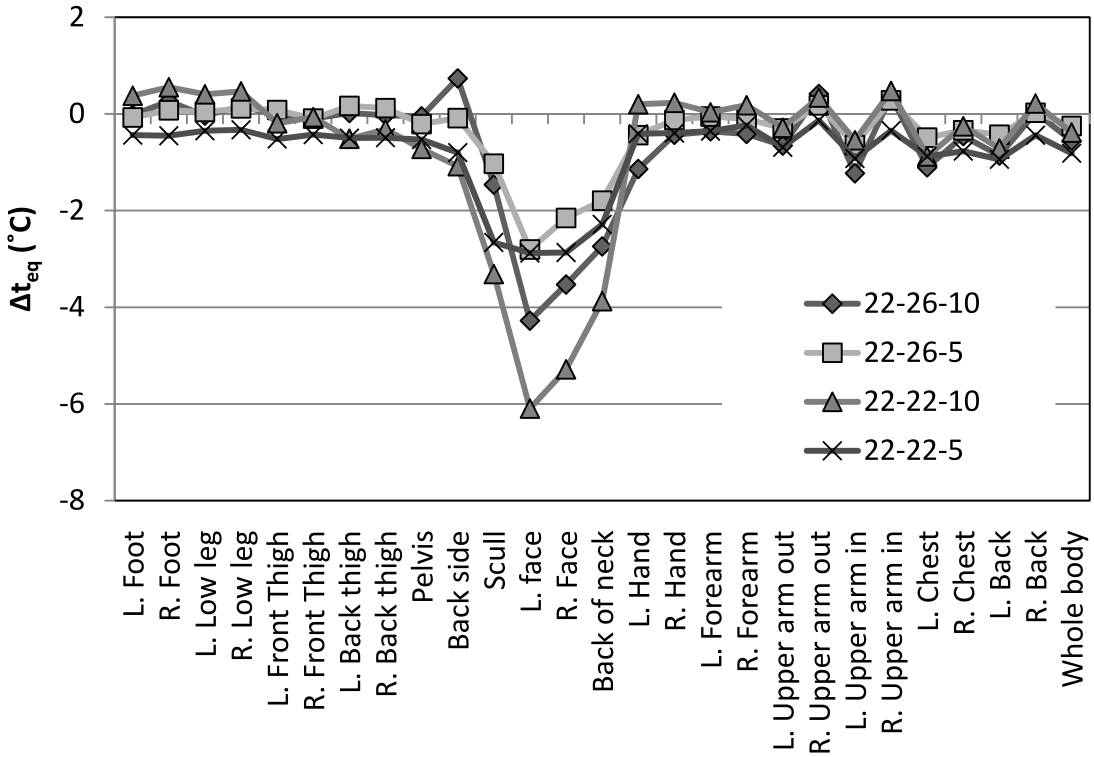


Figure 7.8 Δt_{eq} for the body segments of the thermal manikin obtained with UFAD supply air temperature of 22 ˚C

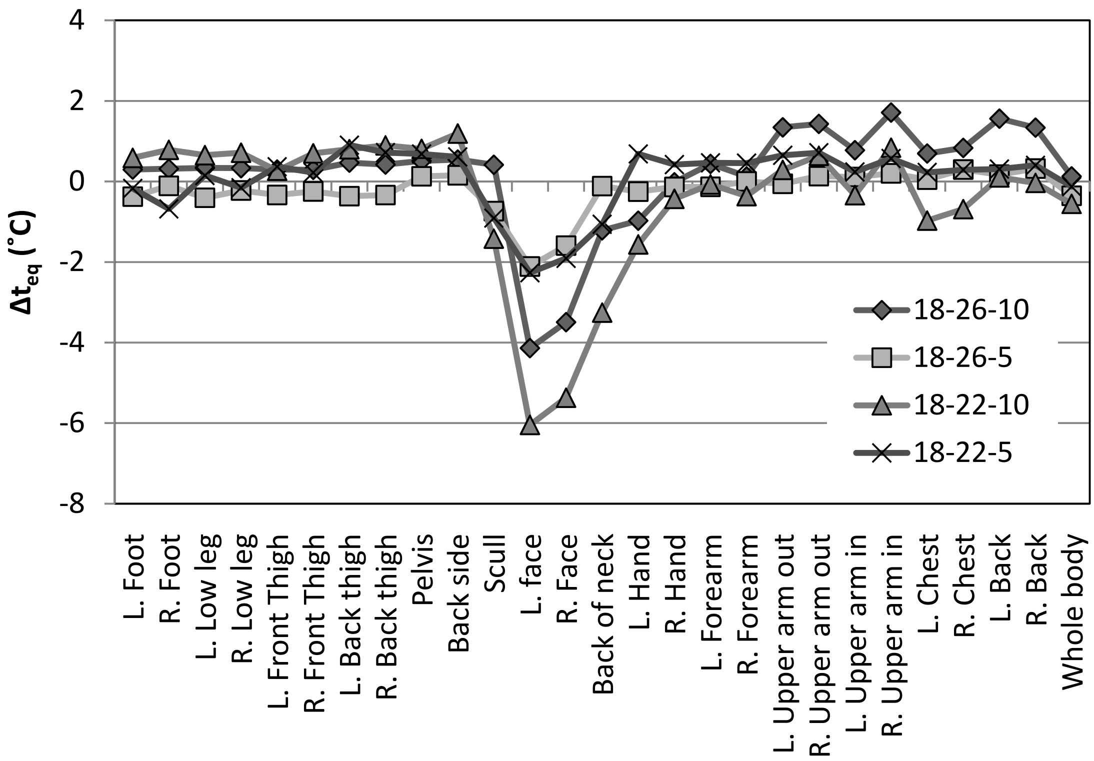


Figure 7.9 Δt_{eq} for the body segments of the thermal manikin obtained with UFAD supply air temperature of 18 ˚C

The results in Figure 7.8 and 7.9 identify that the maximum change of t_{eq} is determined at the facial region. Thus, the focus is placed on the equivalent temperature in the face segment to explore the effect of different PV parameters on the thermal environment in the breathing zone. The Δt_{eq} at the facial region as obtained at the temperature and PV flow rates studied is shown in Figure 7.10. The combination of cooler PV air (22 ˚C) and higher PV air flow rate (10 L/s), i.e. case 22-22-10 and 18-22-10 (Figure 7.10), always lead to the maximum change of t_{eq} (Δt_{eq}= -6 ˚C) at the face when compared with the reference cases. The cooling effects of the combination of warmer PV air (26 ˚C) and higher PV air flow rate (10 L/s), i.e. case 22-26-10 and 18-26-10 (Figure 7.10), are ranked as secondary (Δt_{eq} =-3 ˚C ~ -4 ˚C). Significant changes of t_{eq} are also found when the cooler PV air (22 ˚C) and lower PV air flow rate (5 L/s), i.e. case 22-22-5 and 18-22-5 (Figure 7.10), are used. As expected the minimum changes of t_{eq} are found in cases with warmer PV air (26 ˚C) and lower PV air volume flow rate (5 L/s).

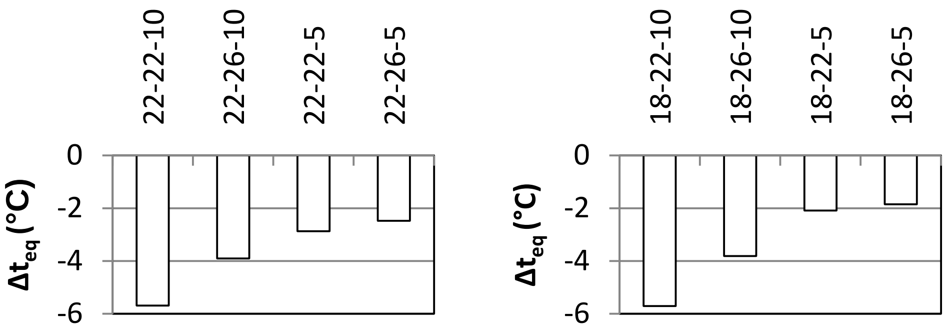


Figure 7.10 Δt_{eq} at face (left: UFAD=22 ˚C, right: UFAD=18 ˚C)

The cooling effects of PV air are mainly attributed to the air movement rather than the temperature difference between the PV air and the ambient air. This indicates that at the facial region, the PV flow is already mixed with the surrounding air. Therefore, the velocity of the PV air flow (0.6~0.7 m/s) becomes the main factor contributing to the convective heat loss from the face of the manikin.

This ability of PV air in cooling the facial region will be discussed in more detail in the section of subjective response studies. Other than the local thermal sensation, the perception and acceptance of the air movement in the facial region are also very important in evaluating the performance of the UFAD-PV system.

7.3 Subjective response

Figures 7.11 and 7.12 show subjects' thermal sensation and preference for air movement reported at the combinations of the environment studied. The difference in subjects' thermal sensation and their preference for air movement is most obvious for the face region. Therefore in this section, the subjective response (thermal sensation and comfort, perception/acceptability of air movement and preference for air movement) are discussed with focus on the facial region and on the overall body. The subjects' responses to the perceived air quality and perceived inhaled air temperature/freshness are also analyzed. Most of the figures shown and discussed in this section are based on average response of the subjects who participated in the experiments. However some of the analyses, as defined in the text, are based on the individual response of the subjects.

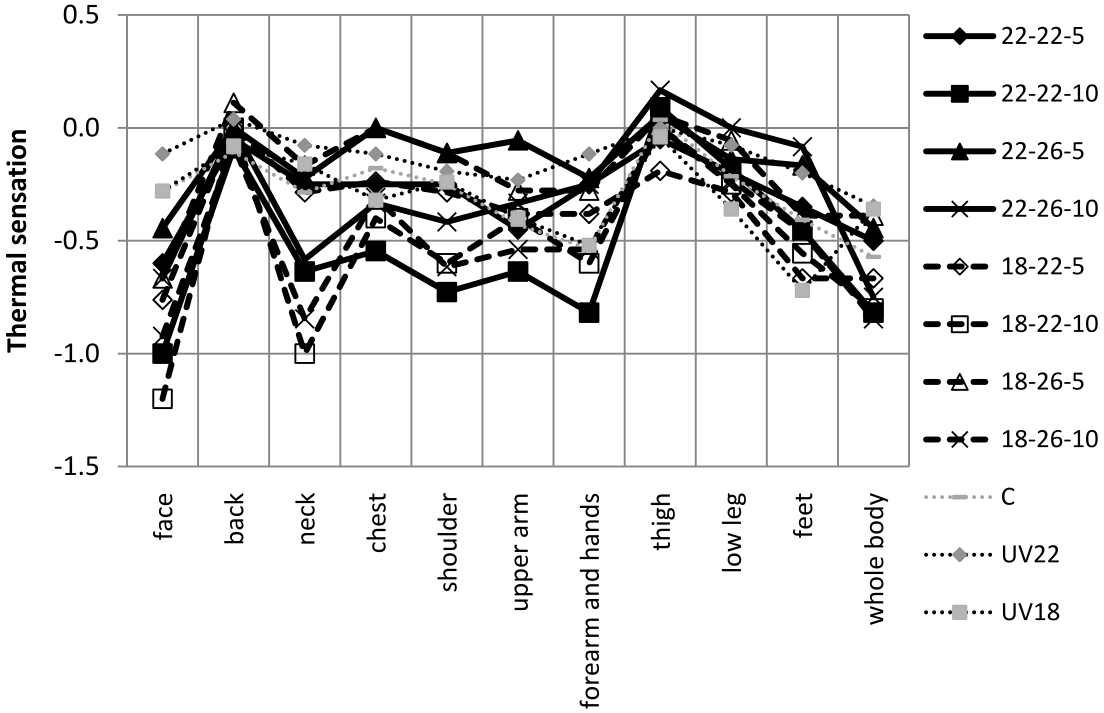


Figure 7.11 Thermal sensations of different body segments and whole body *(Thermal sensation scale: =-3 cold, =-2 cool, =-1 slightly cool, =0 neutral, =+1 slightly warm, =+2 warm, =+3 hot)*

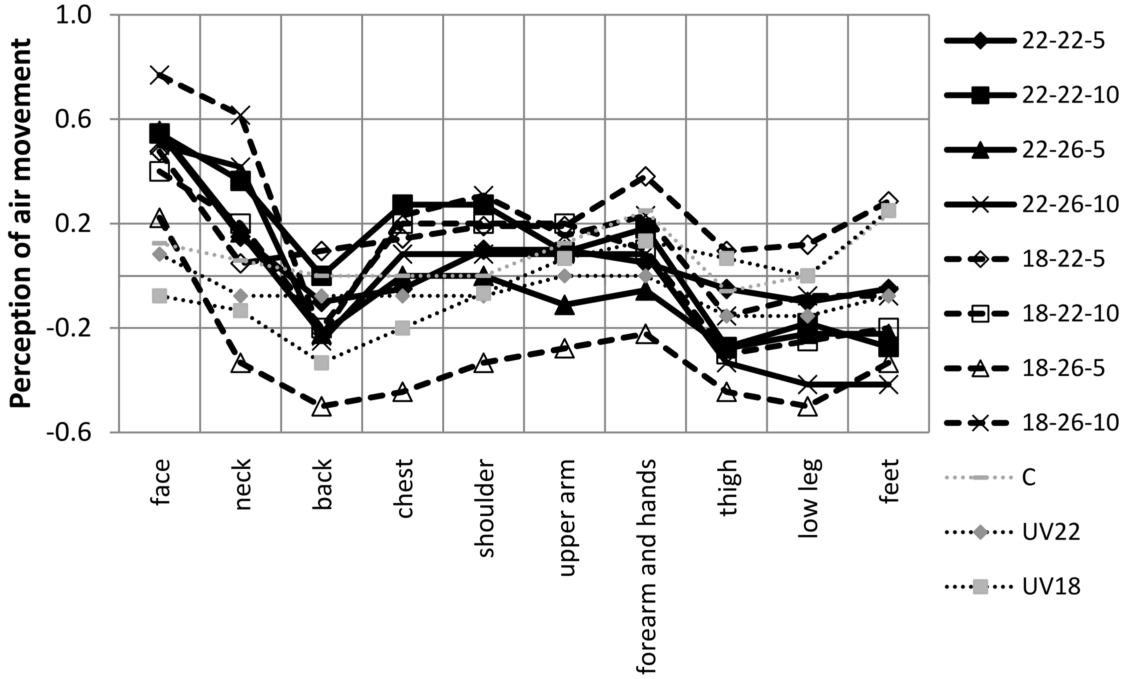


Figure 7.12 Preference for air movement for different body parts and whole body *(Preference for air movement scale: "1": more air movement, "0": no change, "-1": less air movement)*

7.3.1 Thermal sensation and thermal comfort

Thermal sensation (face)

The thermal sensation at the face is shown in Figure 7.13. When PV is used, the occupant's thermal sensation at face is cooler than the cases without PV (only UFAD or only mixing ventilation). The cooler thermal sensation at face is reported with the higher PV air flow rate. At the same PV supply flow rate the thermal sensation at face is reported cooler when the PV supply air temperature is lower. As expected, the coolest sensation is reported at the lowest UFAD supply air temperature, the lowest PV supply air temperature and highest PV air flow rate (18-22-10) while the warmest sensation at face is reported at the warmest UFAD supply air temperature, warmest PV supply air temperature and lowest PV air volume flow rate (22-26-5).

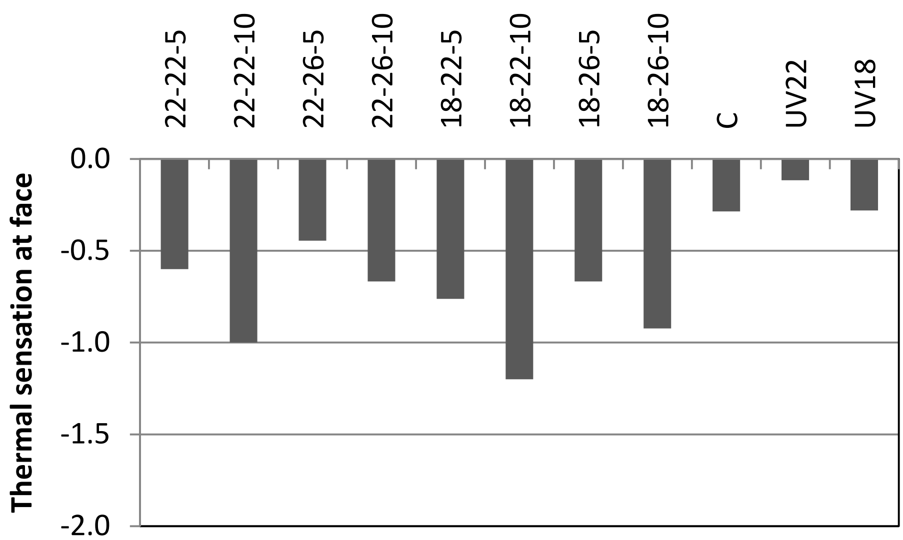


Figure 7.13 Thermal sensation at face *(Thermal sensation scale: =-3 cold, =-2 cool, =-1 slightly cool, =0 neutral, =+1 slightly warm, =+2 warm, =+3 hot)*

The frequencies for each thermal sensation scale which is voted by subjects for facial region are counted and presented in Figure 7.14. In Figure 7.14, the frequency of the vote for "slightly cool" (-1) become apparently higher than "neutral" (0) when PV is used. In the cases without PV, the highest frequency of the thermal sensation vote is mostly "neutral".

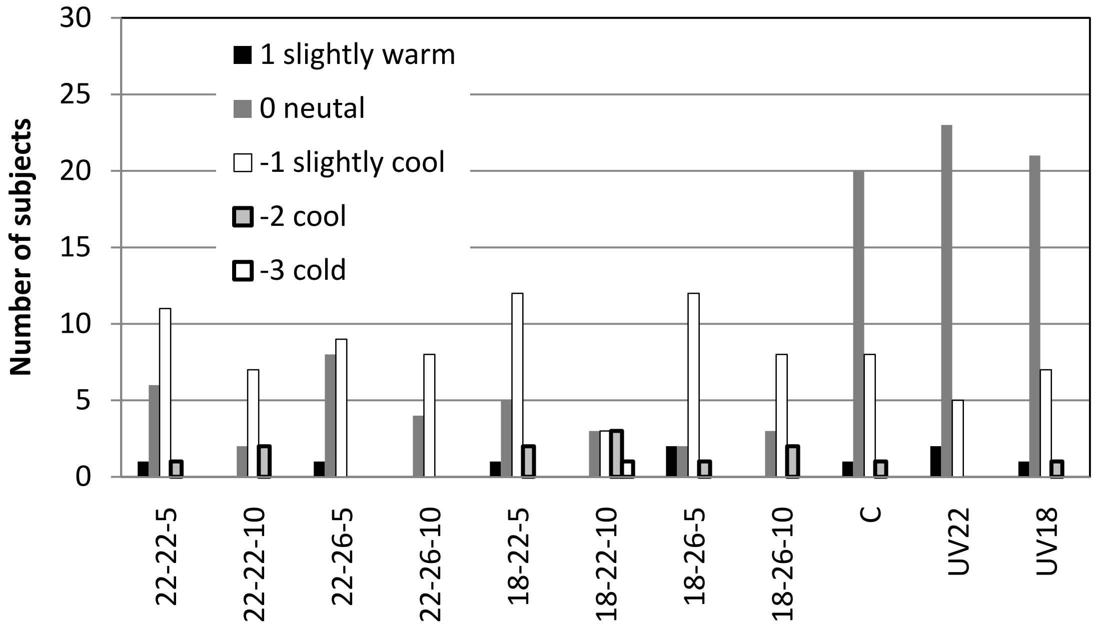


Figure 7.14 Frequency for each thermal sensation scale voted by subjects for face.

The mean values of thermal sensation at face are affected by the combined effect of supply air conditions of PV and UFAD. This is consistent with the results of manikin based equivalent temperature. Thus, the subjects' thermal sensation could be predicted by the manikin based equivalent temperature. The trend line in Figure 7.15 shows that the relationship between these two parameters is relatively strong (with R^2 =0.8). The relationship between thermal sensation at face and t_{eq} at face can be represented by a positive line.

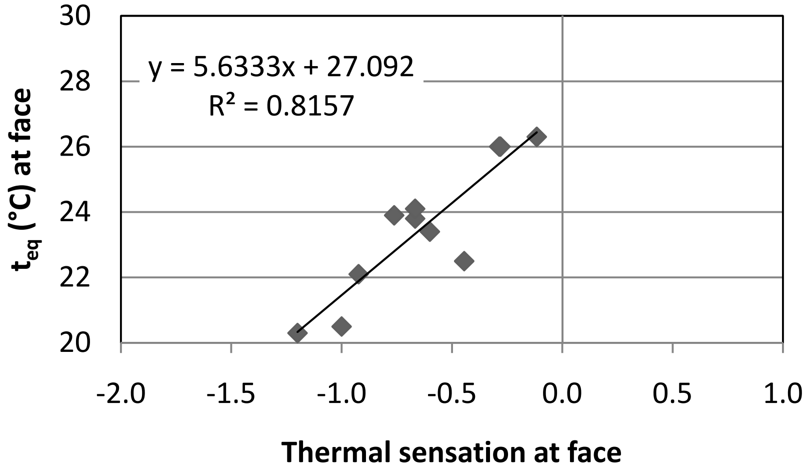
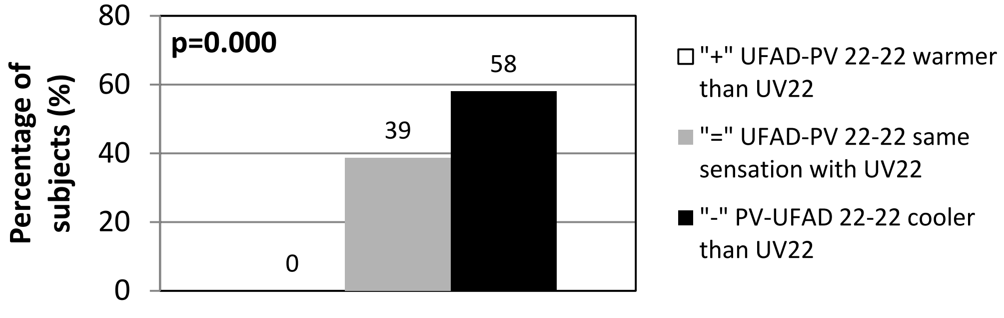


Figure 7.15 Correlation between thermal sensation and t_{eq} at face *(Thermal sensation scale: - 2 – cool, -1 – slightly cool, 0- neutral, 1 – slightly warm)*

The statistical analysis for the results of thermal sensation at face in pairs of UFAD-PV and UFAD alone are shown in Figure 7.16. The p-values in Figure 7.16 a ~ d are the significance with null hypothesis that the thermal sensations at the face are same in cases where PV was used and those where PV was not used. From the p-values in Figure 7.16, it can be concluded that the thermal sensations at the face were significantly cooled by the PV air when compared in pairs with the base case (with UFAD alone, i.e. case UV22 and UV18). The results are consistent with that shown in Figure 7.13, in which the PV air could always result in cooler average thermal sensation at face. A relatively higher percentage of subjects felt cooler at the facial region in cases with PV (55% ~58%). This is in accordance with the results presented in Figure 7.14, which shows higher frequency of the vote for “slightly cool” in cases with PV than in cases without PV.



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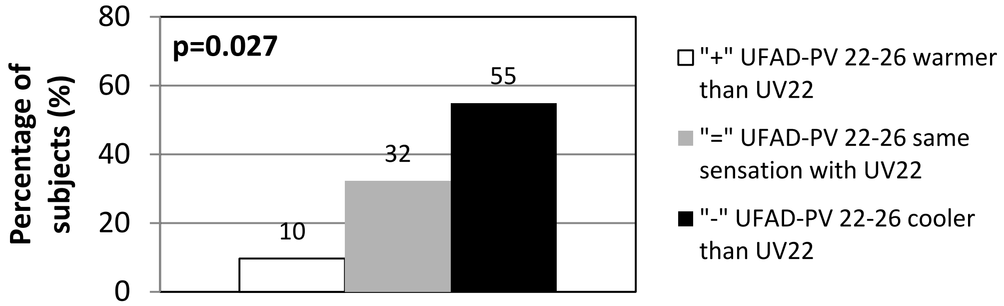

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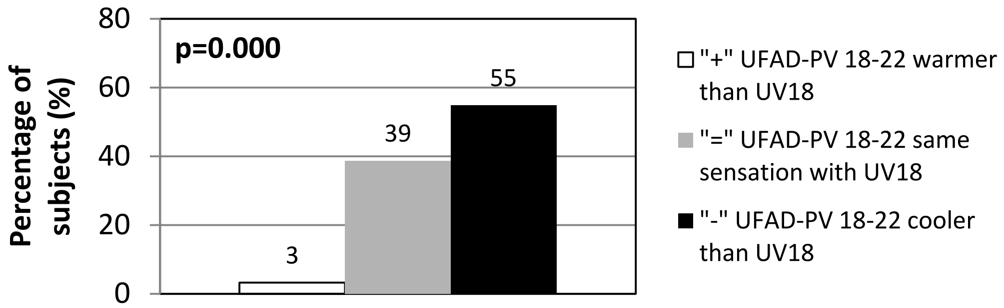

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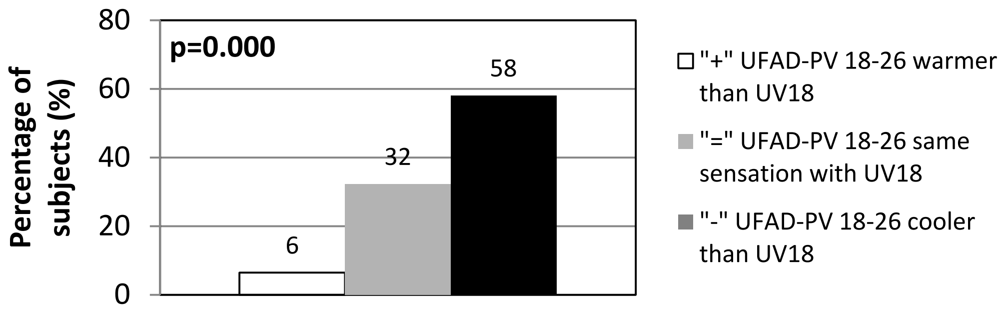

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Figure 7.16 (a, b, c, d) Comparison of thermal sensation at face in pairs of UFAD-PV and UFAD alone for various temperature combinations

Whole body thermal sensation

The average values of the whole body thermal sensation are shown in Figure 7.17. Similar to the thermal sensations at the face, the whole body thermal sensation is cooler when PV was used in comparison with the cases that employed UFAD alone. The cooling effects of the PV are also apparent when compared with ceiling supply.

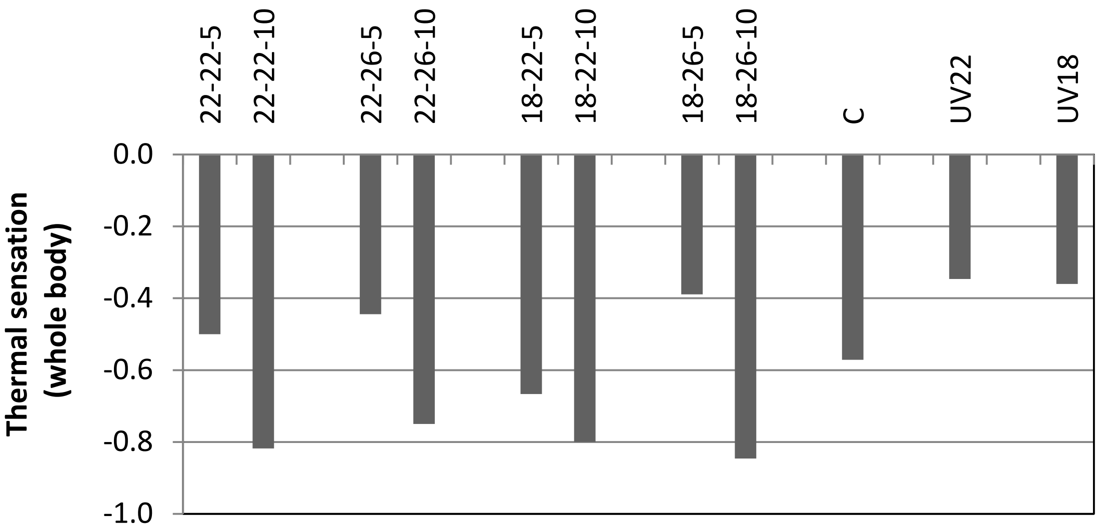


Figure 7.17 Whole body thermal sensations *(Thermal sensation scale: =-3 cold, =-2 cool, =-1 slightly cool, =0 neutral, =+1 slightly warm, =+2 warm, =+3 hot)*

When the average values of the whole body thermal sensation of case UV22 and UV18 are compared with that of the cases served by UFAD-PV (Figure 7.17), it can be seen that the UFAD-PV system always results in the subjects feeling a cooler whole body thermal perception. The difference of the average values of the whole body thermal sensation reported at the PV flow rate of 10 L/s (22-22-10, 22-26-10, 18-22-10, 18-26-10) and with UFAD alone (UV22 and UV18) is larger than the difference of the average values of the whole body thermal sensation reported at the PV flow rate of 5 L/s (22-22-5, 22-26-5, 18-22-5, 18-26-5) and with UFAD alone (UV22 and UV18).

The comparison shows that in most of the cases with UFAD-PV, subjects felt a cooler whole body thermal sensation than in the case with CSMV only. In particular, when higher PV flow rate (10 L/s) is used, the whole body thermal sensations with UFAD-PV are always cooler than that with CSMV (Figure 7.17, case 22-22-10/22-26-10/18-22-10/18-26-10 vs. C). However, for some of the cases studied with lower PV flow rate of 5 L/s (cases 22-22-5, 22-26-5, 18-26-5) warmer whole body thermal sensation than the case with CSMV (case C) is reported. Due to the cooler combination of PV and UFAD supply air temperature (22 °C and 18 °C respectively), the whole body thermal sensation of case 18-22-5 is cooler than that of case C (case with CSMV system).

The individually reported whole body thermal sensation by the subjects with UFAD-PV and UFAD alone is analyzed in pairs in order to identify the effects of PV on the whole body thermal sensation. The results are shown in Figures 7.18 a, b, c, d. The differences are significant only when the cooler PV supply air temperature was used. In Figure 7.18a and 7.18c, the p-values were less than 0.05. With warmer PV supply air temperature, although the cooling effect of PV air on the whole body is not statistically significant when compared in pairs of UFAD-PV and UFAD alone, the percentage of subjects who felt cooler with UFAD-PV is around 40% (Figures 7.18b and 7.18d, 42% and 39% respectively).

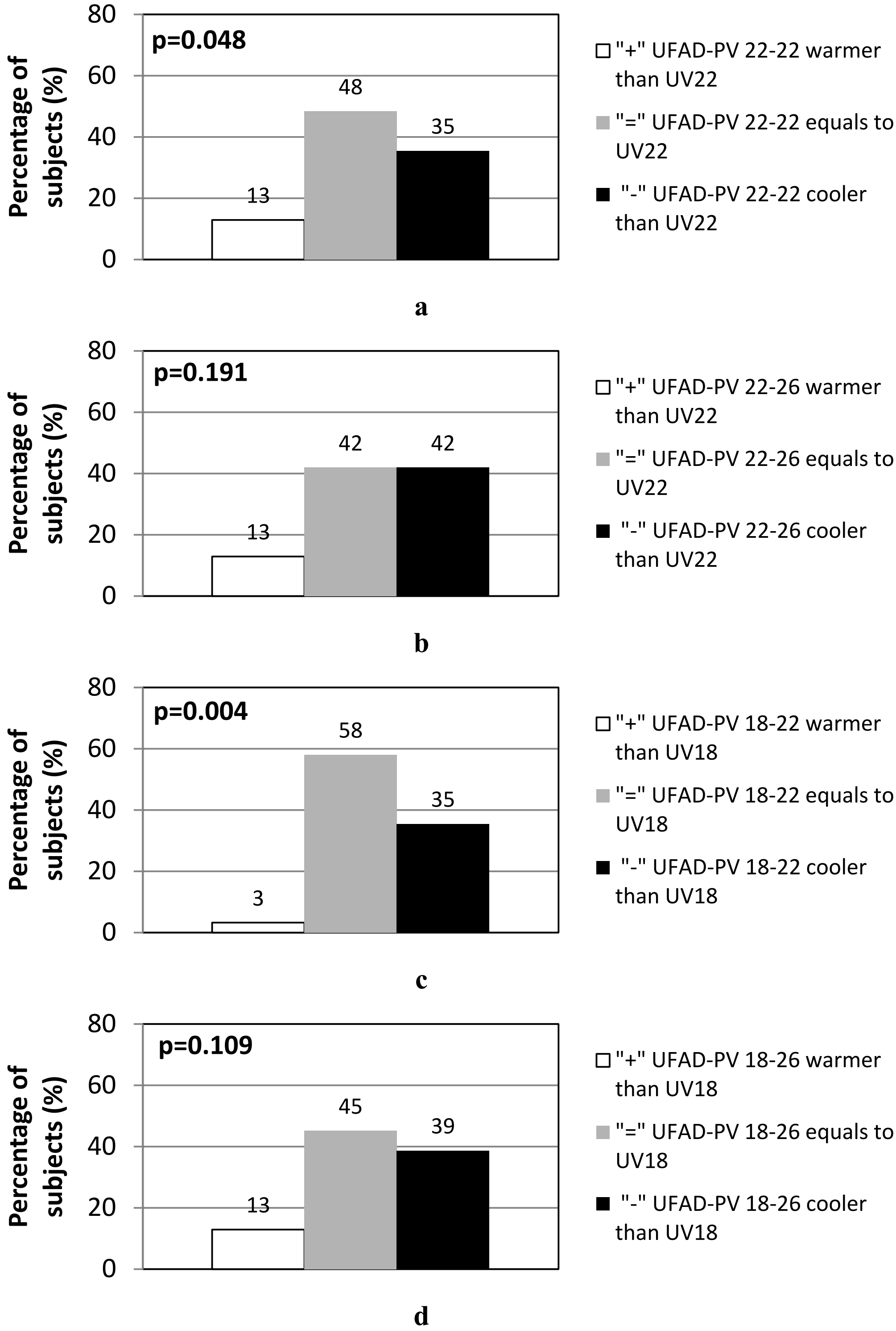


Figure 7.18 (a, b, c, d) Comparison of the whole body thermal sensation in pairs of "UFAD-PV" and "UFAD alone" for various temperature combinations

When comparing the frequency of the group of subjects indicating “UFAD-PV has a cooler sensation than UFAD alone” between Figure 7.16 (thermal sensation at face) and Figure 7.18 (whole body thermal sensation), the percentage of subjects who felt cooler in cases with UFAD-PV are apparently lower for the whole body thermal sensation than for the thermal sensation at face. For example, in Figure 7.16a, 58% of subjects reported that they have a cooler thermal sensation at face in cases with UFAD-PV (22-22) than in case UV22 while the percentage of subjects who report cooler whole body thermal sensation was only 35%. This might be due to the fact that the local body parts would be more sensitive than the whole body when local cooling is addressed at those body parts.

Whole body thermal comfort acceptability

Figure 7.19 shows the whole body thermal comfort acceptability. When PV is applied, the thermal comfort acceptability is always improved when compared with the three reference cases (UV22, UV18 and C). The higher PV air flow rate results in relatively higher level of acceptability. The whole body thermal comfort acceptability increases when the facial region is cooled by the PV air.

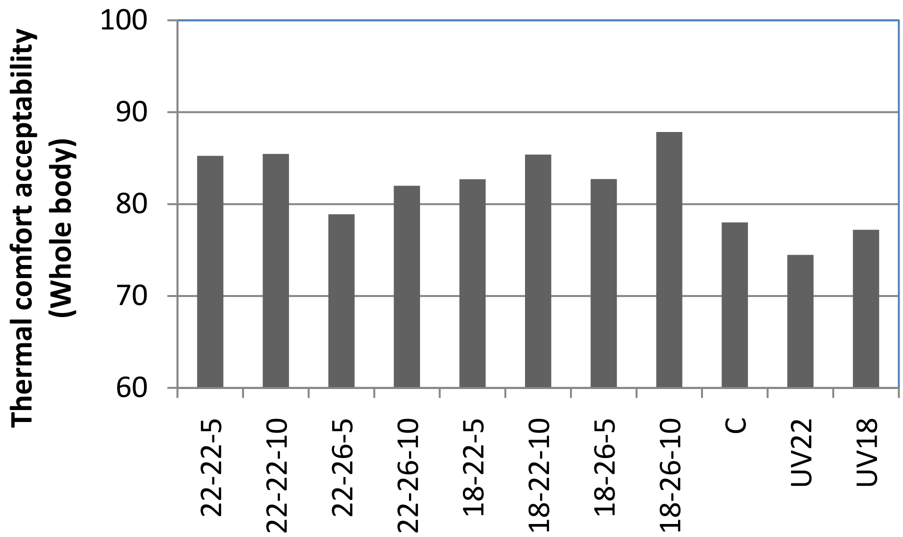
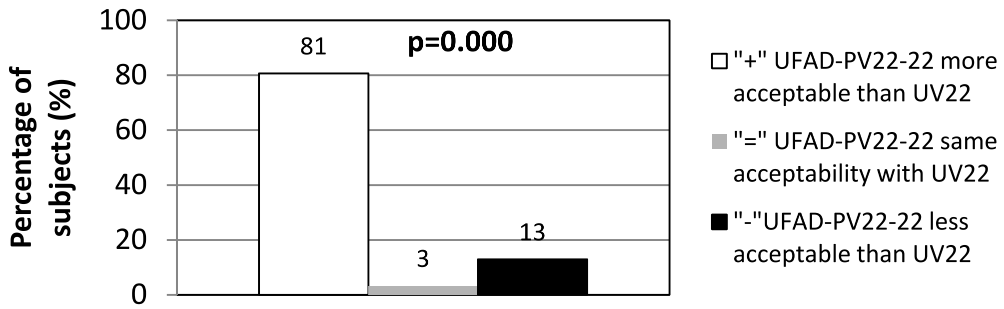


Figure 7.19 Thermal comfort acceptability (whole body) ***(****Thermal comfort acceptability:0 ~50 = very unacceptable ~ just unacceptable, 50~100 = just acceptable ~ very acceptable****)***

The whole body thermal sensation acceptability reported with UFAD-PV and with UFAD alone was compared and the results were analyzed in pairs. These are shown in Figure 7.20. The acceptability of the whole body thermal comfort was significantly improved by applying PV to facial part. Although the cooling effect of PV on the thermal sensation of the whole body is not always significant when the warmer PV air temperature was used (Figure 7.18 b and d), the whole body thermal comfort acceptability is significantly improved by PV with the 26 ˚C supply air temperature (Figure 7.20b and 7.20d).



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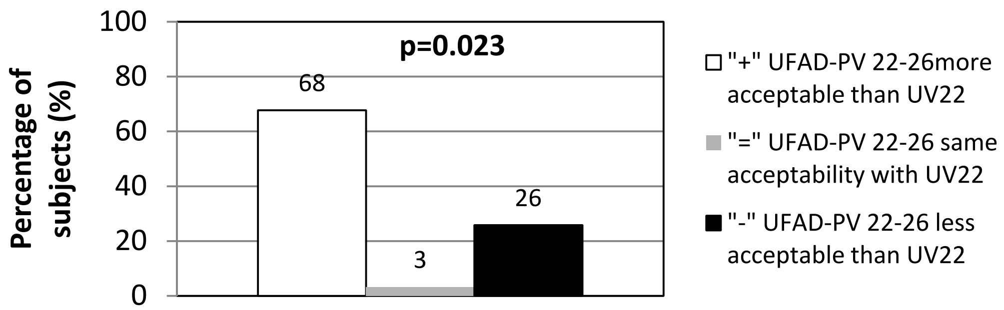

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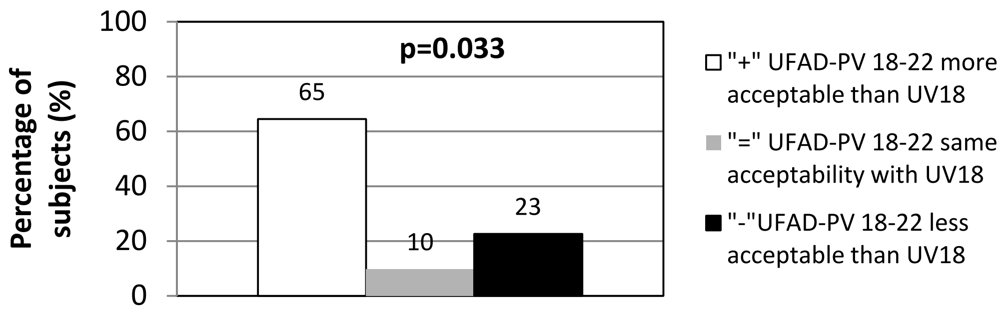

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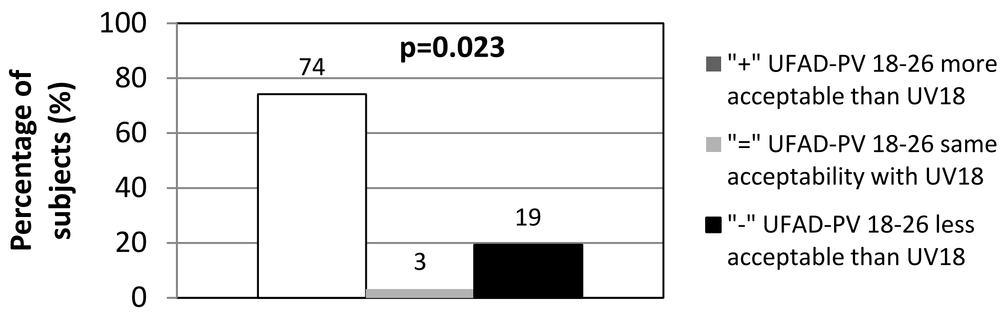

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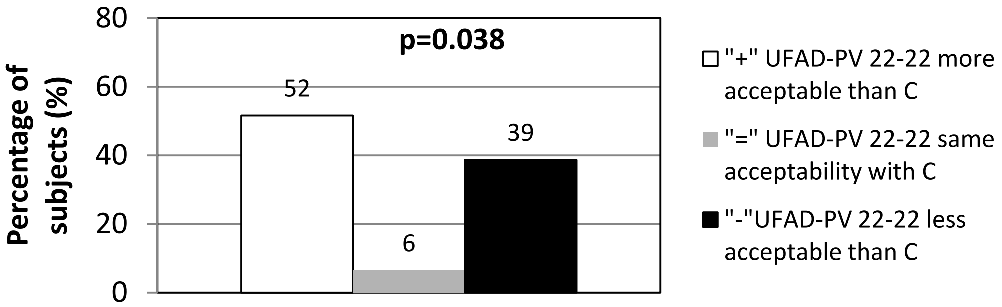
Figure 7.20 (a, b, c, d) Comparison of whole body thermal comfort acceptability in pairs of UFAD-PV and UFAD alone for various temperature combinations

The whole body thermal sensation acceptability reported with UFAD-PV and with CSMV (defined as “C”) alone was compared and the results were analyzed in pairs. These are shown in Figure 7.21. When comparing the whole body thermal sensation acceptability in pairs of UFAD-PV vs. C (Figure 7.21), the positive effect of UFAD-PV on the whole body thermal comfort is found to be significant for most of the cases. It is only in the case of warmer UFAD and PV supply air temperature that the occupants' whole body thermal comfort is not significantly different from that of fully mixing system.



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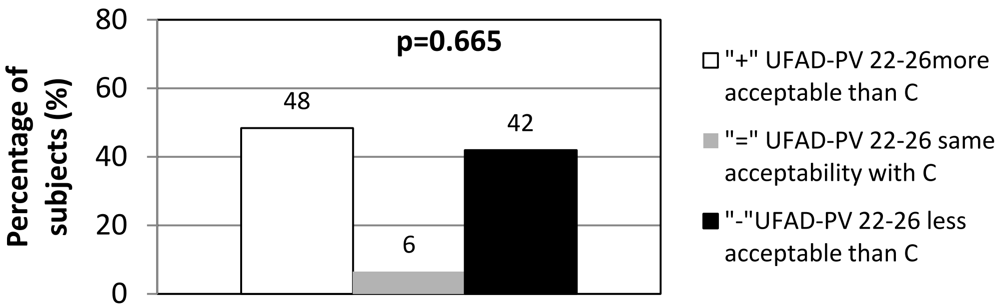

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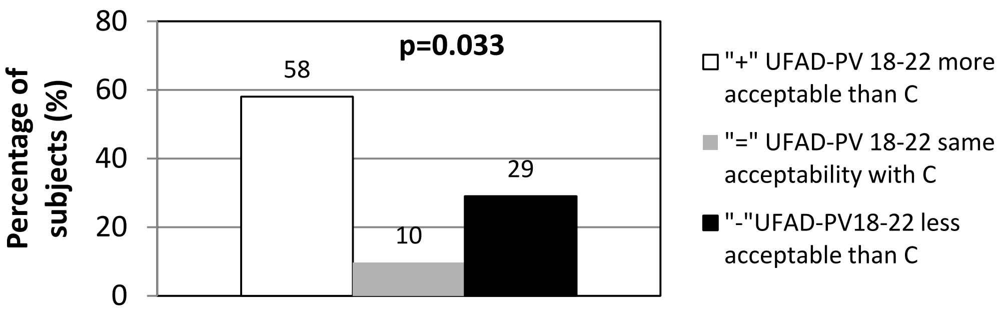

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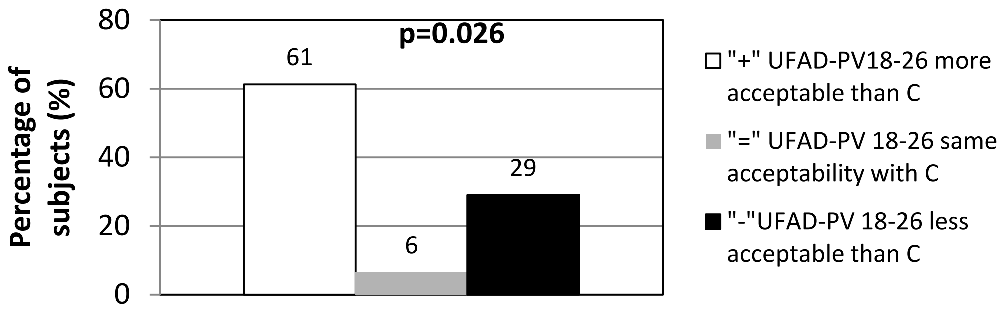

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Figure 7.21 (a, b, c, d) Comparison of thermal comfort acceptability in pairs of UFAD-PV and C (Ceiling supply) for various temperature combinations

The relationship between the average value of face /whole body thermal comfort among all the experimental cases (thick dashed line) and whole body thermal sensation vote is shown in Figure 7.22. For several cases, better evaluation of the whole body thermal comfort is given by the subjects who felt “cool” for their whole body thermal sensations (Figure 7.22, case 18-22-5, 18-26-10, and 18). However, in the case with warmer combinations of PV and UFAD supply air temperature and lower PV flow rate (22-26-5), the highest value of whole body thermal comfort is obtained among those subjects who felt “neutral” for the whole body. Nevertheless, the highest evaluation of the whole body thermal comfort is found when the whole body thermal sensation and face thermal sensation are “slightly cool” for majority of the cases (case 22-22-5, 22-22-10, 22-26-10, 18-22-10, 18-26-5, C and UV22). Thus, the cooling effect of PV on the whole body thermal sensation plays a positive role in improving the whole body thermal comfort.

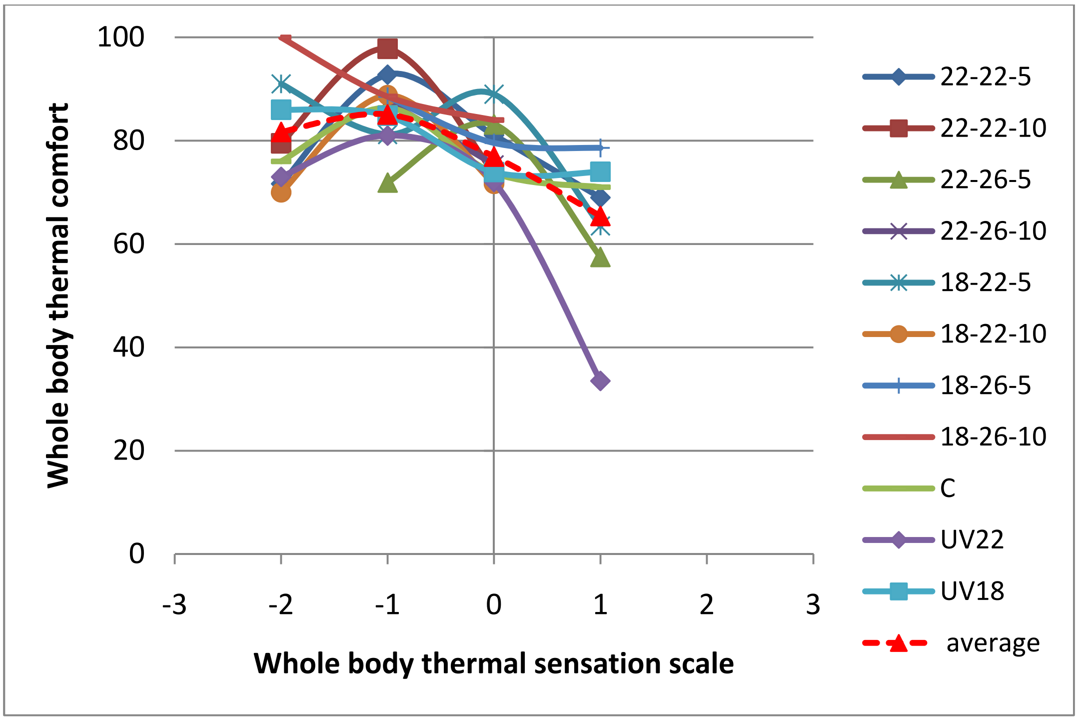


Figure 7.22 Relationship of whole body thermal sensation and whole body thermal comfort acceptability *(Thermal sensation scale: =-3 cold, =-2 cool, =-1 slightly cool, =0 neutral, =+1 slightly warm, =+2 warm, =+3 hot; Thermal comfort acceptability:0 ~50 = very unacceptable ~ just unacceptable, 50~100 = just acceptable ~ very acceptable)*

7.3.2 Perception, acceptability, and preference of air movement at face

Perception of air movement

The perception of air movement averaged for the pool of subjects participating in this study is shown in Figure 7.23. The UFAD-PV system makes the subjects experience “more breezy” perception of the air movement at face when compared with that of the cases with total volume ventilation systems (C, UV22 and UV18). In the cases UV22 and UV18, the perception of air movement at face is between “just right” (0) to “slightly still” (-1), and almost 50% of the subjects reported that they did not feel the air movement at face. When PV is applied, the perception of air movement increased to the range between “just right” (0) to “slightly breezy” (1). However, this “more breezy” perception does not make the subjects feel the air movement at face unacceptable.

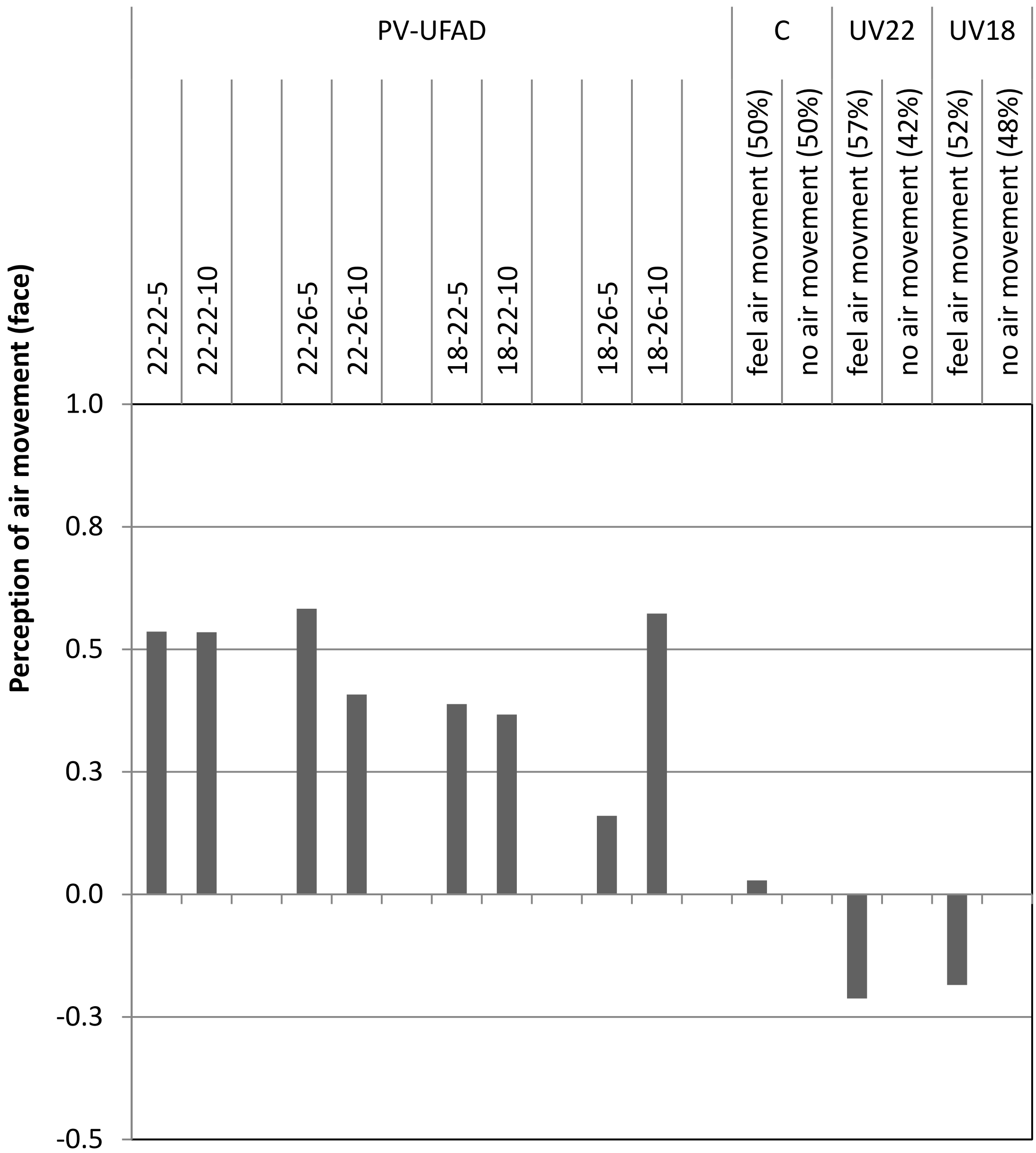


Figure 7.23 Perception of air movement at face

(*Perception of air movement: = -3 much too still, = -2 too still, = -1 slightly still, =0 just right, =1 slightly breezy, =2 too breezy, =+3 much too breezy****)***

Acceptability of air movement

The results of the subjects' acceptability and preference for the air movement show that introducing the PV air in combination with UFAD has a positive effect.

The percentage of subjects who felt unacceptable air movement at face level is shown in Figure 7.24. The percentage of subjects who felt unacceptable air movement at face level is apparently reduced by using UFAD-PV system when compared with the cases using UFAD alone and became comparable to that of the CSMV system. As shown in Figure 7.24, in cases UV22 and UV18, the percentage of subjects who felt unacceptable air movement at face level is 26% and 13% respectively. This value decrease to 3% when 22 ˚C PV air is used (case 22-22-5 and 22-22-10). However, the reduced unacceptability rate appears to be not necessarily only due to the PV air temperature but it also depends on the combination of the UFAD-PV operating conditions. For example, in cases 18-22-5 and 18-26-5, the percentage of subjects who felt unacceptable air movement at face level is 10%, while it is less than that in case UV22 and UV18. Thus, the improvement of acceptability of air movement is not apparent by introducing PV air with those parameters. Nevertheless, as found in section 7.3.1, the thermal sensations at face and whole body for majority of the cases become cooler when higher PV air flow rate is used. Similar observations are also made for the acceptability of air movement at face. In the conditions with 10 L/s PV air flow rate (Figure 7.24, case 22-22-10, 22-26-10, 18-22-10, 18-26-10), the percentage of subjects who felt unacceptable air movement at face level is in the range of 0~3%, which is almost negligible.

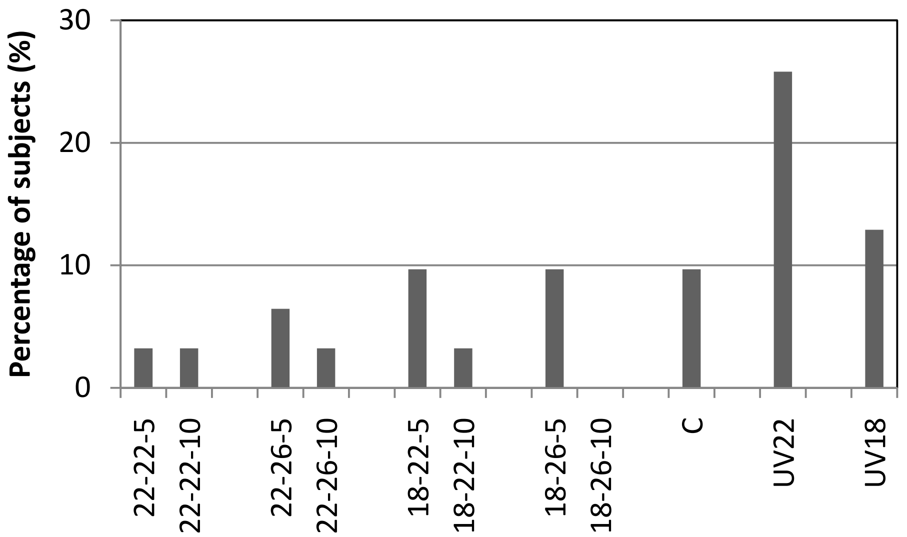


Figure 7.24 Percentage of subjects who felt the air movement at facial part unacceptable

When cooler PV air is used, the effect of PV air on improving the acceptability of air movement at the facial part is statistically significant. As shown in Figures 7.25a and 7.25c, the p-values are less than 0.05, which implies that subjects felt air movement more acceptable using UFAD-PV with PV supply air temperature of 22 °C than using UFAD alone. In the paired cases where there is no significant difference, the percentage of subjects who felt air movement acceptable is higher with UFAD-PV than with UFAD alone. For instance, in Figure 7.25d, the percentage of subjects who felt more acceptable with UFAD-PV (18 °C UFAD supply air temperature and 26 °C PV supply air temperature) than with UFAD (18 °C supply air temperature) is 48% and those who felt worse is 35%.

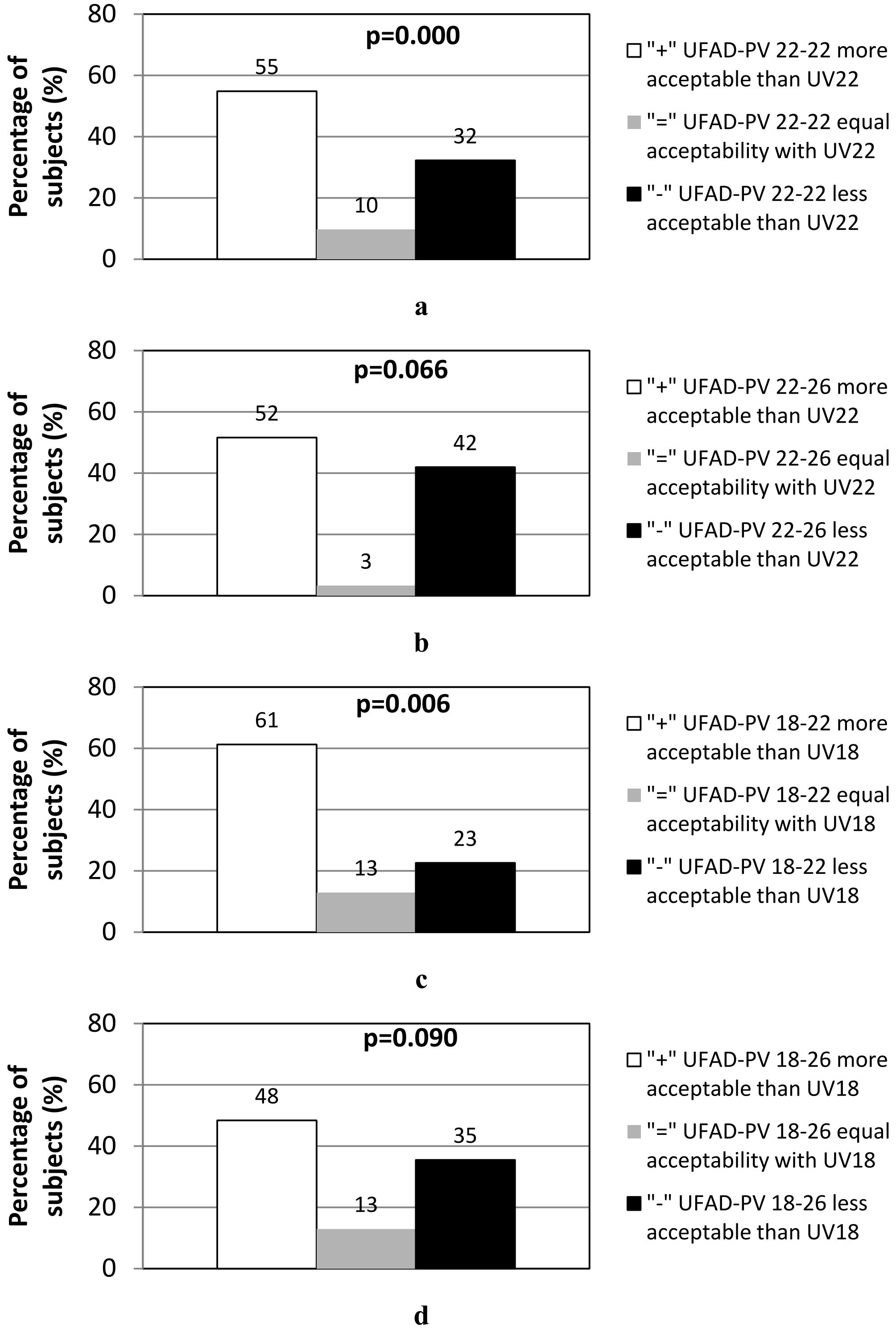


Figure 7.25 (a, b, c, d) Comparison of acceptability of air movement at face in pairs of UFAD-PV and UFAD alone at various temperature combinations

Preference for air movement

The analyses of the results on thermal sensation at the face (Figure 7.16) show that 30- 40% of the subjects have the same thermal sensation in case with and without PV. However, only for about 10% of the subjects the reported acceptability of air movement is the same in cases with and without PV (Figure 7.25). This indicates that there are large differences among the subjects with regard to the perception of the air movement.

Figure 7.26 compares subjects' preference for air movement at face as reported during the conditions studied. These results were obtained at the end of each experimental session. In the three reference cases (mixing, UV22 and UV18), none of the subjects preferred to have less air movement but 37-45% of them preferred to have more air movement. This indicates that in a warm ambient condition, a substantial number of occupants are most likely to be annoyed by the insufficient air movement rather than excessive air movement at facial part.

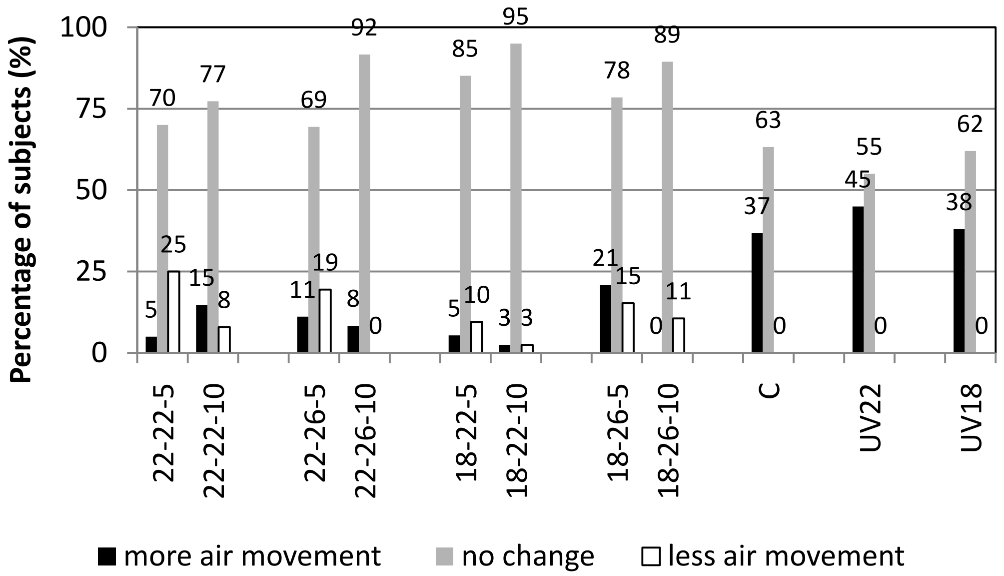


Figure 7.26 Preference for the change of air movement at face

The acceptability of air movement and preference for air movement as reported by the subjects were analyzed together. The relationship between the acceptability of air movement and preference for air movement (Figure 27) reveals that when subjects prefer “no change” for the air movement, the current air movement they were experiencing was most acceptable (preference for air movement=0, acceptability of air movement=85). Thus, by being provided with the opportunity to choose the PV flow rate, 70-95% (Figure 7.26) occupants felt satisfied with the air movement and did not want to adjust the air movement at face (“no change, 0”). The results in Figure 27 also reveal that when the subjects indicated “less” for the air movement (-1), the current air movement they were experiencing was more acceptable than those who preferred “more” (1).

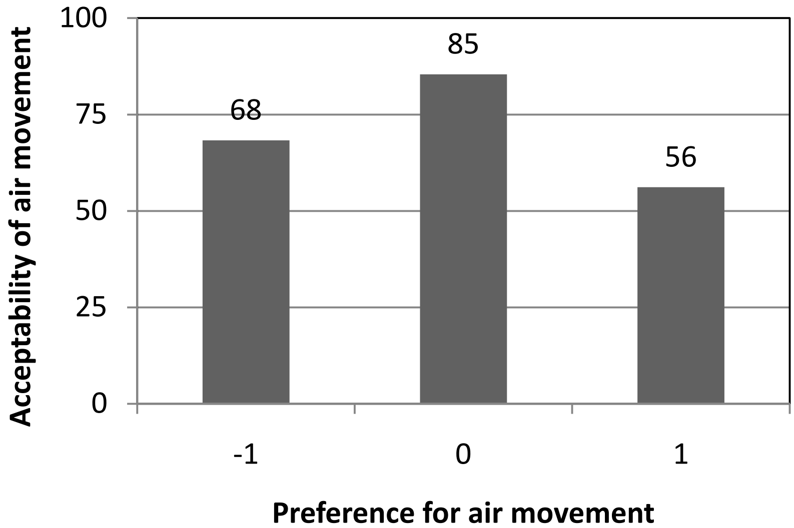


Figure 7.27 Relationship between preference for air movement and acceptability of air movement [face] *(Acceptability of air movement: 0 ~50 = very unacceptable ~ just unacceptable, 50~100 = just acceptable ~ very acceptable; preference for air movement: +1 more air movement; 0 no change; -1 less air movement)*

By being provided with the opportunity to choose a different air flow, majority of subjects could address their acceptable conditions. The subjects’ preference for air movement is influenced by changing the PV air flow rate (Table 7.1).

Table 7.1 Subjects' preference for air movement before and after the change of air flow (percentage)

Case	Preference for air movement	Before (15 mins)	After (150 mins)	
			5 L/s	10 L/s
22-22-5/10	More air movement	29%	5%	9%
	No change	**65%**	**70%**	**82%**
	Less air movement	6%	25%	9%
22-26-5/10	More air movement	32%	11%	8%
	No change	**58%**	**74%**	**92%**
	Less air movement	10%	16%	0%
18-22-5/10	More air movement	32%	0%	0%
	No change	**61%**	**90%**	**100%**
	Less air movement	6%	10%	0%
18-26-5/10	More air movement	39%	10%	0%
	No change	**55%**	**71%**	**85%**
	Less air movement	6%	19%	15%

For example, at the "warm combination of UFAD-PV" (UFAD supply air temperature at 22 °C and PV supply air temperature at 26 °C) the percentage of subjects who prefer "no change" for air movement is 58% and 32% of the subjects preferred "more air movement" before they were allowed to change PV air flow (Figure 7.28, 15 mins). After being provided with the second opportunity to change the air flow between 5 L/s and 10 L/s, the percentage of subjects who prefer "no change" increase to 74% and 92% respectively (Figure 7.28, 150 mins "22-26-5" and "22-26-10"). The percentage of subjects who wanted to have higher air movement is reduced from 32% to 11% among those who finally chose 5 L/s and 0 among those who finally choose 10 L/s. However, there are still 16% of the subjects who preferred even less air movement than 5 L/s and 8% of the subjects who preferred to have more air movement than 10 L/s. Similar trends are found in all the combinations of UFAD-PV conditions.

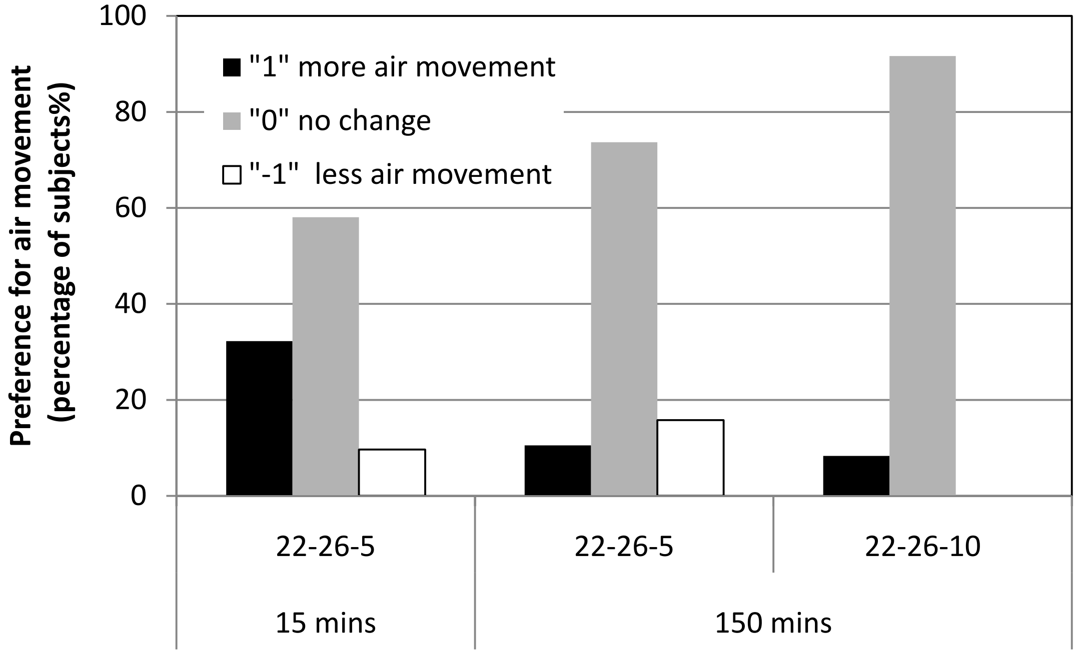


Figure 7.28 Subjects' preference for air movement before and after the change of air flow (UFAD supply air temperature at 22°C and PV supply air temperature at 26°C)

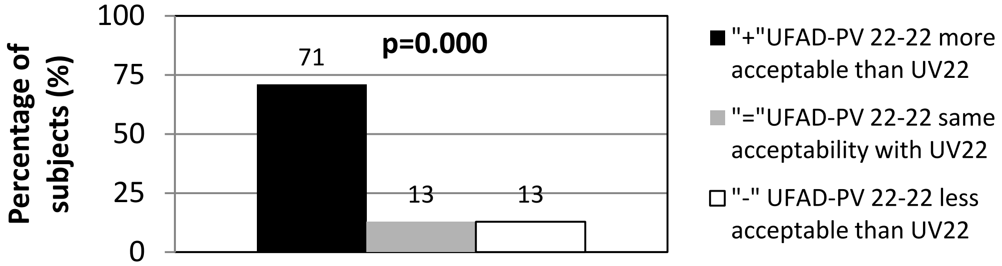
Consistent with previous studies, the human responses and satisfaction levels were found to be significantly improved with the microenvironment when the subjects were given the opportunity for control (Melikov and Knudsen 2007). Majority (70-95%) of subjects feel satisfied with the air movement by changing the PV air flow rate between 5 L/s and 10 L/s. This is a significant improvement compared with the mixing and UFAD systems alone. However, the range of PV air flow provided in this study still could not achieve 100% satisfaction. There are cases of those who wanted even less air movement than 0.3 m/s (corresponding to 5 L/s) and those who wanted more air movement than 0.7 m/s (corresponding to 10 L/s).

7.3.3 Perceived air quality and measured inhaled air quality

Perceived air quality (PAQ)

When the PAQ is compared in pairs of UFAD-PV and UFAD alone, the acceptability of PAQ reported by subjects was significantly improved by applying PV when compared with the reference cases (Figure 7.29 and Figure 7.30). The percentage of subjects who perceived air to be with higher quality with UFAD-PV than with UFAD alone is always higher than 50% (Figure 7.29 a: 71%, b: 58%, c: 77%, d: 65%).

The cooler PV supply air temperature was found to have a positive effect on subjects' acceptability of PAQ. At the same UFAD supply air temperature, the cooler PV supply air temperature always results in a higher percentage of subjects who perceived air more acceptable with UFAD-PV than with UFAD alone. For instance, when comparing in pairs of UFAD-PV and UFAD alone at UFAD supply air temperature of 22 °C, 71% of subjects assessed PAQ with UFAD-PV better than the PAQ with UFAD alone when the PV supply air temperature was 22 °C (Figure 7.29 a.) and only 58% when the PV supply air temperature was 26 °C (Figure 7.29 b.) The same trends could also be found with 18 °C UFAD supply air temperature. For example, in the pair of cases 18-22 vs. UV22 and 18-26 vs. UV22, the percentage of subjects who feel better PAQ with UFAD-PV than with UFAD alone was 77% and 65% respectively. Significant improvement in the perceived air quality (PAQ) is found when the results reported by the subjects with UFAD-PV are compared with the results reported with CSMV alone (Figure 7.30). The comparison of the PAQ in pairs of UFAD-PV and CSMV alone, reveals that more than 50% of the subjects always found the PAQ with UFAD-PV better than with CSMV alone (Figure 7.30a: 81%, b: 68%, c: 77%, d: 65%). Moreover, the positive effect of cooler PV air temperature on PAQ is also found when comparing the PAQ in pairs of UFAD-PV and CSMV. However, the PAQ is not only affected by the air temperature, but also affected by the combined effects of cleanness of the air and air velocity, which is discussed in later parts of this chapter.



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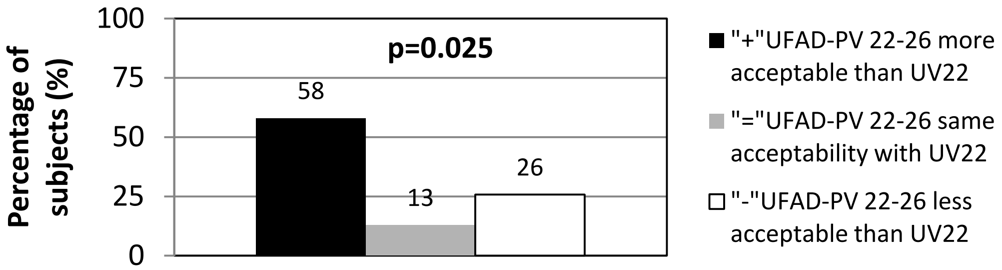

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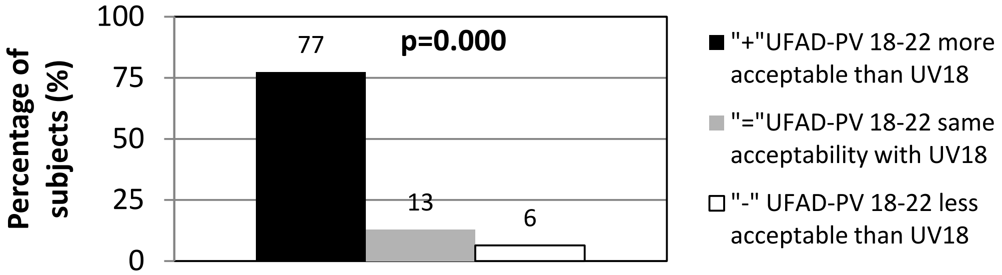

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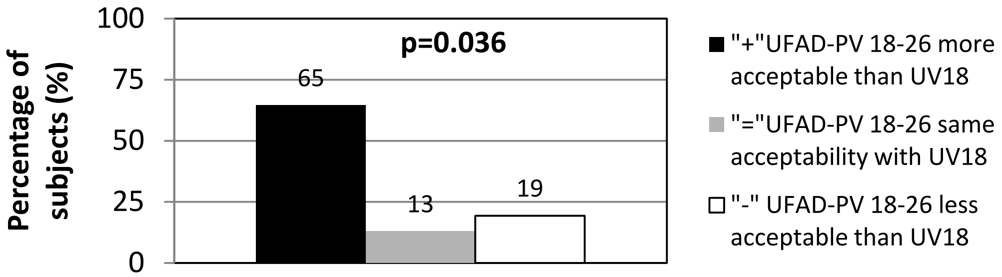

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Figure 7.29 (a, b, c, d) Comparison of PAQ in pairs of UFAD-PV and UFAD alone under various temperature combinations

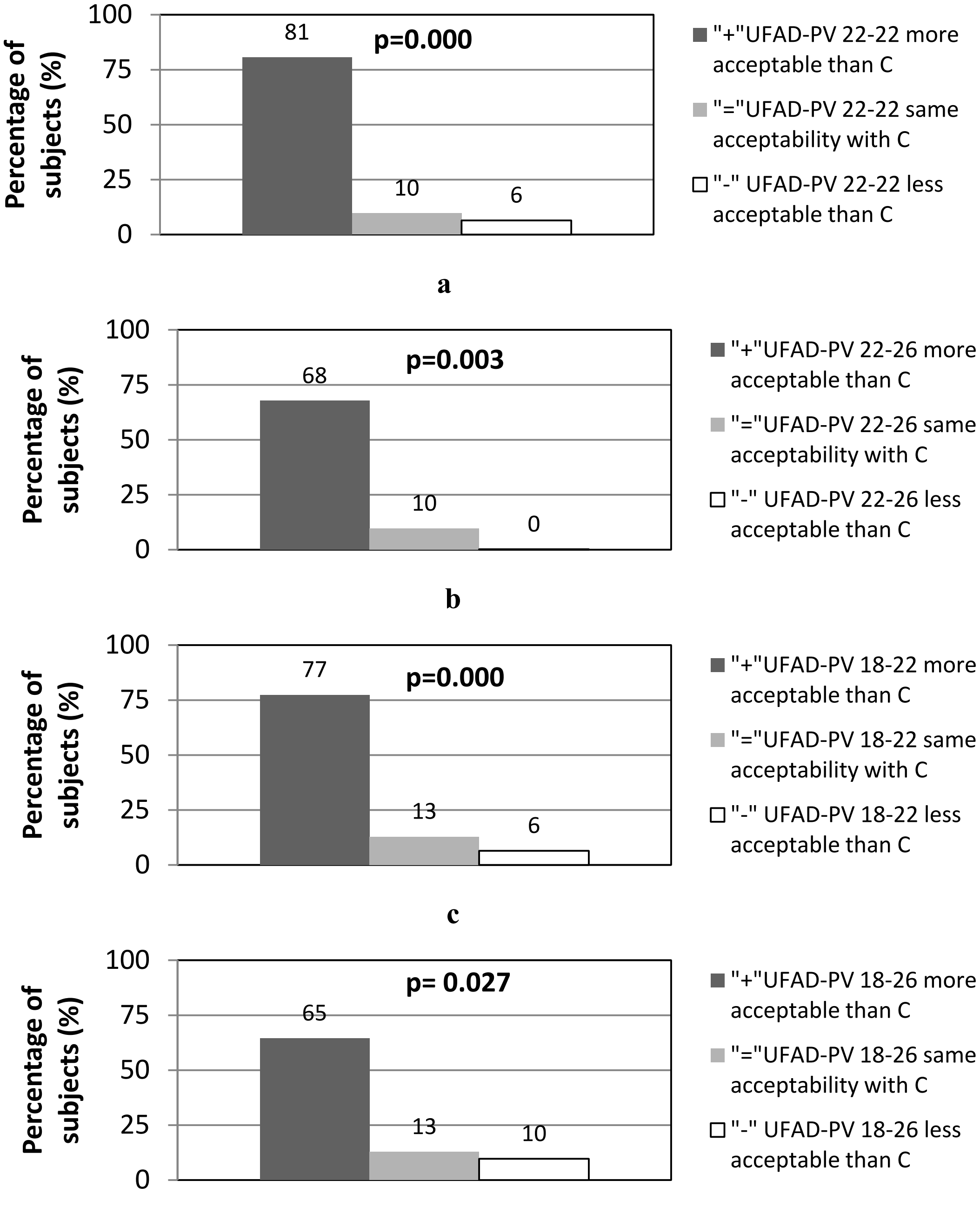

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Figure 7.30 Comparison of PAQ in pairs of UFAD-PV and CSMV system under various temperature combinations

This positive effect of cooler PV air was also found from the average values of the perceived air quality of each experimental case. The PAQs of those cases using 22 °C PV supply air temperature were higher than those using 26 °C PV air (Figure 7.31, 22-22-5/10 vs. 22-26-5/10 and 18-22-5/10 vs. 18-26-5/10). Moreover, the higher PV air flow rate is also found to have a positive effect of improving occupants' perceived air quality. For example, when PV and UFAD supply air temperatures are at 22 °C, the PAQ of the case with 10 L/s PV air flow rate is higher than that with 5 L/s (Figure 7.31, 22-22-5 vs. 22-22-10). The effect of higher PV air flow rate is more apparent when warmer UFAD supply air temperature is used. When the cooler UFAD supply air temperature is used, the differences of PAQ between the cases with different PV air flow rate are not apparent. In most of the cases, the average values of PAQ with UFAD-PV system are always higher than those with total volume ventilation system (CSMV and UFAD alone). Only in cases with warmer PV supply air temperature and lower PV air flow rate (Figure 7.31, case 22-26-5 and 18-26-5), the PAQs are lower than CSMV. However, the PAQ of these two cases were still higher than the PAQ of UFAD alone with the corresponding two levels of UFAD supply air temperature (Figure 7.31 case 22-26-5 vs. UV22 and case 18-22-5 vs. UV18).

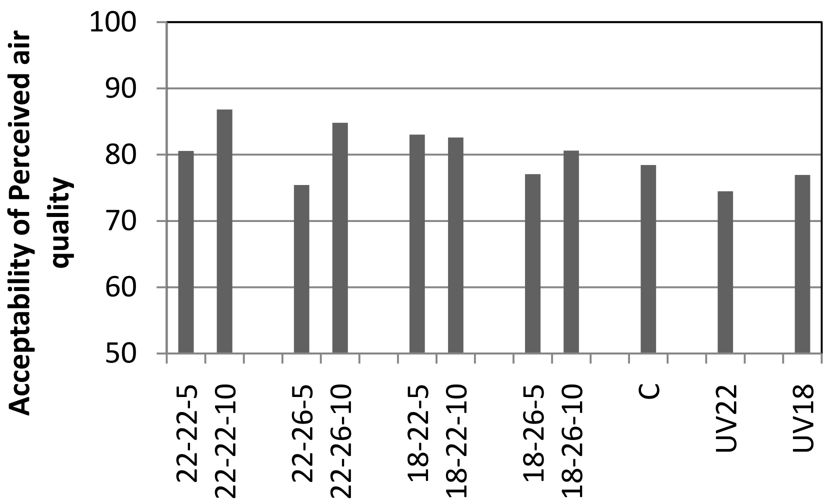


Figure 7.31 Perceived air quality ***(****0 ~50 = very unacceptable ~ just unacceptable, 50~100 = just acceptable ~ very acceptable****)***

The perceived air quality is significantly improved by applying PV when compared with the reference cases. In general, the percentage of subjects who perceived better inhaled air quality with UFAD-PV than the reference cases are above 58%. In most of the cases, the average values of PAQ of the cases with UFAD-PV system are always higher than those with total volume ventilation system. The percentage improvement of PAQ caused by PV is higher in cases with cooler PV air than with warmer PV supply air temperature. Moreover, with the same level of PV supply air temperature, the higher PV air flow rate is found to have the positive effect on improving occupants' perceived air quality.

Measured inhaled air quality and subjective responses

The indices, such as **PEE** (personal exposure effectiveness) and **PEI** (personal exposure index) were calculated based on the concentration of tracer gas measured in the experimental chamber. The indices are used to evaluate the ability of the ventilation system in bringing conditioned outdoor air and protect occupants' from indoor contaminants at the breathing zone.

The PEE and PEI values obtained for the experimental conditions in the present study are shown in Figure 7.32. The findings of previous studies with UFAD alone (Cermak 2004, Cermak and Melikov 2006) are shown as well.

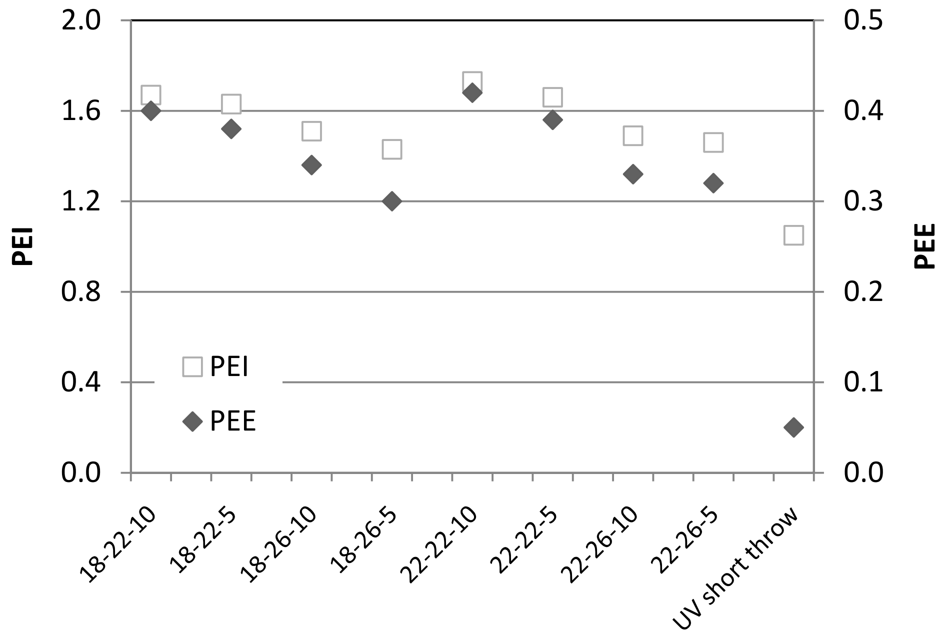


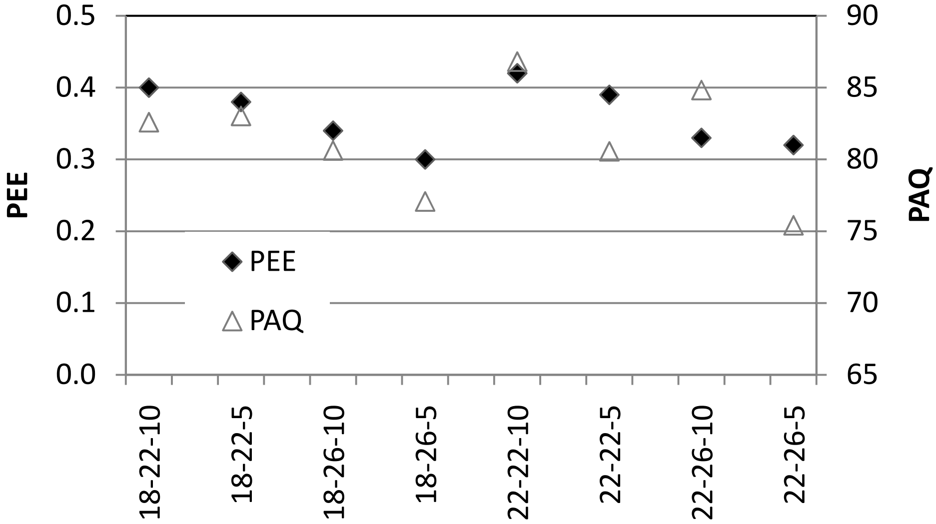
Figure 7.32 PEE and PEI values ("UV short throw" Cermak. 2004, Cermak and Melikov. 2006)

The percentage of PV air or the percentage of outdoor air in the inhaled air does not change a lot when different PV air flow rates (10 L/s and 5 L/s) are used. When comparing the PEE in pairs of 10 L/s and 5 L/s, for example, case 22-22-10 and 22-22-5, the difference between these two PV air flow rates is only 0.03.

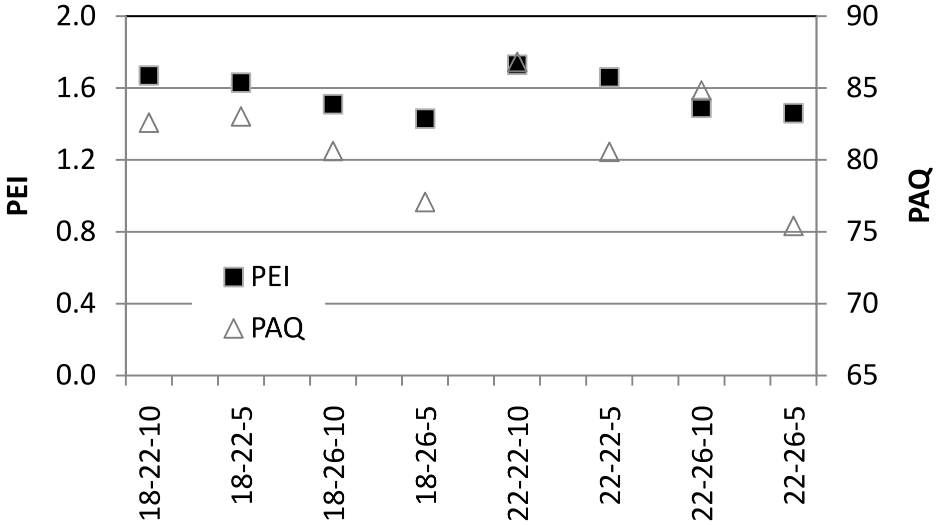
Compared with PV air flow rates, the supply air temperature of PV air has stronger effect on the PEE. It was observed that the cooler PV air was always able to deliver a higher percentage of outdoor air. The PEI shows a similar pattern as PEE. Better performance is achieved with UFAD-PV when compared with total mixing ventilation, which has a PEI=1. The PEI increases with the decrease of PV supply air temperature. The higher supply volume of PV air results in slightly higher PEI but not as apparent as that caused by PV supply air temperature. This indicates that the air in the inhalation zone was rather mixed and was not 100% clean PV air. The mixing pattern of the air at the inhalation region might be affected multiple combination effects of PV and ambient conditions (i.e. PV supply air temperature and flow rate, ambient total volume ventilation supply air temperature and flow rate etc.)

The UFAD supply conditions also have a marginal effect on the PEE and PEI, but not comparable to that of PV. The cooler UFAD supply air temperature tends to result in lower PEE and PEI. This might be due to the thicker thermal plume generated by the thermal manikin that is then more difficult for penetration by the PV air.

The relationship between PEE/PEI and the acceptability of perceived air quality (PAQ) is shown in Figure 7.33 (a, b). At 18 °C UFAD supply air temperature, the PAQ values follow similar trends as that of PEE and PEI. The PAQ and measured inhaled air quality are higher when the cooler PV supply air temperatures are used. However, with 22°C UFAD supply air temperature, the patterns of the distribution of PAQ values are not consistent with that of PEE and PEI. It is observed that the supply air temperature of PV air has stronger effect on the PEE, and that the PAQ is most likely to be affected by the PV supply air flow rate than PV supply air temperature. For example, the cases were ranked as 22-22-10, 22-22-5, 22-26-10, 22-26-5 according to the value of PEE from high to low, while this rank was changed to 22-22-10, 22-26-10, 22-22-5, 22-26-5 regarding the value of PAQ. This indicates that the subjects' perceived air quality is correlated not only with the pollution level in the inhaled air but also to velocity and temperature of the personalized flow at the breathing region.



a



b

Figure 7.33 The relationship between PEE/PEI and PAQ (a: PEE and PAQ, b: PEI and PAQ) ***(PAQ linear scale: 0 - very unacceptable, 100 – very acceptable)***

The PAQ values were found to be strongly correlated with the occupants' perceived inhaled air temperature and freshness of the air. It can be seen from the results in Figure 7.34 that the PAQ has a linear relationship to the subjects' perceived inhaled air freshness and percieved inhaled air temperature. The air freshness increases with the increase of the acceptability of PAQ and the decrease of the perceived temperature of the inhaled air. The PAQ values are also found to decrease with the increase of perceived inhaled air temperature.

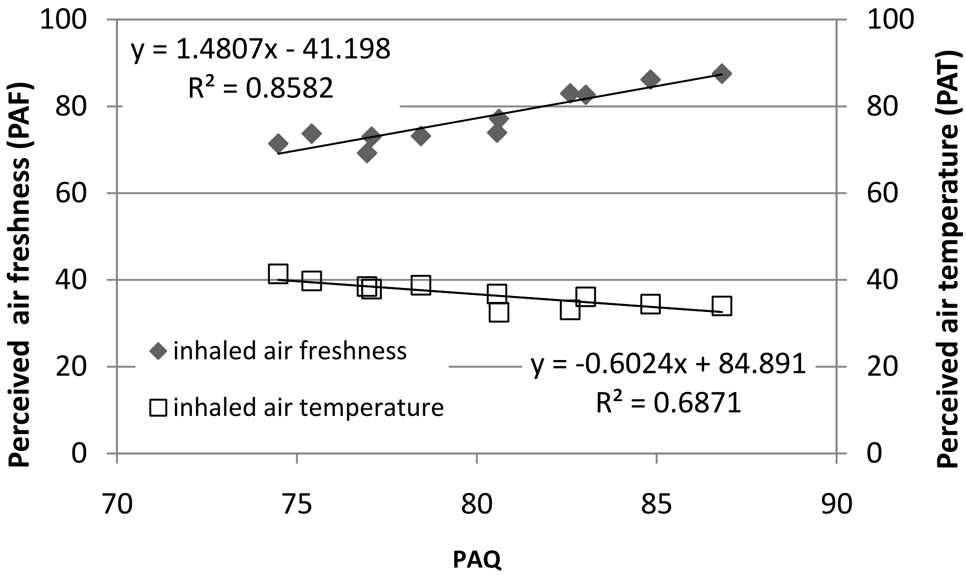


Figure 7.34 The relationships between acceptability of perceived air quality (PAQ) and other perceived inhaled air parameter *(perceived inhaled air temperature: 0~100: cold ~hot; perceived inhaled air freshness: 0~100: stuffy ~fresh; PAQ: 0 ~50 = very unacceptable ~ just unacceptable, 50~100 = just acceptable ~ very acceptable)*

When PV was used, the perceived inhaled air temperatures were cooler than those of reference cases (Figure 7.35). This is consistent with the physical measurement of the inhaled air temperature (Figure 7.36). The PV air in the UFAD-PV could always decrease the inhaled air temperature when compared with that of UFAD alone. The higher PV flow rate (10 L/s) could reduce the inhaled air temperature more apparently than the low flow rate. With the higher PV flow rate, the cooler PV supply air temperature results in cooler inhaled air temperature. The variations of the perceived inhaled air temperature with the change of UFAD-PV operating conditions were also observed to have the same trends with the thermal sensation at face (Figure7.13).

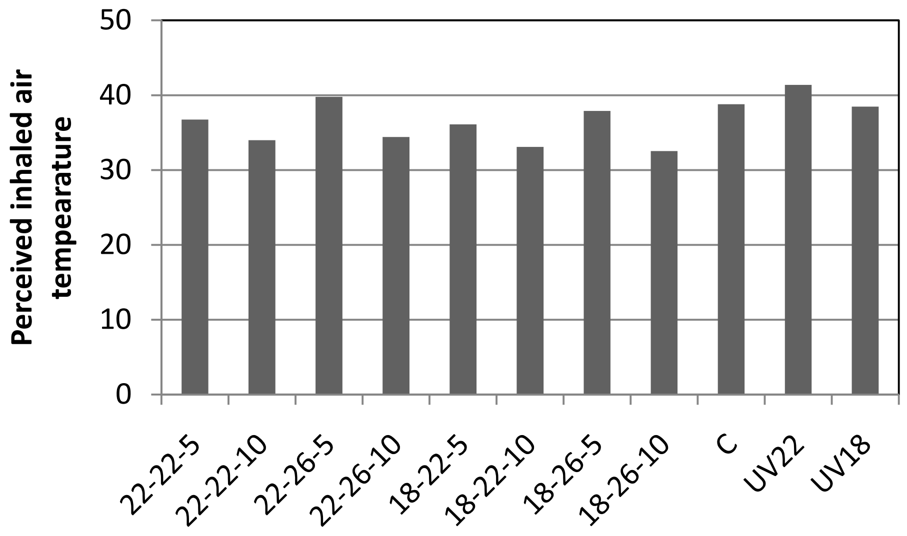
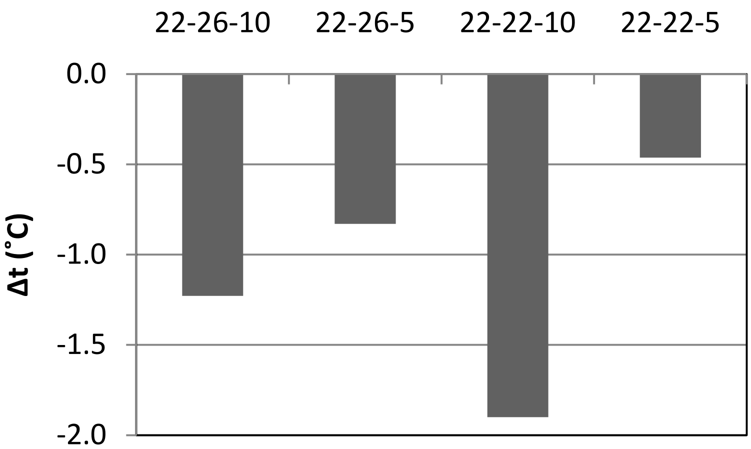
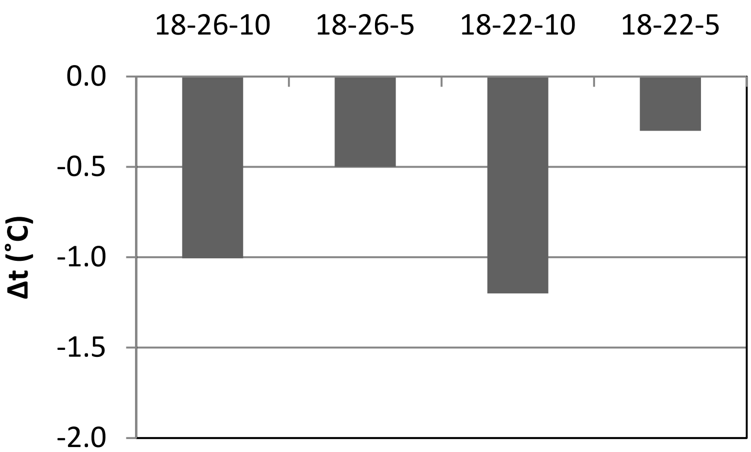


Figure 7.35 Perceived inhaled air temperature *(0~100: cool to hot)*

In Figure 7.36 the difference in the measured inhaled air temperature in the cases with UFAD-PV and the cases with UFAD alone having the same UFAD supply air temperature are used to show the effect of PV air. The PV air could always decrease the inhaled air temperature when compared with that of UFAD alone. The higher PV flow rate (10 L/s) could reduce the inhaled air temperature more apparently than the low flow rate. With the higher PV flow rate, the cooler PV supply air temperature results in cooler inhaled air temperature. When the lower PV flow rate (5 L/s) is used, the warmer PV supply air temperature tends to result in cooler inhaled air temperature. This is attributed to the smaller momentum of the PV air. The cooler PV air might drop down before it reaches the inhalation zone and result in a warmer inhaled air temperature when compared with the warmer PV air.



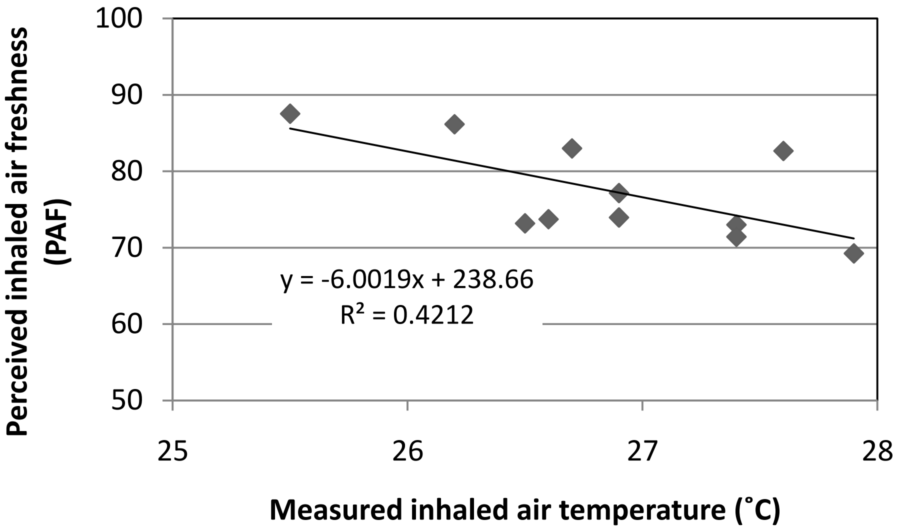
a



b

Figure 7.36 Inhaled air temperature (a: UFAD supply air temperature =22 ˚C, b: UFAD supply air temperature =18 ˚C)

Fang et al. (1998) reported that PAQ improves when temperature and relative humidity of the inhaled air decrease. The analyses of the present results support the finding that elevated temperature of the inhaled air has negative impact on the PAQ. As shown in Figure 7.37 the correlation between the freshness of the air as reported by the subjects decreases with the increase of the temperature of the inhaled air. However the correlation is not strong. It is also seen from Figure 37b,c and Table 7.2 that the perceived inhaled temperature and acceptability of PAQ have weak linear relationship with measured inhaled air temperature and are not significant correlated (at 0.05 confidence level) with measured inhaled air temperature. The reason for the weak correlations can be that the used PV ATD device promoted mixing of the supplied PV air with the warm and polluted room air. As a result the temperature and pollution of the inhaled air did not change in a wide enough range to be felt clearly by the subjects.



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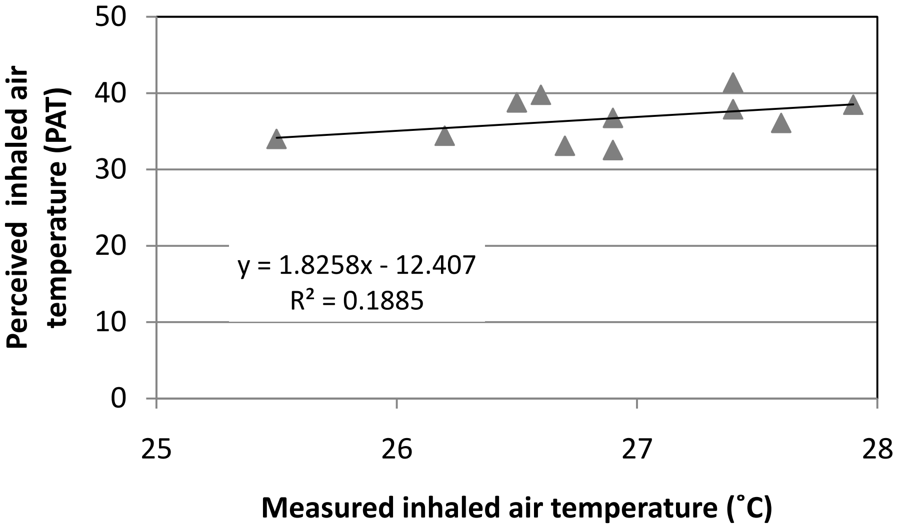

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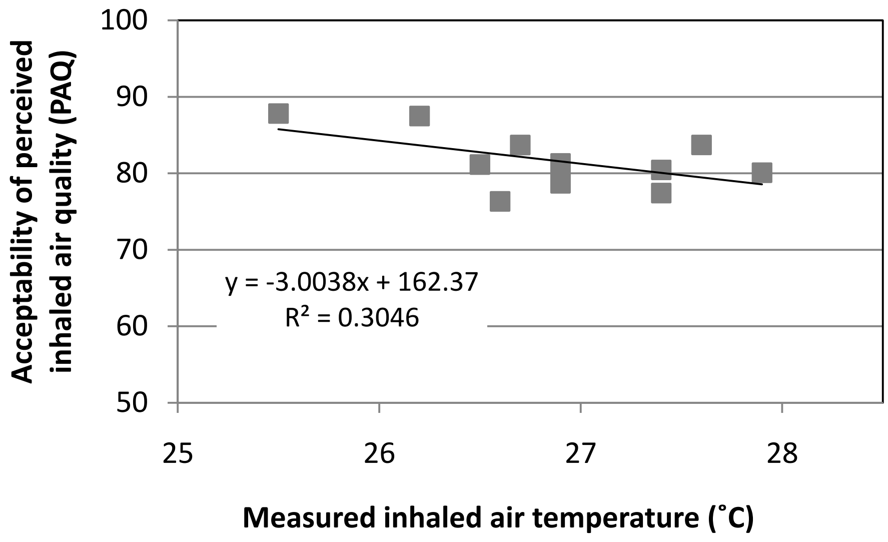


c

Figure 7.37 Correlation between: a. Measured inhaled air temperature and Perceived inhaled air freshness (PAF); b. Measured inhaled air temperature and Perceived inhaled air temperature (PAT); c. Measured inhaled air temperature and Acceptability of perceived air quality. ***(Linear scales: PAF: 0- stuffy, 100 – fresh; PAT: 0 – cold, 100 - hot; PAQ: 0 - very unacceptable, 100 – very acceptable)***

Table 7.2 Pearson correlation between measured inhaled air temperature (t_{inhale}) and human responses of inhaled air, and facial velocity (mean air velocity at 0.15 m from face, 1.3 m height) and human responses of inhaled air (* significant with 0.05 confidence level)

		Perceived inhaled air freshness	Perceived inhaled air temperature	Acceptability of Perceived air quality
t_{inhale}	R	-0.649	0.434	-0.552
	p	0.031*	0.182	0.078
Facial Velocity	R	0.827	-0.872	0.766
	p	0.003*	0.001*	0.01*

Melikov and Kaczmarczyk (2008) and Melikov et al. (2008) reported that elevated facial velocity diminishes the negative impact of increased air temperature, relative humidity and pollution level on PAQ. Further analyses were performed to study the impact of the facial velocity of the personalized flow on PAQ. Table 7.2 shows the Pearson correlation between PAQ and facial velocity (mean air velocity measured at 0.15 cm from face, 1.3 m height, Figure 3). The correlations between facial velocity and perceived inhaled air freshness/temperature and acceptability of PAQ are significant (at 0.05 confidence level). The facial velocity has positive linear relationship with perceived inhaled air freshness and acceptability of PAQ and has negative linear relationship with perceived inhaled air temperature. This is reasonable because the facial velocity and measured inhaled air temperature has a negative relationship (R=-0.77, p=0.009). Thus the results of the present study confirm the positive impact of elevated facial velocity on PAQ and reported in previous studies.

In Figure 7.38, the velocities are clustered into three regions: ≈0.1 m/s (no PV air), ≈0.3 m/s (PV air flow rate 5 L/s) and ≈ 0.7 m/s (PV air flow rate 10 L/s). The acceptability of PAQ increases with the increase of velocity. The linear relationship between acceptability of PAQ and facial velocity is relatively stronger than that between acceptability of PAQ and measured inhaled air quality. Moreover, when comparing the correlation coefficient (R-value) and significance (p-value), the correlation between PAQ and facial velocity are always stronger than that between PAQ and measured inhaled air temperature. As already discussed the mixing of the personalized air with the room air as promoted by the used PV ATD might be the reason.

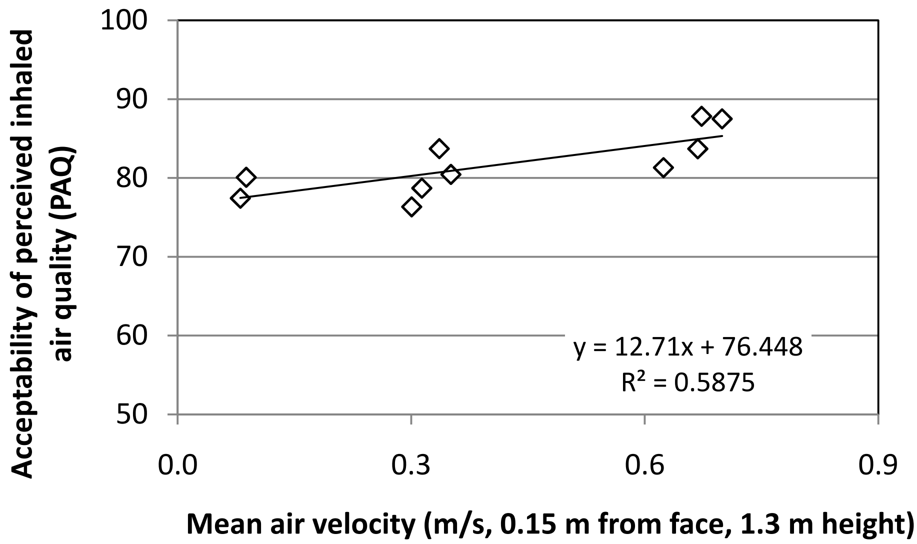


Figure 7.38 Correlation between mean air velocity at facial region and Acceptability of perceived air quality ***(PAQ linear scale: 0 - very unacceptable, 100 – very acceptable)***

7.4 Effect of UFAD-PV- Key findings

- The UFAD-PV with higher PV air flow rate could always reduce air temperature at head level.
- With the used PV diffuser the cooling effects of PV air are mainly contributed to the air movement rather than the temperature difference between the PV air and the ambient air.
- When PV is used, the occupants' thermal sensation at face is significantly cooler than reference cases.
- The cooling effect of PV air on the face and whole body thermal sensation plays a positive role in improving the whole body thermal comfort and the acceptability of air movement.
- By being provided with the opportunity to choose the PV flow rate, more occupants could make themselves comfortable with the air movement.

- The PV air flow can significantly improve the PAQ when compared with reference cases. The impact of air velocity on these parameters was stronger than the impact of PV supply air temperature.

Chapter 8 Energy Analysis

In this chapter, the energy saving opportunity from the UFAD-PV system is analyzed. The cooling capacity requirements for the UFAD-PV system are compared with the CSMV system. The UFAD-PV system shows better performance in removing the internal thermal load by using less total volume supply air. Moreover, by incorporating the heat-pipe unit into the AHU which serves the outdoor air for PV system, energy saving potential is observed in the effective cooling and dehumidification of the outdoor air by achieving pre-cooling and reheating in the heat pipe in a passive manner that does not involve any primary energy. Some of the most stringent PV conditions in the experiments, such as a warm PV air (26 °C), could be achieved in an energy efficient manner by involving the heat-pipe section in the outdoor air AHU.

8.1 Comparison between UFAD-PV and CSMV

The heat removal ability of the CSMV and UFAD-PV are compared by using the index as temperature effectiveness which had been defined in Chapter 5 (Eq. 5.6). The temperature effectiveness shows how effectively the heat load is removed from the room.

In CSMV system, because the room air temperature is identical in the room, the exhaust air temperature is the same as the occupied zone temperature and thus the temperature effectiveness is always equal to 1.

With the UFAD-PV system, because the ambient spaces of the workstations are served by UFAD system, the room air temperatures are stratified along the vertical height of room. The exhaust air temperature is warmer than the average occupied zone temperature. The temperature effectiveness of UFAD-PV system is always greater than one.

Temperature effectiveness (Heat removal effectiveness)

$$\varepsilon_t = (t_{ex} - t_0)/(t_{oz} - t_0) \quad \text{(Eq. 5.6)}$$

where t_{ex} and t_0 are exhaust and supply air temperatures, and t_{oz} is the average occupied zone temperature.)

During the objective and subjective measurements, the parameters in Eq. 5.6 were recorded simultaneously. The exhaust and supply air temperatures of UFAD system were continuously logged by HOBO meters (Table 5.2 and Table 5.3) at return grille and floor supply diffusers respectively. The supply air temperatures of CSMV and PV system were tracked through BAS system (Figure 5.2). The average occupied zone temperature was the mean value of air temperatures at four points (A, B, C and D in Figure 5.1a) at 1.3 m height of the room. The temperatures at those four points were recorded by BAS system and were used to control the supply air volume in order to maintain the room air temperature at 26 ˚C. These system parameters and the computed ε_t are shown in Table 8.1.

It can be found from Table 8.1 that the temperature effectiveness of UFAD-PV is higher than that of CSMV system. The temperature effectiveness values in Table 8.1 indicate that the heat removal ability of the UFAD-PV could be improved between 20-40% when compared with CSMV system. The total air flow rate of UFAD-PV system is 600 L/s when UFAD t_{supply} = 22˚C (120 +480 L/s, Table 8.1) which is 20% less than the total air flow rate of CSMV. When UFAD t_{supply} = 18˚C, the total air flow rate of UFAD-PV is 36 % less than that of CSMV.

Table 8.1 System parameters and temperature effectiveness values

	CS MV	UFAD-PV							
		22-22-5/10		22-26-5/10		18-22-5/10		18-26-5/10	
	CS MV	PV	UFAD	PV	UFAD	PV	UFAD	PV	UFAD
Air Flow rate (L/s)	750	120	480	120	480	120	360	120	360
Supply air temperature (°C)	16.0	22.0	22.0	26.0	22.0	22.0	18.0	26.0	18.0
Return air temperature (°C)	26.2	27.6		28.2		27.8		27.8	
Average occupied zone air temperature	26.2	26.0		26.4		25.8		25.9	
Temperature effectiveness ε_t	1	1.4		1.4		1.2		1.2	

Furthermore, the warmer UFAD supply air temperature results in higher temperature effectiveness than the cooler supply air temperature. When UFAD supply air temperature was 22°C, the temperature effectiveness of UFAD-PV system was 1.4. When UFAD supply air temperature was 18°C, the temperature effectiveness of UFAD-PV system was 1.2.

In addition, the transport energy consumption of PV system for this specific study is about 2.18 W/ (L/s), which is comparable to normal variable speed AHU (2.4 W/ (L/s), SS530 2006). This indicates that when supplying the same amount of outdoor air, the PV system may not result in higher transport energy consumption than the CSMV system. Moreover, although additional fan energy was always demanded to deliver PV air through ductwork to occupant's breathing zone, the overall fan transport energy of UFAD-PV system is not necessarily higher than CSMV and/or UFAD system which work together with desktop fan (Yang et al. 2010).

8.2 Integrating with heat pipe unit in PV AHU

In hot and humid climates, the dehumidification of the outdoor air supplied by the HVAC system is more crucial than in temperate climates with regard to energy use (Yau 2007). This is even more significant and challenging with Personalized Ventilation (PV) system that aims to provide clean outdoor air directly to the breathing zone. In this case, additional energy for reheating might become necessary to provide personalized air with acceptable temperature and humidity. By incorporating a heat-pipe unit into the Air Handling Unit (AHU) for the PV system, the energy used to pre-cool and reheat the outdoor air could be saved (Yau 2007, 2008; Sekhar and Chong 2007). This will also enable some of the more challenging conditions of indoor temperature and humidity to be achieved in an energy efficient manner.

The schematic of PV air AHU integrated with heat pipe is shown in Figure 8.1. The outdoor air at condition T1 is pre-cooled by the evaporator section of the heat pipe to T2, which is purely a sensible cooling process and occurs at a constant dew point temperature. The pre-cooled air is then cooled and dehumidified by the cooling coil to condition T3 at a much lower dew point temperature, which is determined by the desired humidity level of the PV supply air in the occupied zones. The overcooled air at T3 is now heated by the condenser section of the heat pipe to T4 and is further heated to T5 by the re-heater if necessary to achieve the desired PV supply air temperature in the room. It is to be noted that the entire process of heating from T3 through T4 and T5 occurs at the same dew point temperature and is a sensible heating process. The desired RH level of the PV supply air can be controlled either by the RH sensor or T3 (off-coil temperature), which controls the modulating valve of the cooling coil. The temperature sensor T5 controls the

PV supply air temperature by controlling the heater. Temperature sensors T1, T2 and T4 are essentially for monitoring purposes and are not involved in any control process. The air flow sensor (AFS) is used to maintain the desired PV air flow quantity by controlling the variable speed drive (VSD) of the PV fan in the air handling unit.

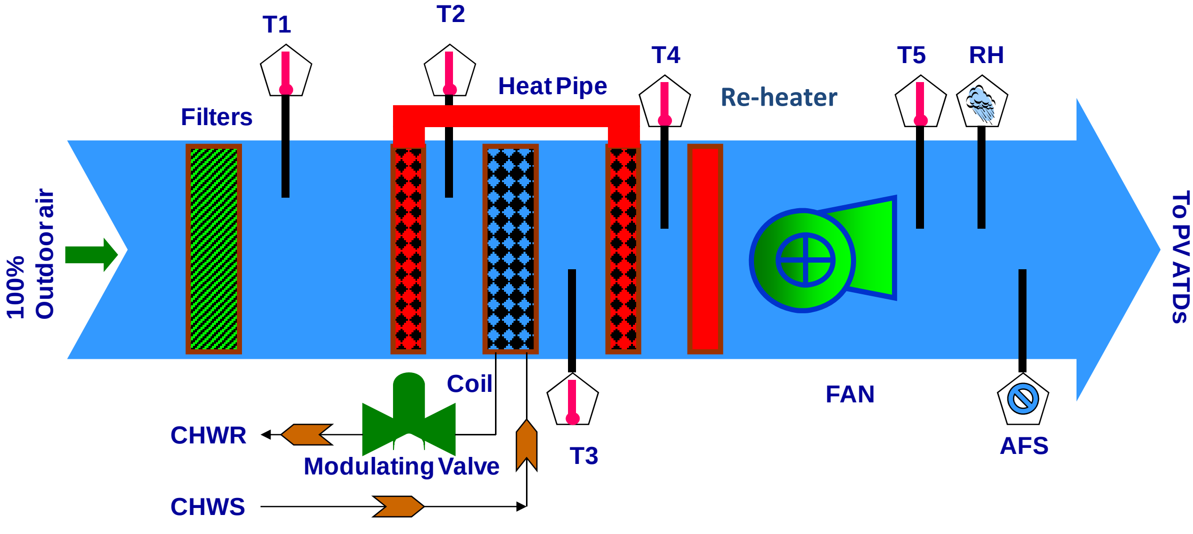


Figure 8.1 Heat pipe integrated Outdoor Air Handling Unit for Personalized Ventilation system

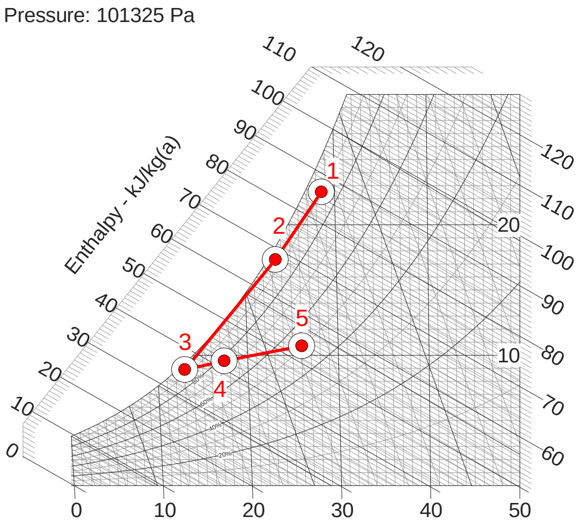
Instead of directly interacting with the cooling coil, the filtered outdoor air passes through the evaporator section of the heat pipe unit and is pre-cooled before entering the cooling coil section. The overcooled and dehumidified outdoor air leaving the cooling coil then interacts with the condenser section of the heat pipe and will be re-heated. Thus, the energy for pre-cooling and reheating of the outdoor air could be saved.

The parameters at the points shown in Figure 8.1 were recorded by BAS system (Figure 5.2b) during the experiments with human subjects and objective measurements (Table 5.1). The average values of those parameters (during the 2.5 hours experimental sessions) are listed in Table 8.2.

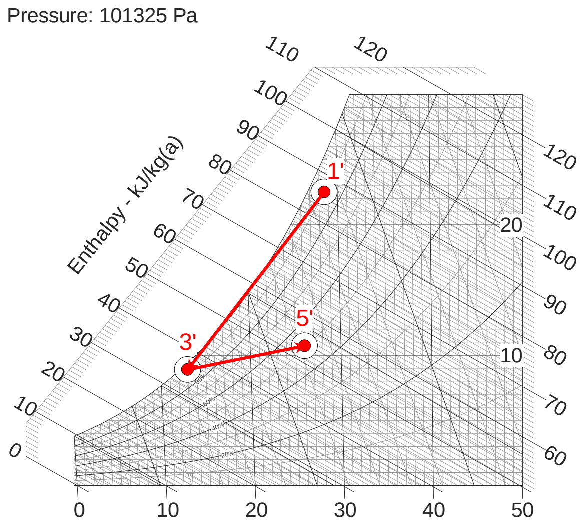
Table 8.2 Parameters measured at the points shown in Figure 8.1

PV=22˚C			PV=26˚C	
T1 (˚C)	29.8		T1 (˚C)	28.6
RH1(%)	82.1		RH1(%)	90.0
T2(˚C)	23.8		T2(˚C)	23.4
T3(˚C)	13.0		T3(˚C)	13.0
T4(˚C)	16.9		T4(˚C)	17.4
T5(˚C)	22.0		T5(˚C)	26.0
RH2(%)	63.2		RH2(%)	50.8
Heater output (kWh)	0.8		Heater output (kWh)	4.2

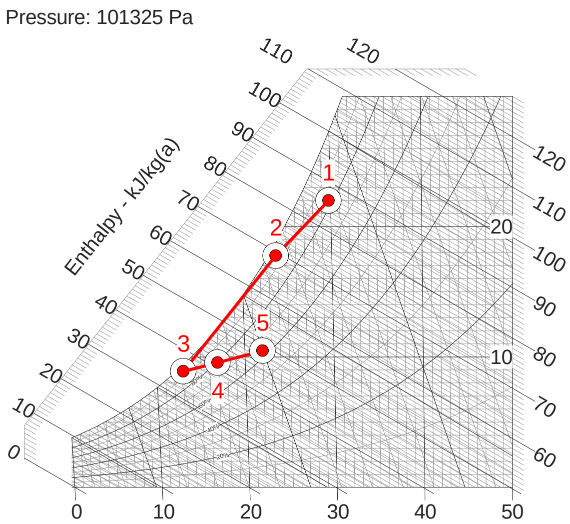
From Table 8.2, it can be found that the heat pipe is able to decrease the outdoor air temperature to 5~6˚C in the pre-cool (evaporator) section and can increase the air temperature after the cooling coil by about 4˚C in the re-heater (condenser) section. When cooler PV supply air temperature was used to serve the occupants, less reheat energy is demanded to reach the 22˚C PV supply air temperature. As had been discussed in Chapter 7, the cooler PV air is more preferred by occupants. Hence cooler PV supply air temperature coupled with the provision for the occupants to choose their preferred PV air flow rate can be recommended for system design and operation. When incorporating with heat pipe, the preferred condition could be achieved by using minimum energy. The process of conditioning the outdoor air is shown in Figure 8.2. To illustrate the energy saving potential of the heat pipe, the performance of PV-AHU is analyzed by a comparison of two different sets of operating characteristics – one without the heat pipe and the other with the heat pipe. (Figure 8.2 a, b, c and d). The energy saving ratio (ε_{HP}) defined in Chapter 5 (Eq. 5.7) is then calculated. The energy saving ratio (ε_{HP}) is the same for the cases with 22 °C and 26 °C PV supply air temperatures. The calculated value of ε_{HP} is 0.356, which indicates the ratio of the energy saving from free cooling and heat recovery to the total energy input was 35.6%.



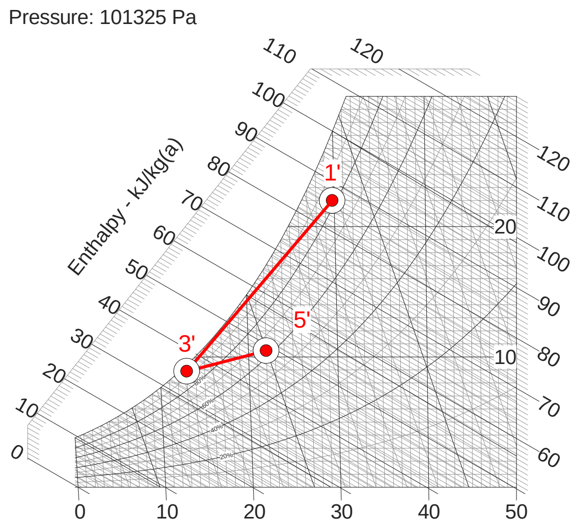
a) PV=26˚C with heat pipe



b) PV=26˚C without heat pipe



c) PV=22˚C with heat pipe



d) PV=22˚C without heat pipe

Figure 8.2 Psychrometric conditions of PV-AHU
a) PV= 26 ˚C with heat pipe, b) PV=26˚C without heat pipe,
c) PV=22˚C with heat pipe, d) PV=22˚C without heat pipe

8.3 Conclusion

Heat removal abilities were found 20% ~40% improved by using UFAD-PV system when compared with that of CSMV system. The UFAD-PV system shows better performance in removing the internal thermal load by using less total volume supply air. The more efficiency with which the system removes the heat in the space the more energy saving could be expected from the fan energy. According to the Fan law, the energy saving from the UFAD system compared with CSMV is between 17 and 28.6% due to the reduced supply air volume. Although additional fan energy is always demanded to deliver PV air through ductwork to occupant's breathing zone, the transport energy of the PV system of current studies show the comparative performance with normal CSMV system, thus the overall fan transport energy of UFAD-PV is not necessarily higher than CSMV and/or UFAD system.

Furthermore, by incorporating the heat-pipe unit into the PV AHU the energy savings from pre-cooling and reheating was up to 35.6% of total energy consumption of the PV AHU when compared with a conventional system that does not employ a heat pipe. Moreover, the most demanding conditions for the PV supply air temperatures could be achieved by using less reheat energy when the heat pipe was involved.

Chapter 9 Conclusions and Recommendation

9.1 Conclusions

In the combined systems of personalized ventilation and total volume ventilation, as described in former studies (Melikov 2004), the air flow near the occupant is affected by the interaction of thermal plume of human body, localized ventilation flow (PV air) and the thermal plume of other heat sources near the occupants. In the present study, the performance of PV in conjunction with UFAD was examined. The physical measurements (temperature, velocity and draft rating distributions and manikin based equivalent temperature) obtained in this study validate the hypotheses for improved thermal comfort in the case of PV in conjunction with UFAD when compared with ceiling supply mixing ventilation system and UFAD system alone. The results of the subjective responses also validate the hypotheses.

- PV air can reduce the uncomfortable "warm head" sensation and can increase the acceptability of PAQ by providing cool and fresh air at the facial level in environment served by UFAD with warmer supply air temperature;
- The warmer supply air temperature of UFAD can reduce the risk of local discomfort due to "cold feet";
- The reduced local thermal discomfort will change the overall thermal sensation and improve overall thermal comfort.

The increased air temperature supplied by the UFAD system decrease the over-cooling of the feet and improved the acceptability of the local thermal sensation. The supply of personalized air from the front provide cooling to the face, the head and the upper body parts and subjects' local thermal sensation and whole body thermal sensation. The acceptability of air movement is increased by using the UFAD-PV when compared with using UFAD alone. The supply of the cooler and cleaner outdoor air directly to the occupants' breathing zone improves the acceptability of PAQ. The subjects' thermal sensation is shown to have a positive linear relationship with the manikin based equivalent temperature in the facial region and a negative linear relationship with DR in the feet region. This implies that cooler PV air would be beneficial for the facial region as it would provide cooler sensation and the warmer UFAD supply air temperature would result in lower Draught Rating and improved thermal sensation at feet. It is also shown that the measured inhaled air quality indices (PEI and PEE) are strongly influenced by PV supply air temperature. The PEI increases with the decrease of PV supply air temperature, i.e. the portion of clean outdoor personalized air in the inhaled air is larger when the supply air is cool. Perceived air freshness, perceived air temperature and acceptability of PAQ improve with the increase of the facial velocity. The impact of air velocity on these parameters was stronger than the impact of PV supply air temperature.

The UFAD-PV system shows better performance in removing the internal thermal load by using less total volume supply air. Furthermore, by incorporating the heat-pipe unit into the PV AHU, the energy savings from pre-cooling and reheating was up to 35.6% of total energy consumption while the most demanding indoor acceptable conditions could be achieved. This finding validates the hypothesis that "Integrating heat pipes with a conventional cooling coil enables the warmer supply air temperature of PV system without compromising dehumidification levels and leads to energy conservation."

9.2 Recommendation

In the present study, the indoor RH level was controlled at 50% (+/- 5%) for all experimental cases. The effect of different humidity level of the ambient on the subjective responses might be worth exploring.

The individual control with larger range of PV air flow rate is also worth studying. The range of PV air flow provided in this study still could not achieve 100% satisfaction. There were cases of those who wanted even less air movement than 0.3m/s (corresponding to 5L/s) and those who wanted more air movement than 0.7m/s (corresponding to 10L/s).

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Appendices

Appendix 1 Questionnaires

Questionnaire 1

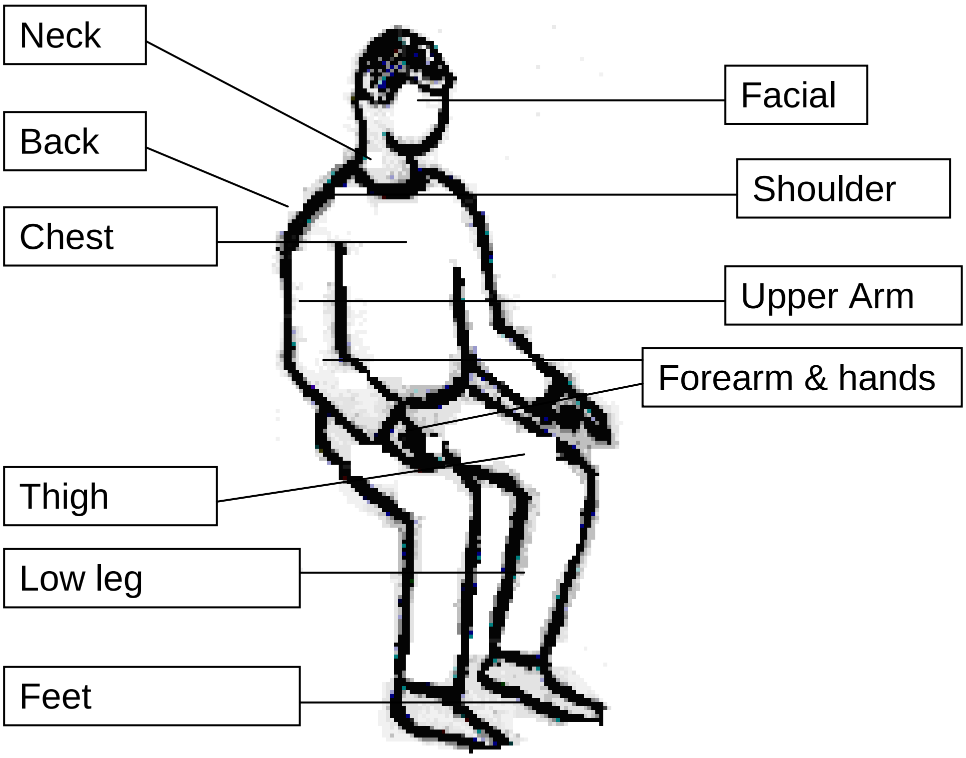
Group Number:

Name:

1. Thermal Sensation

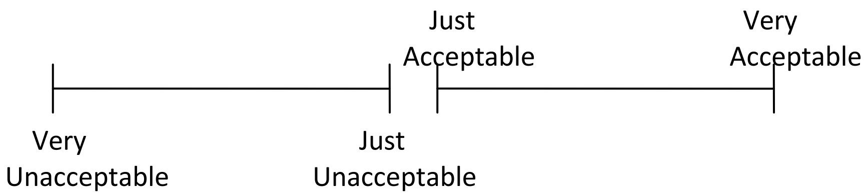
Please select a number in each of the 10 boxes in the diagram below to indicate the thermal sensation of each body section. The 7-value numerical scale to be used appears in the table below:

+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold



Please also assess your thermal sensation for your whole body:

2. Please assess the acceptability of your whole body thermal comfort condition in the following continuous scale. Please do NOT mark between “Just Unacceptable” and “Just acceptable”:

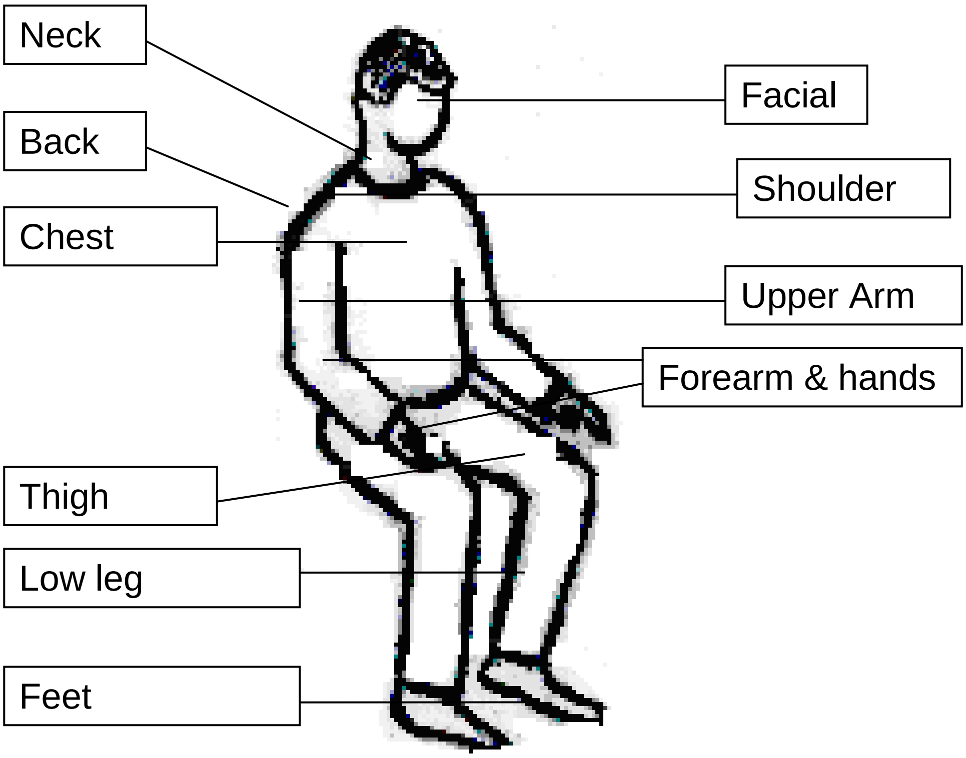


3. Air Movement Perception

Do you feel air movement: yes no

If “yes” please enter a number in each of the 5 boxes in the diagram below to indicate the air movement perception of each body section. The 7-value numerical scale to be used appears in the table below. If you don’t feel any air movement, just choose “No” in the corresponding box.

+3	much too breezy
+2	too breezy
+1	slightly breezy
0	just right
-1	slightly still
-2	too still
-3	much too still



4. Please assess the acceptability of the air movement in the following continuous scale. Please do NOT mark between "Just Unacceptable" and "Just acceptable":

a1. Please assess the acceptability of the air movement on the face part

Just Acceptable | Very Acceptable

Very Unacceptable | Just Unacceptable

a2. Please indicate the change in the air movement preferred on the face part?

☐ Less air movement | ☐ No change | ☐ More air movement

b1. Please assess the acceptability of the air movement on neck

Just Acceptable | Very Acceptable

Very Unacceptable | Just Unacceptable

b2. Please indicate the change in the air movement preferred on neck?

☐ Less air movement | ☐ No change | ☐ More air movement

c1. Please assess the acceptability of the air movement on back

Just Acceptable — Very Acceptable

Very Unacceptable — Just Unacceptable

c2. Please indicate the change in the air movement preferred on back?

☐ Less air movement ☐ No change ☐ More air movement

d1. Please assess the acceptability of the air movement on chest

Just Acceptable — Very Acceptable

Very Unacceptable — Just Unacceptable

d2. Please indicate the change in the air movement preferred on chest?

☐ Less air movement ☐ No change ☐ More air movement

e1. Please assess the acceptability of the air movement on shoulder

Just Acceptable — Very Acceptable

Very Unacceptable — Just Unacceptable

e2. Please indicate the change in the air movement preferred on shoulder?

☐ Less air movement

☐ No change

☐ More air movement

f1. Please assess the acceptability of the air movement on upper arm

Very Unacceptable — Just Unacceptable | Just Acceptable — Very Acceptable

f2. Please indicate the change in the air movement preferred on upper arm?

☐ Less air movement

☐ No change

☐ More air movement

g1. Please assess the acceptability of the air movement on forearm and hands

Very Unacceptable — Just Unacceptable | Just Acceptable — Very Acceptable g2. Please indicate the change in the air movement preferred on forearm and hands?

☐ Less air movement ☐ No change ☐ More air movement

h1. Please assess the acceptability of the air movement on thigh

Very Unacceptable — Just Unacceptable | Just Acceptable — Very Acceptable

h2. Please indicate the change in the air movement preferred on thigh?

☐ Less air movement ☐ No change ☐ More air movement

i1. Please assess the acceptability of the air movement on low leg

Very Unacceptable — Just Unacceptable | Just Acceptable — Very Acceptable

i2. Please indicate the change in the air movement preferred on low leg?

☐ Less air movement ☐ No change ☐ More air movement j1. Please assess the acceptability of the air movement on feet

Just Acceptable | Very Acceptable

Very Unacceptable | Just Unacceptable

j2. Please indicate the change in the air movement preferred on feet?

☐ Less air movement

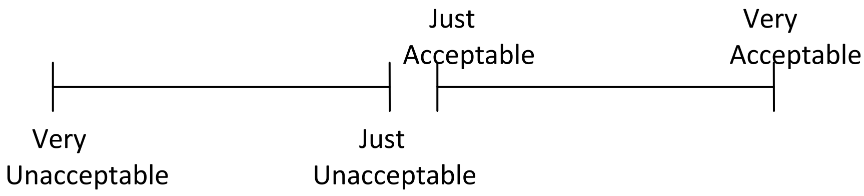
☐ No change

☐ More air movement

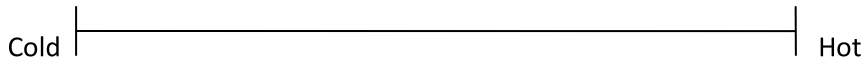
Questionnaire 2

1. Please respond to the following questions:

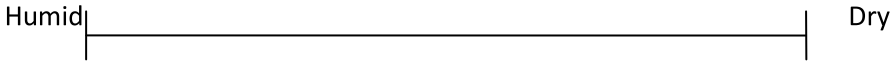
a. Please assess the inhaled air quality (do not mark between “Just Unacceptable” and “Just acceptable”):



b. Please assess the inhaled air temperature:

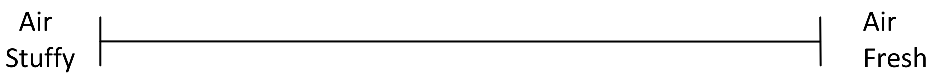


c. Please assess the inhaled air humidity:



d. Please assess the odour of inhaled air:

e. Please assess the freshness of inhaled air:



2. Please respond to the following questions:

Nose Dry	Nose Not Dry
Lips Dry	Lips Not Dry
Eyes Dry	Eyes Not Dry
Severe Headache	No Headache
Difficult To Think	Head Clear
Eyes Aching	Eyes Not Aching
Dizzy	Not Dizzy
Tired	Not Tired
Feeling Bad	Feeling Good

4. Evaluation of noise level:

Dissatisfied — Satisfied

5. Evaluation of lighting level:

Dissatisfied — Satisfied

Questionnaire 3

Please tick which of the following dress you are wearing:

Underwear/ Innerwear	☐ Panties ☐ G strings	☐ Singlet ☐ T-shirt	☐ Shirt with long sleeves ☐ Briefs	☐ Stockings ☐ Bra	
Shirts/Blouses	☐ short sleeves ☐ Long sleeves light weight shirt	☐ Long sleeves normal shirt ☐ Long sleeves flannel shirt	☐ Tube top ☐ Long sleeves light weight blouse	☐ Long sleeves turtleneck blouse	
Trousers	☐ shorts ☐ exercise shorts	☐ Light weight trousers ☐ Normal trousers	☐ Bermudas ☐ Overalls		
Skirts, Dresses	☐ Light skirt, 15cm above knees ☐ Knee-length heavy skirt	☐ Light skirt, 15cm below knee ☐ Long sleeves winter dress	☐ Sleeves light dress		
Socks	☐ Socks	☐ Thick ankle socks ☐ Thick long socks	☐ High insulative fibre-pelt vest ☐ High insulative fibre-pelt jacket		
Shoes	☐ Sandals, mules	☐ Thin soled shoes ☐ Thick soled shoes	☐ Ankle boot ☐ Boots		

If you wear something that you can't find proper description from above, please write here.____
____

Appendix 2 Details of Subjects

Table A2.1 Details of Subjects

Female		Number	Minimum	Maximum	Mean	Std. Error	Std. Deviation
	AGE	15	20	22	21	0.3	0.8
	HEIGHT (m)	15	1.5	1.7	1.6	0.0	0.0
	WEIGHT (kg)	15	45.0	65.0	50.4	2.2	6.2
Male		Number	Minimum	Maximum	Mean	Std. Error	Std. Deviation
	AGE	15	19	24	23	0.6	1.8
	HEIGHT (m)	15	1.6	1.8	1.7	0.0	0.1
	WEIGHT (kg)	15	50.0	82.0	61.0	3.5	9.9
ALL		Number	Minimum	Maximum	Mean	Std. Error	Std. Deviation
	AGE	30	19	24	22	0.4	1.7
	HEIGHT (m)	30	1.5	1.8	1.7	0.0	0.1
	WEIGHT (kg)	30	45.0	82.0	55.8	2.7	10.2

(Std. Error: Standard Error, Std. Deviation: Standard Deviation)

Table A2.2 Number of subjects who choose 5 L/s or 10 L/s

Exp. Condition	Number of Subjects	Number of Female	Number of male
22-26-5	18	9	9
22-26-10	12	6	6
22-22-5	19	11	8
22-22-10	11	4	7
18-26-5	17	10	7
18-26-10	13	5	8
18-22-5	20	13	7
18-22-10	10	2	8

Appendix 3 Statistic of Subjective Responses

Thermal sensation scale: cold = -3, cool = -2, slightly cool = -1, neutral = 0, slightly warm = 1, warm = 2, hot = +3						
thermal sensation (face)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	-2	1	-0.6	0.2	0.7
22-22-10	11	-2	0	-1.0	0.2	0.6
22-26-5	18	-1	1	-0.4	0.1	0.6
22-26-10	12	-1	0	-0.7	0.1	0.5
18-22-5	20	-2	1	-0.8	0.2	0.7
18-22-10	10	-3	0	-1.2	0.3	1.0
18-26-5	17	-2	1	-0.7	0.2	0.8
18-26-10	13	-2	0	-0.9	0.2	0.6
C	30	-2	1	-0.3	0.1	0.6
UV22	30	-1	1	-0.1	0.1	0.5
UV18	30	-2	1	-0.3	0.1	0.6
thermal sensation (back)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	-1	1	-0.1	0.1	0.5
22-22-10	11	-2	1	-0.1	0.3	0.8
22-26-5	18	-1	1	0.0	0.1	0.6
22-26-10	12	-1	1	0.0	0.2	0.6
18-22-5	20	-1	1	0.0	0.1	0.4
18-22-10	10	-2	1	0.0	0.3	0.8
18-26-5	17	-2	1	0.1	0.2	0.8
18-26-10	13	-1	1	-0.1	0.2	0.6
C	30	-2	1	-0.1	0.1	0.6
UV22	30	-1	1	0.0	0.1	0.6
UV18	30	-2	1	-0.1	0.1	0.7
thermal sensation (neck)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	-2	1	-0.3	0.2	0.7
22-22-10	11	-2	0	-0.6	0.2	0.7
22-26-5	18	-1	1	-0.2	0.2	0.6
22-26-10	12	-1	0	-0.6	0.1	0.5
18-22-5	20	-2	1	-0.3	0.2	0.8
18-22-10	10	-2	0	-1.0	0.3	0.9
18-26-5	17	-2	1	-0.2	0.2	0.9
18-26-10	13	-2	0	-0.8	0.2	0.6
C	30	-2	1	-0.3	0.1	0.7
UV22	30	-1	1	-0.1	0.1	0.6
UV18	30	-2	1	-0.2	0.1	0.7
thermal sensation (chest)						

	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	-2	1	-0.3	0.1	0.6
22-22-10	11	-2	0	-0.5	0.2	0.7
22-26-5	18	-1	1	0.0	0.1	0.6
22-26-10	12	-1	0	-0.3	0.1	0.5
18-22-5	20	-2	1	-0.2	0.2	0.7
18-22-10	10	-2	0	-0.4	0.2	0.7
18-26-5	17	-2	1	0.0	0.2	0.9
18-26-10	13	-1	1	-0.3	0.2	0.6
C	30	-2	1	-0.2	0.1	0.7
UV22	30	-2	1	-0.1	0.1	0.7
UV18	30	-2	1	-0.3	0.1	0.7
thermal sensation (shoulder)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	-1	1	-0.3	0.1	0.6
22-22-10	11	-2	0	-0.7	0.2	0.6
22-26-5	18	-1	1	-0.1	0.1	0.6
22-26-10	12	-1	0	-0.4	0.1	0.5
18-22-5	20	-2	1	-0.3	0.2	0.7
18-22-10	10	-2	0	-0.6	0.2	0.7
18-26-5	17	-2	1	-0.1	0.2	0.7
18-26-10	13	-1	0	-0.6	0.1	0.5
C	30	-2	1	-0.3	0.1	0.6
UV22	30	-1	1	-0.2	0.1	0.6
UV18	30	-2	1	-0.2	0.1	0.7
thermal sensation (upper arm)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	-2	1	-0.5	0.2	0.7
22-22-10	11	-2	0	-0.6	0.2	0.7
22-26-5	18	-1	1	-0.1	0.1	0.5
22-26-10	12	-1	0	-0.3	0.1	0.5
18-22-5	20	-2	1	-0.4	0.2	0.7
18-22-10	10	-2	0	-0.4	0.2	0.7
18-26-5	17	-2	1	-0.3	0.2	0.8
18-26-10	13	-1	0	-0.5	0.1	0.5
C	30	-2	1	-0.4	0.1	0.7
UV22	30	-2	1	-0.2	0.1	0.7
UV18	30	-2	1	-0.4	0.1	0.6
thermal sensation (forearm and hands)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	-1	1	-0.3	0.1	0.6
22-22-10	11	-2	0	-0.8	0.2	0.6
22-26-5	18	-2	1	-0.2	0.2	0.7
22-26-10	12	-1	1	-0.3	0.2	0.6
18-22-5	20	-2	1	-0.4	0.2	0.8

18-22-10	10	-2	0	-0.6	0.2	0.7
18-26-5	17	-2	1	-0.3	0.2	0.8
18-26-10	13	-1	0	-0.5	0.1	0.5
C	30	-2	1	-0.5	0.1	0.7
UV22	30	-1	1	-0.1	0.1	0.6
UV18	30	-2	1	-0.5	0.2	0.8
thermal sensation (thigh)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	-1	1	-0.1	0.1	0.5
22-22-10	11	-2	2	0.1	0.3	0.9
22-26-5	18	-1	1	0.1	0.1	0.5
22-26-10	12	-1	2	0.2	0.2	0.8
18-22-5	20	-2	1	-0.2	0.1	0.6
18-22-10	10	-2	1	0.0	0.3	0.8
18-26-5	17	-2	2	0.1	0.2	0.8
18-26-10	13	-1	2	0.0	0.2	0.7
C	30	-2	2	0.0	0.1	0.6
UV22	30	-2	2	0.0	0.1	0.7
UV18	30	-2	2	0.0	0.2	0.8
thermal sensation (low leg)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	-1	1	-0.3	0.1	0.6
22-22-10	11	-2	1	-0.2	0.2	0.8
22-26-5	18	-1	1	-0.1	0.1	0.6
22-26-10	12	-1	2	0.0	0.2	0.9
18-22-5	20	-2	1	-0.2	0.2	0.8
18-22-10	10	-2	1	-0.1	0.2	0.7
18-26-5	17	-2	2	0.0	0.2	0.8
18-26-10	13	-1	1	-0.2	0.2	0.6
C	30	-2	1	-0.2	0.1	0.6
UV22	30	-2	1	-0.1	0.1	0.7
UV18	30	-2	1	-0.4	0.1	0.7
thermal sensation (feet)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	-1	1	-0.4	0.1	0.6
22-22-10	11	-2	2	-0.5	0.3	1.1
22-26-5	18	-1	1	-0.2	0.2	0.8
22-26-10	12	-1	2	-0.1	0.3	1.2
18-22-5	20	-3	1	-0.7	0.2	1.0
18-22-10	10	-2	0	-0.6	0.2	0.7
18-26-5	17	-2	1	-0.4	0.2	0.8
18-26-10	13	-1	1	-0.5	0.2	0.7
C	30	-1	1	-0.4	0.1	0.6
UV22	30	-2	1	-0.2	0.2	0.8
UV18	30	-2	1	-0.7	0.2	0.8

thermal sensation (whole body)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	-2	1	-0.5	0.2	0.8
22-22-10	11	-2	0	-0.8	0.2	0.8
22-26-5	18	-1	1	-0.4	0.2	0.7
22-26-10	12	-1	0	-0.8	0.1	0.5
18-22-5	20	-2	1	-0.7	0.2	0.9
18-22-10	10	-2	0	-0.8	0.2	0.6
18-26-5	17	-2	1	-0.4	0.2	1.0
18-26-10	13	-2	0	-0.8	0.2	0.6
C	30	-2	1	-0.6	0.1	0.7
UV22	30	-2	1	-0.3	0.1	0.7
UV18	30	-2	1	-0.4	0.1	0.7
Whole body thermal comfort acceptability: 0 (very unacceptable) ~ 100 (very acceptable), with an interval in between 50 (just unacceptable) and 50 (just acceptable)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	53	100	85.3	3.5	15.7
22-22-10	11	55	100	85.5	4.4	14.7
22-26-5	18	45	100	78.9	3.5	14.8
22-26-10	12	44	100	82.0	4.7	16.4
18-22-5	20	27	100	82.7	4.1	18.6
18-22-10	10	68	100	85.4	3.9	12.2
18-26-5	17	53	100	82.7	3.0	12.7
18-26-10	13	61	100	87.8	4.1	14.9
C	30	50	100	78.0	3.0	15.8
UV22	30	25	100	74.5	4.4	22.5
UV18	30	53	100	77.2	3.1	15.7

Perception of air movement: +3 Much too air movement; +2 Too breezy; +1 Slightly breezy; 0 Just right; -1 Slightly still; -2 Too still; -3 Much too still						
perception of air movement (face)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	-1	2	0.6	0.2	0.7
22-22-10	11	0	1	0.5	0.2	0.5
22-26-5	18	0	1	0.6	0.1	0.5
22-26-10	12	0	1	0.5	0.2	0.5
18-22-5	20	-1	1	0.5	0.1	0.6
18-22-10	10	0	1	0.4	0.2	0.5
18-26-5	17	-2	1	0.2	0.2	0.8
18-26-10	13	0	2	0.8	0.2	0.7
C	30	-1	1	0.1	0.1	0.5
UV22	30	0	1	0.1	0.1	0.3
UV18	30	-1	1	-0.1	0.1	0.5

perception of air movement (back)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	-1	1	-0.1	0.1	0.6
22-22-10	11	-1	1	0.0	0.1	0.4
22-26-5	18	-1	1	-0.2	0.2	0.6
22-26-10	12	-1	0	-0.3	0.1	0.5
18-22-5	20	-3	3	0.1	0.2	1.0
18-22-10	10	-1	0	-0.2	0.1	0.4
18-26-5	17	-3	0	-0.5	0.2	0.9
18-26-10	13	-1	0	-0.2	0.1	0.4
C	30	-1	3	1.2	0.3	1.5
UV22	30	-1	3	1.5	0.3	1.6
UV18	30	-1	3	1.0	0.3	1.7
perception of air movement (neck)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	-1	2	0.2	0.2	0.7
22-22-10	11	0	1	0.4	0.2	0.5
22-26-5	18	-1	1	0.2	0.1	0.6
22-26-10	12	0	1	0.4	0.1	0.5
18-22-5	20	-3	3	0.0	0.3	1.2
18-22-10	10	-2	1	0.2	0.3	0.9
18-26-5	17	-3	0	-0.3	0.2	0.8
18-26-10	13	0	1	0.6	0.1	0.5
C	30	-1	3	1.2	0.3	1.5
UV22	30	-1	3	1.5	0.3	1.6
UV18	30	-1	3	1.1	0.3	1.6
perception of air movement (chest)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	-1	1	-0.1	0.1	0.6
22-22-10	11	0	1	0.3	0.1	0.5
22-26-5	18	-1	1	0.0	0.1	0.5
22-26-10	12	-1	1	0.1	0.1	0.5
18-22-5	20	-3	3	0.1	0.2	1.1
18-22-10	10	-1	1	0.2	0.2	0.6
18-26-5	17	-3	0	-0.4	0.2	0.9
18-26-10	13	0	1	0.2	0.1	0.4
C	30	-1	1	0.0	0.1	0.4
UV22	30	-1	1	-0.1	0.1	0.5
UV18	30	-1	1	-0.2	0.1	0.6
perception of air movement (shoulder)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	-1	1	0.1	0.1	0.6
22-22-10	11	0	1	0.3	0.1	0.5
22-26-5	18	-1	1	0.0	0.1	0.5
22-26-10	12	-1	1	0.1	0.1	0.5

18-22-5	20	-3	3	0.2	0.2	1.1
18-22-10	10	-1	1	0.2	0.2	0.6
18-26-5	17	-3	1	-0.3	0.2	0.9
18-26-10	13	0	1	0.3	0.1	0.5
C	30	-1	1	0.0	0.1	0.4
UV22	30	-1	0	-0.1	0.1	0.3
UV18	30	-1	1	-0.1	0.2	0.6
perception of air movement (upper arm)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	-1	1	0.1	0.1	0.4
22-22-10	11	-1	1	0.1	0.2	0.5
22-26-5	18	-1	1	-0.1	0.1	0.5
22-26-10	12	-1	1	0.1	0.1	0.5
18-22-5	20	-2	3	0.2	0.2	0.9
18-22-10	10	-1	1	0.2	0.2	0.6
18-26-5	17	-2	1	-0.3	0.2	0.8
18-26-10	13	0	1	0.2	0.1	0.4
C	30	0	1	0.1	0.1	0.3
UV22	30	0	0	0.0	0.0	0.0
UV18	30	-1	1	0.1	0.1	0.5
perception of air movement (forearm and hands)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	-1	1	0.1	0.1	0.4
22-22-10	11	0	1	0.2	0.1	0.4
22-26-5	18	-1	1	-0.1	0.1	0.5
22-26-10	12	-1	1	0.1	0.1	0.5
18-22-5	20	-1	3	0.4	0.2	0.9
18-22-10	10	-1	1	0.1	0.2	0.6
18-26-5	17	-2	1	-0.2	0.2	0.6
18-26-10	13	0	1	0.2	0.1	0.4
C	30	0	1	0.3	0.1	0.4
UV22	30	0	0	0.0	0.0	0.0
UV18	30	0	1	0.1	0.1	0.4
perception of air movement (thigh)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	-1	1	-0.1	0.1	0.5
22-22-10	11	-1	0	-0.3	0.1	0.5
22-26-5	18	-2	1	-0.3	0.2	0.7
22-26-10	12	-2	0	-0.3	0.2	0.7
18-22-5	20	-3	3	0.1	0.2	1.0
18-22-10	10	-2	0	-0.3	0.2	0.7
18-26-5	17	-3	0	-0.4	0.2	0.9
18-26-10	13	-1	1	-0.2	0.2	0.6
C	30	-1	0	-0.1	0.1	0.2
UV22	30	-1	0	-0.2	0.1	0.4

UV18	30	-1	1	0.1	0.1	0.5
perception of air movement (low leg)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	-2	1	-0.1	0.2	0.7
22-22-10	11	-1	0	-0.2	0.1	0.4
22-26-5	18	-1	1	-0.2	0.1	0.5
22-26-10	12	-2	0	-0.4	0.2	0.7
18-22-5	20	-3	3	0.2	0.2	1.1
18-22-10	10	-2	1	-0.2	0.2	0.8
18-26-5	17	-3	0	-0.5	0.2	0.9
18-26-10	13	-1	1	-0.1	0.1	0.5
C	30	-1	1	0.0	0.1	0.4
UV22	30	-1	0	-0.2	0.1	0.4
UV18	30	-1	1	0.0	0.1	0.5
perception of air movement (feet)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	-2	1	-0.1	0.2	0.7
22-22-10	11	-1	0	-0.2	0.1	0.4
22-26-5	18	-1	1	-0.2	0.1	0.5
22-26-10	12	-2	0	-0.4	0.2	0.8
18-22-5	20	-3	3	0.0	0.2	1.1
18-22-10	10	-2	0	-0.3	0.2	0.7
18-26-5	17	-3	0	-0.5	0.2	0.9
18-26-10	13	-1	1	-0.1	0.1	0.5
C	30	-1	1	0.0	0.1	0.3
UV22	30	-1	0	-0.2	0.1	0.4
UV18	30	-1	1	0.0	0.1	0.6

Acceptability of air movement: 0 (very unacceptable) ~ 100 (very acceptable), with an interval in between 50 (just unacceptable) and 50 (just acceptable)						
acceptability of air movement (face)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	36	100	83.3	3.7	16.7
22-22-10	11	50	100	82.6	4.9	16.3
22-26-5	18	44	100	79.8	4.4	18.6
22-26-10	12	46	100	82.8	4.9	16.9
18-22-5	20	46	100	83.0	3.9	18.0
18-22-10	10	50	100	85.2	4.8	15.3
18-26-5	17	24	100	77.5	4.9	21.0
18-26-10	13	53	100	83.2	4.4	15.9
C	30	49	99	72.1	3.6	17.3
UV22	30	12	100	71.2	5.1	25.8
UV18	30	45	100	76.0	4.0	19.8

acceptability of air movement (back)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	42	100	78.5	4.7	20.9
22-22-10	11	50	100	81.6	5.2	17.4
22-26-5	18	36	100	73.4	4.9	20.6
22-26-10	12	39	100	73.9	5.7	19.6
18-22-5	20	26	100	81.4	4.8	22.1
18-22-10	10	50	100	76.9	4.5	14.2
18-26-5	17	20	100	73.6	5.9	25.0
18-26-10	13	55	100	76.8	4.3	15.4
C	30	48	100	76.6	3.8	20.3
UV22	30	9	100	70.2	5.2	26.3
UV18	30	23	100	74.1	4.4	22.2
acceptability of air movement (neck)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	52	100	83.2	4.0	17.7
22-22-10	11	50	100	81.8	5.4	17.9
22-26-5	18	33	100	77.9	4.9	20.9
22-26-10	12	50	100	81.7	4.9	17.0
18-22-5	20	33	100	81.7	4.5	20.7
18-22-10	10	50	100	82.4	4.8	15.0
18-26-5	17	6	100	74.3	6.1	26.0
18-26-10	13	58	100	82.5	3.8	13.8
C	30	1	100	72.7	4.5	23.7
UV22	30	6	100	68.6	5.3	26.9
UV18	30	31	100	73.1	4.3	21.4
acceptability of air movement (chest)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	37	100	78.9	4.5	20.3
22-22-10	11	66	100	87.4	3.6	12.0
22-26-5	18	35	100	75.0	4.8	20.2
22-26-10	12	50	100	80.8	4.8	16.6
18-22-5	20	28	100	81.1	4.6	21.3
18-22-10	10	23	96	75.4	6.7	21.3
18-26-5	17	14	100	74.3	6.2	26.1
18-26-10	13	56	100	81.2	4.4	16.0
C	30	50	100	76.6	3.7	19.6
UV22	30	11	100	69.5	5.2	26.4
UV18	30	39	100	74.1	4.3	21.5
acceptability of air movement (shoulder)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	53	100	83.9	3.9	17.4
22-22-10	11	43	97	80.4	5.9	19.6
22-26-5	18	43	100	77.8	4.3	18.2
22-26-10	12	50	100	79.8	5.3	18.3

18-22-5	20	25	100	79.9	4.6	21.2
18-22-10	10	50	100	83.8	4.6	14.5
18-26-5	17	17	100	75.6	6.0	25.6
18-26-10	13	58	100	81.4	4.2	15.0
C	30	50	100	76.2	3.7	19.8
UV22	30	9	100	70.7	5.1	26.0
UV18	30	29	100	74.6	4.4	22.0
acceptability of air movement (upper arm)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	53	100	83.2	3.8	17.0
22-22-10	11	34	100	81.0	6.7	22.3
22-26-5	18	41	100	78.5	4.5	19.3
22-26-10	12	50	100	82.4	4.9	17.0
18-22-5	20	30	100	80.3	4.5	20.5
18-22-10	10	50	100	83.5	5.2	16.4
18-26-5	17	18	100	75.5	6.1	25.9
18-26-10	13	56	100	84.1	3.7	13.3
C	30	50	100	79.0	3.6	18.8
UV22	30	0	100	71.9	5.9	30.0
UV18	30	39	100	77.6	3.9	19.7
acceptability of air movement (forearm and hands)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	33	100	79.2	4.6	20.7
22-22-10	11	50	100	87.1	4.9	16.3
22-26-5	18	38	100	73.9	4.7	19.9
22-26-10	12	50	100	80.8	5.0	17.4
18-22-5	20	50	100	83.7	3.8	17.3
18-22-10	10	50	100	80.7	4.9	15.6
18-26-5	17	15	100	78.8	5.3	22.4
18-26-10	13	59	100	85.0	4.0	14.5
C	30	39	100	77.5	3.7	19.7
UV22	30	7	100	73.3	5.4	27.8
UV18	30	44	100	77.3	3.9	19.7
acceptability of air movement (thigh)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	37	100	80.7	4.5	20.2
22-22-10	11	36	100	75.6	6.8	22.6
22-26-5	18	23	100	73.9	5.4	22.9
22-26-10	12	36	100	72.8	7.0	24.1
18-22-5	20	30	100	80.2	4.6	21.1
18-22-10	10	32	100	70.7	7.8	24.6
18-26-5	17	30	100	77.6	5.5	23.3
18-26-10	13	50	100	78.9	4.2	15.3
C	30	50	100	77.6	3.8	20.1
UV22	30	12	100	71.5	5.2	26.6

UV18	30	41	100	76.1	4.0	20.0
acceptability of air movement (low leg)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	52	100	83.3	3.9	17.6
22-22-10	11	38	100	77.1	6.8	22.5
22-26-5	18	42	100	76.7	4.4	18.7
22-26-10	12	35	100	73.1	7.3	25.2
18-22-5	20	25	100	80.4	4.8	22.0
18-22-10	10	17	100	68.1	8.3	26.1
18-26-5	17	25	100	76.1	5.5	23.5
18-26-10	13	50	100	76.8	4.4	16.0
C	30	50	100	77.6	3.6	19.0
UV22	30	10	100	72.1	5.2	26.6
UV18	30	38	100	75.8	3.9	19.4
acceptability of air movement (feet)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	34	100	80.3	4.3	19.2
22-22-10	11	50	100	81.7	5.7	18.9
22-26-5	18	39	100	73.7	4.7	20.0
22-26-10	12	14	100	70.4	8.0	27.8
18-22-5	20	20	100	78.2	5.0	23.1
18-22-10	10	7	100	64.6	8.4	26.4
18-26-5	17	19	100	68.3	6.1	26.0
18-26-10	13	50	100	78.2	4.2	15.1
C	30	9	100	74.0	4.3	22.9
UV22	30	65	100	84.1	2.5	11.1
UV18	30	41	100	75.8	4.1	20.3

Preference for air movement: +1 more air movement; 0 no change; -1 less air movement						
preference for air movement (face)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	-1	1	-0.2	0.1	0.5
22-22-10	11	-1	1	0.0	0.1	0.4
22-26-5	18	-1	1	-0.1	0.1	0.5
22-26-10	12	0	1	0.1	0.1	0.3
18-22-5	20	-1	0	-0.1	0.1	0.3
18-22-10	10	0	0	0.0	0.0	0.0
18-26-5	17	-1	1	-0.1	0.1	0.5
18-26-10	13	-1	0	-0.2	0.1	0.4
C	30	0	1	0.3	0.1	0.4
UV22	30	0	1	0.4	0.1	0.5
UV18	30	0	1	0.4	0.1	0.5
preference for air movement (back)						

	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	0	1	0.2	0.1	0.4
22-22-10	11	0	1	0.3	0.1	0.5
22-26-5	18	0	1	0.4	0.1	0.5
22-26-10	12	0	1	0.3	0.1	0.5
18-22-5	20	0	1	0.1	0.1	0.4
18-22-10	10	0	1	0.2	0.1	0.4
18-26-5	17	-1	1	0.3	0.1	0.6
18-26-10	13	0	1	0.2	0.1	0.4
C	30	0	1	0.3	0.1	0.5
UV22	30	0	1	0.5	0.1	0.5
UV18	30	0	1	0.4	0.1	0.5
preference for air movement (neck)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	0	1	0.2	0.1	0.4
22-22-10	11	0	1	0.2	0.1	0.4
22-26-5	18	0	1	0.3	0.1	0.5
22-26-10	12	-1	1	0.1	0.1	0.5
18-22-5	20	0	1	0.0	0.0	0.2
18-22-10	10	0	1	0.1	0.1	0.3
18-26-5	17	0	1	0.2	0.1	0.4
18-26-10	13	0	1	0.1	0.1	0.3
C	30	0	1	0.3	0.1	0.5
UV22	30	0	1	0.5	0.1	0.5
UV18	30	0	1	0.4	0.1	0.5
preference for air movement (chest)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	0	1	0.2	0.1	0.4
22-22-10	11	0	1	0.2	0.1	0.4
22-26-5	18	0	1	0.4	0.1	0.5
22-26-10	12	0	1	0.1	0.1	0.3
18-22-5	20	0	1	0.1	0.1	0.3
18-22-10	10	-1	1	0.0	0.1	0.5
18-26-5	17	0	1	0.3	0.1	0.5
18-26-10	13	0	1	0.1	0.1	0.3
C	30	0	1	0.3	0.1	0.4
UV22	30	0	1	0.5	0.1	0.5
UV18	30	0	1	0.4	0.1	0.5
preference for air movement (shoulder)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	0	1	0.1	0.1	0.3
22-22-10	11	0	1	0.2	0.1	0.4
22-26-5	18	0	1	0.2	0.1	0.4
22-26-10	12	0	1	0.2	0.1	0.4
18-22-5	20	0	1	0.0	0.0	0.2

18-22-10	10	0	1	0.1	0.1	0.3
18-26-5	17	0	1	0.1	0.1	0.3
18-26-10	13	0	1	0.1	0.1	0.3
C	30	0	1	0.3	0.1	0.4
UV22	30	0	1	0.5	0.1	0.5
UV18	30	0	1	0.4	0.1	0.5
preference for air movement (upper arm)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	0	1	0.1	0.1	0.2
22-22-10	11	0	1	0.1	0.1	0.3
22-26-5	18	0	1	0.2	0.1	0.4
22-26-10	12	0	1	0.1	0.1	0.3
18-22-5	20	0	1	0.0	0.0	0.2
18-22-10	10	0	0	0.0	0.0	0.0
18-26-5	17	-1	1	0.1	0.1	0.4
18-26-10	13	0	0	0.0	0.0	0.0
C	30	0	1	0.2	0.1	0.4
UV22	30	0	1	0.4	0.1	0.5
UV18	30	0	1	0.2	0.1	0.4
preference for air movement (forearm and hands)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	0	1	0.1	0.1	0.3
22-22-10	11	-1	1	0.0	0.1	0.4
22-26-5	18	-1	1	0.2	0.1	0.5
22-26-10	12	0	1	0.1	0.1	0.3
18-22-5	20	-1	1	0.0	0.1	0.4
18-22-10	10	0	0	0.0	0.0	0.0
18-26-5	17	-1	1	0.1	0.1	0.5
18-26-10	13	0	0	0.0	0.0	0.0
C	30	-1	1	0.1	0.1	0.4
UV22	30	0	1	0.4	0.1	0.5
UV18	30	-1	1	0.2	0.1	0.5
preference for air movement (thigh)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	0	1	0.1	0.1	0.3
22-22-10	11	0	1	0.2	0.1	0.4
22-26-5	18	0	1	0.3	0.1	0.5
22-26-10	12	0	1	0.3	0.1	0.5
18-22-5	20	0	1	0.0	0.0	0.2
18-22-10	10	0	1	0.3	0.2	0.5
18-26-5	17	0	1	0.1	0.1	0.3
18-26-10	13	0	1	0.1	0.1	0.3
C	30	0	1	0.3	0.1	0.4
UV22	30	0	1	0.5	0.1	0.5
UV18	30	0	1	0.3	0.1	0.5

preference for air movement (low leg)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	0	1	0.2	0.1	0.4
22-22-10	11	0	1	0.2	0.1	0.4
22-26-5	18	-1	1	0.2	0.1	0.5
22-26-10	12	0	1	0.3	0.1	0.5
18-22-5	20	0	1	0.1	0.1	0.3
18-22-10	10	0	1	0.3	0.2	0.5
18-26-5	17	-1	1	0.1	0.1	0.5
18-26-10	13	0	1	0.2	0.1	0.4
C	30	0	1	0.2	0.1	0.4
UV22	30	0	1	0.4	0.1	0.5
UV18	30	0	1	0.3	0.1	0.5
preference for air movement (feet)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	0	1	0.1	0.1	0.3
22-22-10	11	0	1	0.2	0.1	0.4
22-26-5	18	-1	1	0.1	0.1	0.6
22-26-10	12	0	1	0.3	0.1	0.5
18-22-5	20	-1	1	-0.1	0.1	0.4
18-22-10	10	0	1	0.3	0.2	0.5
18-26-5	17	-1	1	0.1	0.1	0.5
18-26-10	13	0	1	0.1	0.1	0.3
C	30	-1	1	0.1	0.1	0.5
UV22	30	0	1	0.4	0.1	0.5
UV18	30	0	1	0.2	0.1	0.4

Acceptability of perceived air quality: 0 (very unacceptable) ~ 100 (very acceptable), with an interval in between 50 (just unacceptable) and 50 (just acceptable)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	54	100	78.7	3.5	15.7
22-22-10	11	60	100	87.8	4.3	14.3
22-26-5	18	55	94	76.3	3.0	12.7
22-26-10	12	66	100	87.5	3.5	12.1
18-22-5	20	50	100	83.7	3.4	15.7
18-22-10	10	60	100	83.7	5.8	18.2
18-26-5	17	33	100	80.4	4.5	19.0
18-26-10	13	45	100	81.3	5.2	18.7
C	30	49	100	81.1	3.0	15.9
UV22	30	40	100	77.4	3.9	20.0
UV18	30	50	100	80.1	3.3	16.7
Perceived inhaled air temperature: 0 (cold) ~ 100 (hot)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation

22-22-5	19	9	72	36.8	3.6	16.0
22-22-10	11	14	50	34.0	3.2	10.5
22-26-5	18	20	71	39.8	2.7	11.6
22-26-10	12	23	50	34.4	2.8	9.6
18-22-5	20	9	63	36.1	3.0	13.9
18-22-10	10	19	50	33.1	2.9	9.3
18-26-5	17	9	70	37.9	4.0	16.9
18-26-10	13	15	58	32.5	3.0	10.7
C	30	9	67	38.8	2.5	13.3
UV22	30	13	61	41.4	2.5	12.5
UV18	30	3	66	38.5	3.1	15.5
Perceived inhaled air humidity: 0 (humid) ~ 100 (dry)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	42	90	59.7	3.0	13.6
22-22-10	11	21	68	54.5	4.3	14.3
22-26-5	18	41	90	62.2	3.1	13.0
22-26-10	12	26	88	59.5	5.1	17.8
18-22-5	20	37	91	58.4	2.7	12.5
18-22-10	10	50	77	62.7	3.0	9.6
18-26-5	17	35	91	58.7	3.6	15.5
18-26-10	13	37	75	59.5	3.4	12.4
C	30	34	89	57.4	2.3	12.4
UV22	30	32	84	56.6	2.1	10.7
UV18	30	50	84	60.9	2.0	9.9
Perceived inhaled air odour: 0 (No odour) ~ 100 (Overwhelming odour)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	0	42	8.8	2.5	11.1
22-22-10	11	0	44	8.6	4.8	15.9
22-26-5	18	0	44	10.1	3.3	14.0
22-26-10	12	0	46	7.3	4.2	14.5
18-22-5	20	0	50	10.0	3.5	16.0
18-22-10	10	0	43	7.6	5.1	16.2
18-26-5	17	0	61	12.5	4.5	19.1
18-26-10	13	0	55	10.2	5.4	19.3
C	30	0	50	10.1	2.6	14.0
UV22	30	0	60	7.8	2.8	14.1
UV18	30	0	72	11.2	3.6	18.2
Perceived inhaled air freshness: 0 (stuffy) ~ 100 (fresh)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	41	100	74.0	4.9	21.8
22-22-10	11	50	100	87.5	4.9	16.1
22-26-5	18	23	100	73.7	5.6	23.6
22-26-10	12	47	100	86.2	4.6	15.9
18-22-5	20	50	100	82.7	4.2	19.4
18-22-10	10	50	100	83.0	6.4	20.3

18-26-5	17	32	100	73.0	6.1	26.1
18-26-10	13	35	100	77.2	7.0	25.4
C	30	8	100	73.2	4.8	25.4
UV22	30	16	100	71.4	5.4	27.6
UV18	30	21	100	69.2	5.3	26.4
Dry nose: 0 (Nose dry) ~ 100 (Nose not dry)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	16	100	64.7	5.9	26.3
22-22-10	11	28	100	59.5	8.3	27.6
22-26-5	18	7	100	63.5	6.9	29.1
22-26-10	12	34	100	61.7	7.4	25.7
18-22-5	20	25	100	67.1	5.7	26.3
18-22-10	10	17	70	43.6	5.1	16.1
18-26-5	17	30	100	72.5	6.2	26.5
18-26-10	13	16	82	47.4	5.8	20.9
C	30	21	100	61.4	5.2	27.5
UV22	30	30	100	64.3	4.7	24.0
UV18	30	16	100	60.7	5.3	26.7
Dry lips: 0 (lips dry) ~ 100 (lips not dry)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	13	100	58.0	6.9	31.0
22-22-10	11	26	100	52.1	8.1	26.9
22-26-5	18	16	100	57.6	7.4	31.4
22-26-10	12	33	100	63.8	8.4	29.0
18-22-5	20	19	100	60.0	6.0	27.6
18-22-10	10	31	74	46.5	5.3	16.7
18-26-5	17	21	100	66.5	6.9	29.1
18-26-10	13	14	91	46.2	6.0	21.8
C	30	12	100	54.5	5.1	26.9
UV22	30	27	100	56.5	5.1	25.8
UV18	30	10	100	51.0	5.6	27.8
Dry eyes: 0 (eyes dry) ~ 100 (eyes not dry)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	9	100	61.3	5.7	25.6
22-22-10	11	25	100	65.3	8.2	27.2
22-26-5	18	15	100	59.2	6.5	27.6
22-26-10	12	34	100	76.1	6.9	23.9
18-22-5	20	34	100	69.8	5.5	25.3
18-22-10	10	15	80	44.3	6.5	20.4
18-26-5	17	26	100	69.7	6.8	28.7
18-26-10	13	15	98	51.5	7.5	26.9
C	30	20	100	67.9	5.0	26.4
UV22	30	28	100	68.4	5.0	25.6
UV18	30	16	100	65.2	5.4	27.0
Headache: 0 (severe headache) ~ 100 (no dry)						

	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	32	100	85.1	4.8	21.5
22-22-10	11	75	100	93.0	2.7	8.8
22-26-5	18	47	100	90.1	4.0	17.0
22-26-10	12	82	100	95.7	1.8	6.3
18-22-5	20	49	100	89.5	3.8	17.5
18-22-10	10	83	100	97.0	2.0	6.4
18-26-5	17	31	100	91.3	4.0	17.1
18-26-10	13	41	100	90.0	4.7	17.0
C	30	48	100	89.8	2.7	14.2
UV22	30	51	100	91.7	2.6	13.4
UV18	30	48	100	91.4	2.9	14.4
Difficult to think: 0 (difficult to think) ~ 100 (head clear)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	53	100	91.9	2.9	12.8
22-22-10	11	70	100	91.6	3.1	10.3
22-26-5	18	50	100	88.9	3.7	15.5
22-26-10	12	39	100	88.4	5.1	17.8
18-22-5	20	50	100	89.0	3.8	17.5
18-22-10	10	84	100	94.8	2.0	6.4
18-26-5	17	50	100	90.9	3.7	15.7
18-26-10	13	36	100	83.2	5.7	20.5
C	30	50	100	88.0	2.8	14.7
UV22	30	50	100	89.7	2.9	14.9
UV18	30	53	100	90.7	2.4	12.2
Eyes aching: 0 (eyes aching) ~ 100 (eyes not aching)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	11	100	76.4	5.5	24.6
22-22-10	11	46	100	89.0	5.0	16.7
22-26-5	18	33	100	75.6	5.8	24.6
22-26-10	12	50	100	88.1	4.7	16.3
18-22-5	20	28	100	76.2	5.5	25.0
18-22-10	10	43	100	80.9	6.0	18.9
18-26-5	17	39	100	79.8	5.3	22.4
18-26-10	13	45	100	79.5	6.1	21.9
C	30	30	100	80.5	3.9	20.8
UV22	30	40	100	81.7	4.2	21.6
UV18	30	37	100	81.5	4.0	20.2
Dizzy: 0 (dizzy) ~ 100 (not dizzy)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	51	100	93.2	2.8	12.4
22-22-10	11	78	100	94.5	2.7	8.8
22-26-5	18	50	100	91.4	3.6	15.2
22-26-10	12	77	100	94.0	2.3	8.0
18-22-5	20	50	100	90.2	3.8	17.4

18-22-10	10	82	100	95.5	2.4	7.4
18-26-5	17	49	100	91.1	3.9	16.5
18-26-10	13	29	100	88.8	5.3	19.2
C	30	48	100	91.3	2.5	13.4
UV22	30	49	100	92.6	2.8	14.2
UV18	30	47	100	92.2	2.4	12.2
Tired: 0 (tired) ~ 100 (not tired)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	43	100	78.1	4.1	18.2
22-22-10	11	68	100	91.3	3.2	10.8
22-26-5	18	50	100	84.7	4.1	17.5
22-26-10	12	21	100	81.0	6.8	23.6
18-22-5	20	24	100	79.8	4.7	21.6
18-22-10	10	23	100	83.6	7.8	24.8
18-26-5	17	26	100	79.3	5.9	25.0
18-26-10	13	22	100	84.2	6.6	23.8
C	30	16	100	75.9	4.5	23.9
UV22	30	27	100	79.9	4.3	21.8
UV18	30	35	100	81.3	4.3	21.7
Feeling bad: 0 (feeling bad) ~ 100 (feeling good)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	50	100	82.6	3.5	15.5
22-22-10	11	70	100	90.9	3.0	9.9
22-26-5	18	23	100	81.2	5.2	22.0
22-26-10	12	60	100	85.0	3.4	11.9
18-22-5	20	50	100	83.2	3.9	17.6
18-22-10	10	50	100	84.7	5.4	17.1
18-26-5	17	39	100	77.8	4.8	20.2
18-26-10	13	50	100	85.6	4.9	17.6
C	30	49	100	83.7	2.7	14.2
UV22	30	35	100	81.4	3.9	20.1
UV18	30	53	100	80.2	3.2	16.2
Noise: 0 (dissatisfied) ~ 100 (satisfied)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	73	100	92.9	1.9	8.7
22-22-10	11	64	100	90.2	3.5	11.5
22-26-5	18	16	100	87.1	4.8	20.2
22-26-10	12	73	100	88.1	3.4	11.9
18-22-5	20	50	100	90.2	3.3	15.3
18-22-10	10	67	100	89.6	3.9	12.5
18-26-5	17	35	100	87.6	4.7	19.7
18-26-10	13	63	100	87.2	3.4	12.4
C	30	50	100	86.5	2.6	13.6
UV22	30	50	100	87.5	2.7	13.7
UV18	30	73	100	90.5	1.9	9.7

Lighting: 0 (dissatisfied) ~ 100 (satisfied)						
	N	Minimum	Maximum	Mean	Std. Error	Std. Deviation
22-22-5	19	41	100	87.2	3.7	16.6
22-22-10	11	64	100	87.2	3.9	13.0
22-26-5	18	50	100	84.7	3.9	16.8
22-26-10	12	41	100	86.0	5.2	18.0
18-22-5	20	43	100	86.0	4.0	18.5
18-22-10	10	68	100	89.3	4.1	12.9
18-26-5	17	40	100	86.1	4.1	17.4
18-26-10	13	68	100	88.8	3.1	11.3
C	30	43	100	85.3	3.0	15.9
UV22	30	42	100	85.3	3.2	16.1
UV18	30	41	100	87.2	2.9	14.4

Appendix 4 Publications From This PhD Research

Peer-reviewed journals

1) **Ruixin Li, S.C. Sekhar and A.K. Melikov, 2010.** *Thermal Comfort and Indoor Air Quality in rooms with Integrated Personalized Ventilation and Under-Floor Air Distribution Systems.* **ASHRAE HVAC&R Research (*In press- accepted for publication*).**

   ABSTRACT : A comprehensive study comprising physical measurements and human subject experiments was conducted to explore the potential for improving occupants' thermal comfort and indoor air quality (IAQ) using personalized ventilation (PV) system combined with under-floor air distribution (UFAD) system. The integrated PV-UFAD system, when operated at relatively high temperature of the air supplied from the UFAD system, provided comfortable cooling of the facial region, improved inhaled air quality and decreased the risk of "cold feet" which is often reported in rooms with UFAD alone. This paper explores associations between the physical measurements and human responses in a room served with PV-UFAD system. The experiments were conducted in a field environmental chamber served by two dedicated systems – a primary air handling unit (AHU) for 100% outdoor air that is supplied through the PV air terminal devices and a secondary AHU for 100% re circulated air that is supplied through UFAD outlets. Velocity and temperature distribution in the chamber were measured. A breathing thermal manikin was used to measure the heat loss from numerous body segments and to determine the equivalent temperature. The responses of 30 human subjects were collected. The experiments were performed at various combinations of room air and PV air temperatures. The results reveal improved overall thermal sensation and decrease of "cold feet" complaints as well as improved inhaled air quality (including perceived air quality) with PV-UFAD in comparison with the reference case of UFAD alone or mixing ventilation with ceiling supply diffuser. Increase of predicted draft rating (DR) with the decrease of the local thermal sensation at the feet was identified. The manikin based equivalent temperature determined for the face was positively correlated with thermal sensation at the face region. The measured inhaled air quality indices (personalised exposure effectiveness and personalised exposure index) were improved by decreasing PV supply air temperature. The perceived inhaled air freshness increased with the decrease of the inhaled air temperature and increase of facial velocity.

2) **Li Ruixin, S.C.Sekhar and A.K.Melikov, 2010**, *Thermal comfort and IAQ assessment of under-floor air distribution system integrated with personalized ventilation in hot and humid climate.* **Building and Environment journal**, Elsevier, Volume 45, Issue 9, *Pages 1906-1913.*

ABSTRACT: The potential for improving occupants' thermal comfort with personalized ventilation (PV) system combined with under-floor air distribution (UFAD) system was explored through human response study. The hypothesis was that cold draught at feet can be reduced when relatively warm air is supplied by UFAD system and uncomfortable sensation as "warm head" can be reduced by the PV system providing cool and fresh outdoor air at the facial level. A study with 30 human subjects was conducted in a Field Environmental Chamber. The chamber was served by two dedicated systems e a primary air handling unit (AHU) for 100% outdoor air that is supplied through the PV air terminal devices and a secondary AHU for 100% recirculated air that is supplied through UFAD outlets. Responses of the subjects to the PV-UFAD system were collected at various room air and PV air temperature combinations. The analyses of the results obtained reveal improved acceptability of perceived air quality and improved thermal sensation with PV-UFAD in comparison with the reference case of UFAD alone or mixing ventilation with ceiling supply diffuser. The local thermal sensation at the feet was also improved when warmer UFAD supply air temperature was adopted in the PV-UFAD system.

Conference Papers

1) **Li, Ruixin and S C Sekhar, 2006.** "Comparison of Performance of Under-floor and Ceiling Supply System in a Field Environmental Chamber Study". **Healthy Buildings 2006**, ed. E.de Oliveira Fernandes, M.Gameiro da Silva, J.Rosado Pinto. Indoor Climate, vol. II (2006): 145-148. Lisbon: E.de Oliveira Fernandes, M.Gameiro da Silva, J.Rosado Pinto. (Healthy Buildings 2006, 4 - 8 Jun 2006, Centro de Congressos, Lisboa, Portugal)

   ABSTRACT: In the modern workplaces, it is important to consider both the thermal requirements as well as the energy demand. For a sustainable design of the built environment, it is crucial to ensure that the conditioned air reaches the occupants in the most effective manner. In this paper, typical modes of air distribution, such as the ceiling supply and under-floor supply systems are investigated by using a breathing thermal manikin in a controlled environmental chamber in a tropical climate context. In this chamber, the thermal manikin is exposed to environmental conditions which are provided by ceiling supply and under-floor supply system respectively. The room air temperature distribution and the thermal manikin's responses are detected to describe how the air distribution modes affect the room thermal environment and occupants' thermal sensation.

2) **Li, Ruixin and S C Sekhar, 2007.** "Numerical Simulation of Personalized Ventilation in Conjunction with Under Floor Air Distribution System". In Proceedings of **ROOMVENT 2007,**

International Conference on Air Distribution in Rooms, Helsinki, Finland. (13-15 June 2007)

ABSTRACT: The performance of a separate ventilation and thermal load air-conditioning system which is composed of personalized ventilation and under-floor air conditioning (PV-UFAD) system is explored through numerical simulation method. For UFAD, the most common thermal dissatisfaction seems to be caused by the non-uniform thermal environment as thermal stratification leads to cold feet and draft discomfort. With warmer supply air temperature, the "cold feet" perception can be eliminated, but another uncomfortable sensation as "warm head" will arise. It is hypothesized that PV air will reduce this uncomfortable sensation by providing cold and fresh air at the facial level. The simulation is conducted with warmer underfloor supply air temperature (18-22 ℃) under certain air supply rate and with constant PV parameter (Tsupply=20 ℃, Vsupply=10 L/s). The simulation of the room environment with UFAD is also conducted to make a comparison. The room air temperature and velocity distribution and the ability to deliver outdoor air to occupant's breathing level with these two systems are used as performance indices.

3) **Li Ruixin, S.C. Sekhar and Florence Khoo, 2008**. "Study of warmer supply air temperature in under-floor air distribution system (UFAD) in hot and humid climates". In Proceedings of **Indoor Air 2008, The 11th International Conference on Indoor Air Quality and Climate**, Copenhagen, Denmark (17-22 August 2008).

ABSTRACT: In under-floor air distribution (UFAD) systems, during cooling application, the cool supply air is delivered into the room through floor mounted supply outlets. The "cold feet" complaint is often reported by occupants as uncomfortable thermal sensation. This uncomfortable sensation may be due to the higher air velocity and lower air temperature near the floor supply outlet. In this study, the effect of warmer supply air temperature (SAT) in UFAD system is examined in the context of humid climates through field measurements and numerical simulations. The results of this study indicate that with a warmer UFAD supply air temperature, the cold draft can be reduced. However, the temperature at head level may become too warm to be acceptable. The feasibility of integrating personalized ventilation (PV) system is further explored by extending the validated UFAD numerical model by supplying cool PV air at occupant's facial level.

4) **Li Ruixin, SC.Sekhar and Arsen Melikov, 2009.** "Human response to the thermal environment served by personalized ventilation combined with under-floor air distribution system". ***Roomvent 2009, The 11th International Conference on Air Distribution in Rooms***. Busan: Roomvent 2009 Secretariat. (Roomvent 2009, 24 - 27 May 2007, BEXCO (Busan Exhibition & Convention Center), Busan, South Korea).

ABSTRACT: The potential for improving occupants' thermal comfort and energy saving with personalized ventilation (PV) combined with under-floor air distribution (UFAD) system was explored. The hypothesis was that cold draught at feet can be reduced when relatively warm air is supplied by UFAD system and uncomfortable sensation as "warm head" can be reduced by the PV system providing cool and fresh air at the facial level. In order to test this hypothesis a study with human subjects was conducted in the field environment chamber served by PV-UFAD system. Responses of the subjects to the PV-UFAD were collected at various room air and PV air temperature combinations. The analyses of the results obtained reveal improved acceptability of perceived air quality and improved thermal sensation with PV-UFAD in comparison with the reference case of only UFAD or mixing ventilation with ceiling supply diffuser. The local thermal sensation at the feet was also improved when warmer UFAD supply air temperature was adopted in PV-UFAD system.

5) **Li Ruixin, S.C.Sekhar and Arsen Melikov, 2009**. "Air movement preference and acceptability with personalized ventilation in conjunction with under-floor air supply". ***HB2009 - The Ninth International Healthy Buildings Conference and Exhibition*** Syracuse: Syracuse University. (13 - 17 Sep 2009, Oncenter Complex, Syracuse, United States).

   ASBTRACT: Large differences exist between people with regard to preferred indoor environment. Individual control of the microenvironment at each workplace will make it possible for occupants to achieve preferred environment. In this study, the individual preference of local air movement was investigated under non-uniform microenvironment generated by personalized ventilation in conjunction with an under floor air distribution (UFAD) system. Human subjects were given the opportunity to choose the PV air flow between 5 L/s and 10 L/s as a means of control of his/her microenvironment. The results reveal large differences between the subjects with regard to the preferred air flow. It was found that the number of subjects who do not want to change the air movement increased after they had made a choice between the two air flow rate (5 L/s and 10 L/s).

6) **S.C.Sekhar, Li Ruixin and A.K.Melikov, 2010**. "Use of Heat-pipe for Energy Efficiency Improvement of Personalized Ventilation System Combined with Under-floor Air Distribution System in a Hot and Humid Climate". In Proceedings of ***CLIMA 2010, Antalya, Turkey*** (Paper presented at CLIMA 2010 conference, 9-12 May 2010).

   ABSTRACT: In hot and humid climates, the dehumidification of outdoor air supplied by the HVAC system is more crucial than in temperate climates with regard to energy use and to achieve thermal comfort By incorporating a heat-pipe unit into the Air Handling Unit (AHU) for the personalized ventilation (PV) system, the energy used to pre-cool and reheat the outdoor air could be saved. Thus, no active energy is needed for pre-cooling and reheating the outdoor air. This strategy was evaluated during experiments designed to study human response to various environmental conditions generated by PV in combination with Under-Floor Air Distribution. The PV supply air temperature was 22 °C and 26 °C. By incorporating the heat pipe unit into the PV AHU the energy savings from pre-cooling and reheating was up to 35.6% of total energy consumption while the most demanding indoor acceptable conditions could be achieved.

7) **Li Ruixin, S.C. Sekhar, A.K. Melikov, 2010**. Personalized Ventilation integrated with under-floor air distribution system - Protection of occupants from indoor airborne agents. **ASHRAE IAQ 2010: Airborne Infection Control – Ventilation, IAQ & Energy (*10-12 November 2010, Kuala Lumpur, Malaysia*). (*Abstract accepted*).**

ABSTRACT: The idea of personalized ventilation (PV) is to supply clean outdoor air directly to the breathing zone of each occupant. In this research, the performance of PV combined with under floor air distribution system was investigated with a focus on evaluating performance not just based on thermal comfort but also on IAQ criteria including the protection of occupants from indoor airborne agents. A breathing thermal manikin was used to mimic real human being. Tracer gas (SF_6) measurements were performed to investigate the performance of the PV-UFAD system in terms of the ability to provide occupants with 100% conditioned outdoor air. The tracer gas (SF_6) was discharged in the center of the room to simulate a pollutant source. The concentration of the tracer gas was continuously sampled at 3 locations in the room at 1.3m height, return grill and at the manikin's mouth by a multi-gas sampler and analyzer based on the principle of infra-red photo-acoustic spectrometry. The PV system was studied with 2 levels of air flow rate (10L/s and 5 L/s) and 2 levels of supply air temperature (22 ˚C and 26 ˚C) in an ambient room temperature of 26 ˚C. Two ventilation effectiveness indices of PV: Personal exposure effectiveness (PEE) and personal exposure index (PEI) was used to evaluate the performance of the PV-UFAD system. It was found that enhanced performance could be achieved with PV-UFAD system when compared with ceiling supply mixing ventilation system and UFAD system alone. Cooler PV supply air temperature and higher PV air flow rate always resulted in better performance and may be considered as a strategy to protect occupants from indoor airborne agents more effectively. The percentage of PV air in the inhaled air or the percentage of outdoor air in the inhaled air does not change a lot when different PV air flow rates (10 L/s and 5 L/s) are used. Compared with PV air flow rates, the supply air temperature of PV air has stronger effect on the PEE. It was observed that the cooler PV air was always able to deliver a higher percentage of outdoor air.