Comfort Preferences for Passive Chilled Beams Versus Variable Air Volume and Under Floor Air Distribution

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Abstract

Introduction
This paper presents lab-based evaluations of indoor thermal preferences from human subjects, under three different air conditioning systems, namely Passive Chilled Beams (PCB), Variable Air Volume (VAV) and Under Floor Air Distribution (UFAD).

Method
The preference data was collected using an A-B comparison research design. The study included structured feedback from a sample of 30 participants who spent a day in the Indoor Environment Quality (IEQ) Laboratory carrying out their normal work. Subjects, sourced from the property sector, provided feedback at specified intervals on comfort vectors and room preferences (which related to different Air Conditioning systems). Room environmental data together with forehead, hand and ankle skin temperatures were recorded at regular intervals. Each air conditioning system was controlled by its corresponding zone mounted temperature sensor. The control strategies for the respective air conditioning systems were based on settings observed during earlier filed studies. The occupied zone temperature was maintained constant at 22.5 +/- 0.5 Degrees Centigrade in all cases.

Results & Discussion
The findings indicate a thermal preference for PCB (62%, 0.95CI = 70%, 53%) when compared to VAV (38%, 0.95CI = 51%, 26%) and PCB (63%, 0.95CI = 71%, 54%) versus UFAD (37%, 0.95CI = 50%, 25%). Thermal preference was negligibly different between VAV (48%, 0.95CI = 60%, 35%) compared to UFAD (53%, 0.95CI = 61%, 44%).

The findings also showed that the differences between the air temperatures at wall at 1.7 m and occupied zone at 1.1 M depended on the type of air conditioning system.

Conclusion
Logistic Regression analysis, similar to that carried out in the food and wine industry, was used to understand the parameters that contributed to these preferences. Skin temperature difference between head and ankle of the subjects was found to be significant when comparing PCB with UFAD (p = 0.003) and when comparing PCB with VAV systems (p = 0.032). This confirms the thermal comfort adage about cooler head and warmer feet being preferable.

Key Words: Indoor Thermal Comfort, VAV, UFAD, Passive Chilled Beams, Thermal Preference
INTRODUCTION

Architecture is more than the art of constructing individual buildings. It is also the creation of environment. Buildings do not exist in isolation. They not only impose their character on their surroundings but also have an incalculable effect on the lives of human beings who inhabit them. Conti (1978)

International attention continues to focus on the way buildings are built and operated in response to the challenges of greenhouse gas reductions and associated climate change implications. With the building sector contributing 34% of global carbon dioxide (CO2) emissions (IPCC Report Chap. 9 - 2013), sustainable building technologies have been identified as one of the most cost-effective approaches for improving energy efficiency and reducing the operational carbon footprint. In modern day office building, Heating, Ventilating and Air-Conditioning (HVAC) systems strive to provide a healthy and comfortable environment for the occupants. Typical energy consumption of an air based air conditioning system in a commercial building can be broken down to Fans (34%), Cooling (27%), Heating (17%), Pumps (16%) & Cooling Towers (6%) as per Factsheet HVAC Breakdown – industry.gov.au. This forms a significant component of the operational carbon footprint.

For office buildings where energy efficiency measures have been adopted indiscriminately, it is becoming more evident that there is increased risk of compromising Indoor Environmental Quality (IEQ) for building occupants (Thomas L E, 2012).

Against this backdrop it is not surprising that there is an intensification of research activity on the topic of IEQ in recent years. The IEQ aspect relevant to this study involves Air Conditioning systems and thermal comfort. There are several papers written on HVAC and Comfort. The three types of air conditioning systems prevalent in commercial buildings in Australia are:

• Variable Air Volume (VAV), where the conditioned air volume, generally supplied via the ceiling, varies in response to the heating or cooling load requirements in an occupied zone. Return air, back to a central air handling unit, is normally via the ceiling space as well.
• Under Floor Air Distribution (UFAD), where conditioned air is supplied to an under floor plenum created by raised flooring. Air diffusion is through floor-mounted diffusers that can be located to suit the furniture layout. The return air, back to a central air handling unit, is at a higher level, usually via grilles or slots in the ceiling.
• Chilled Beams (also referred to as Radiant Cooling), where cooling is through a cold medium, commonly a chilled water coil, utilising the heat transfer principles of convection and radiation (where exposed). Heating in that case is through heated fresh air or room mounted radiant hot water heaters.

There are two types of chilled beam systems:
• Active Chilled Beam (ACB) – a ceiling mounted unit which has supply air outlets (generally conditioned outside air) as an integral component that facilitates, via nozzles, induction of room air over the cooling coil and thereby increasing the cooling capacity; and
• Passive Chilled Beam (PCB) – a ceiling mounted unit comprising a cooling coil. There is an independent outside air supply system.

In both cases, conditioned outside air caters for the mandatory fresh air requirements and latent cooling aspects. In most applications, active chilled beams, which can handle higher cooling capacities, serve the perimeter of buildings whilst passive chilled beams serve the interior zones.

The aims of this study include:

1. Investigating thermal preferences of Passive Chilled Beams Versus VAV & UFAD in an IEQ Laboratory, which incorporates these types of HVAC systems. Passive Chilled Beams have been selected because in a typical commercial application in an interior zone of building they serve a majority of the office population. Passive Chilled Beams also have a more stable cooling load as compared to Active Chilled Beams, which vary considerably in line with solar loads, as they typically serve the perimeter areas due to their ability to handle increased cooling capacities.
2. Using human subjects to provide their preferences as opposed to thermal manikins
3. Selecting samples of human subjects who spend a majority of their working lives in air conditioned offices from the working population.
4. Carrying out field studies of exemplar buildings to ascertain HVAC related parameters that could be applied in the Lab.
5. Ensuring that indoor environments, especially the air occupied temperature, is maintained within the limits as observed in field studies
6. Carrying out statistical analysis using the techniques utilised by industries that sample preferences such as food and wine tasting applications.

METHODOLOGY

FIELD STUDIES

During the summer of 2013-2014, field studies were carried out in nine exemplar buildings in Sydney – three air conditioned with VAV, three with UFAD and three with Chilled Beams air conditioning systems, with the express aim to gather the following data that would be used to set up subsequent Lab studies:

- Zone temperatures and humidity levels
- Zone air velocities
- Zone radiant temperatures
- Control strategies and respective system set-points
- Occupant feedback, as relayed to Facility Managers, on zone conditions
- Energy Ratings of the building
- Maintenance issues
- Annual Operating costs

Miniature data loggers were utilized to record the zone temperatures (perimeter and interior areas) every 15 minutes, over a period of two weeks (minimum) in each case, to ensure that the respective air conditioning control strategies were achieving required zone conditions uniformly. Information obtained from the filed studies was applied to the systems set-up in the IEQ Laboratory, where comfort related evaluations were carried, through feedback from human subjects.

SUBJECTS

Thirty (30) subjects took part in the evaluation in the Lab. Subjects were selected on a random basis from the property sector. The selection of the subjects involved listing all the likely candidates (typically office workers who generally spend most of their time in air conditioned offices) from random firms in Sydney, based on availability of the subjects to attend the full day session at the IEQ Lab and be able to carry out their ‘normal’ office work remotely. Firms dealing in air conditioning aspects of the property industry were avoided as it was believed that there could be potentially pre-existing bias by the employees for specific air conditioning system types. Once the final list of participants was compiled, each participant was allocated a day to attend through randomization. The seating of the subjects in the two rooms was also randomized. Three (3) subjects attended per day over a period of ten (10) days. Details for each subject were recorded. These included age, weight, gender and the method of travel to the IEQ Lab. Clothing value was assessed by observation. Photos were taken of each subject to ascertain the clothing (clo) value and keep a record of the clothing worn. There were 15 males and 15 females. The age ranged from 20 to 60 years– mean was 36. The mean height of the subjects was 168 cm. The mean weight of the subjects was 68 kg

IEQ LAB

Comfort evaluations were carried out in the Indoor Environment Quality (IEQ) Laboratory at the University of Sydney’s Faculty of Architecture, Design and Planning. Technical and physical details of the IEQ Lab are covered by de Dear et al, (2012). The Lab chambers’ fit-out resembles grade-A commercial office spaces. The perimeter zone of each lab is adjacent to an “environmental corridor” that is able to simulate “outdoor” ambient conditions that could create a selected climate. In this case it was Sydney, Australia.

Lab 1 has two air conditioning zones – approximately 35 sq m on the left side and approximately 25 sq M on the right hand side. The air conditioning in Lab 1 can be switched between Under Floor Air Distribution (UFAD) and Variable Air Volume (VAV) systems. It was partitioned, using moveable screens to enable the right hand side of the room to be utilised for the evaluation whilst the left hand side provided space for acclimatisation, by the subjects, prior to commencement of the evaluations.
Lab 2 is served by Chilled Beams air conditioning systems. With the partitioning of Lab 1, the right hand side and Lab 2 became the same physical size – approximately 25 sq M.

Three (3) workstations were set up in each of the chambers as shown below.

![FIG 1 IEQ LAB - Chambers 1 & 2 – Arrangements](image)

Participation, with three subjects per day, was from 8.30 am to 6.00 pm. The evaluation was over ten (10) days. The position of each participant was identified with a code such that the responses corresponded to their physical location, within the respective chambers.

**INDOOR ENVIRONMENT**

A state-of-the-art Building Management System (BMS), incorporating Direct Digital Controls (DDC), serves the IEQ Laboratory.

Following items were recorded, every 15 minutes, on the BMS:

- Air temperature in Occupied Zone at 1.1 m
- Air temperature in Occupied Zone at 0.1 m
- Globe temperature in Occupied Zone at 0.6 m – converted to MRT
- Air temperature – wall sensor - at 1.7 m
- Air temperature – wall sensor - at 1.1 m.
- Air temperature – wall sensor - at 0.6 m.
- Air temperature – wall sensor - at 0.1 m.
- Air Humidity – wall sensor – at 1.7 m. This was converted to Absolute Humidity.
- Using dedicated sensors and recording equipment – air velocities were recorded at 1.1 m and 0.1 m in two locations – between the three subjects – in each of the rooms.

The outside air corridor was set to mean summer temperature of 32 Deg C, as experienced in Sydney. The system settings within each room, for each HVAC mode, were replicated from the data gathered during field studies.

The set-point for the indoor was 22.5 °C +/- 0.5 °C – in line with observations made during the field studies.

**LABORATORY PROCEDURE**

Subjects were requested to wear normal office attire suitable for summer time. The data was obtained using an A-B comparison research design. The design required subjects to spend 1 hour in each of the two chambers, where the air conditioning system differed.

The procedure and sequence of movements between the Chambers was as follows:
FIG 3 IEQ LAB - Chambers 1 & 2 – EXPERIMENT PROCEDURE

Notes:
Vote 1 (every 15 minutes):
(i) Indication of how the subject felt from thermal comfort perspective, by sliding the pointer on the 7 points thermal sensation scale.
(ii) Indication of whether the subject preferred to be cooler or warmer or remain the same by sliding the pointer on a 3 points scale.

Vote 2 (every 30 minutes):
(i) Indication of how the participant felt around the ankle by sliding the pointer on the 7 points thermal sensation scale.
(ii) Indication of how the participant felt around the head by sliding the pointer on the 7 points thermal sensation scale.

Vote 3 - was asked after 30 mins and 60 mins after moving from one chamber to another as to whether the subject preferred the environment the subject was in compared to the environment the subject came from.

Subjects were required to spend a minimum of 0.5 hour in Lab 1 (left side area) to acclimatise. Randomisation techniques were employed for the seating arrangements in Lab 1 (right hand side area) and Lab 2. The subjects were not made aware of the type of HVAC system in operation during any of the evaluations. Subjects were requested to carry out their normal work, generally using the allocated Desktop Computers or their own Laptops. The time period was 1.0 hour for each of the air conditioning modes in the two Labs, during which the subjects were required to respond to Vote 1 and Vote 2 questions via IPads. The air conditioning system sequencing in Lab 1 was either Variable Air Volume (VAV) or Under Floor Air Distribution (UFAD) depending on the day and whether it was morning or afternoon session, in line with the randomisation strategy.

After 1 hour the subjects were required to go to Lab 2. The HVAC setting was Chilled Beams (passive). Once again the subjects were required to spend another hour and respond to Vote 1 and Vote 2 questionnaires. In addition to that, a room preference question was asked after 30 minutes and 60 minutes. After 1.0 hour, the subjects were requested to return to Chamber 1. The HVAC setting was Under Floor Air Distribution (UFAD) or Variable Air Volume (VAV), once again, depending on the day and the session. The subjects were required to spend another 1.0 hour and respond to Vote 1, Vote 2 and Vote 3 questionnaires. After 1.0 hour the HVAC setting was changed in Chamber 1 to VAV and after half hour and one hour a question was asked in relation to environment preference between the
prevailing and the previous environments. The same process was repeated in the afternoon but in reverse i.e. starting with UFAD instead of VAV or starting with VAV instead of UFAD in line with the randomisation selection as described as above.

**SKIN TEMPERATURE MEASUREMENT**

Every half hour skin temperatures were taken using an Infrared Digital Camera. Various options were investigated for obtaining Skin Temperature and use of Infrared Digital Camera was chosen on the basis that it was least obtrusive for the subjects. This also suited the overall objective to make the subjects feel that they were in an “office” environment rather than in a laboratory should other options, such as attachment of sensors on the body, were to be utilized.

Research Assistant carried out the skin temperature measurements. This provided uniformity and consistency in taking the readings. The measurements were taken of the forehead, back of hand and ankle of each subject and recorded every 30 minutes.

Following are examples of the procedure adopted:

![FIG 4. Skin Temperature Measurement using FLIR Infrared Camera.](image)
DATA ANALYSIS & OUTCOMES

HVAC System Preferences

The results indicate a significant preference (p = 0.004) for Passive Chilled Beams system when compared to both VAV and UFAD. However there is negligible difference between the UFAD and VAV preferences (p = 0.6).

Since the preferences were based on feedback from human subjects, Logistic Regression analysis, similar to that used in wine and food tasting, was utilised to investigate as to which of the parameters were contributing to the choice of the preferences.

The following is a summary of the outcomes:

Table 1 – Impact of key parameters on thermal preferences

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PCB Vs VAV</th>
<th>PCB Vs UFAD</th>
<th>UFAD Vs VAV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skin Temp - Head minus Ankle</td>
<td>P = 0.041</td>
<td>P = 0.001</td>
<td>P = 0.786</td>
</tr>
<tr>
<td>Skin Temp - Head</td>
<td>P = 0.203</td>
<td>P = 0.003</td>
<td>P = 0.554</td>
</tr>
<tr>
<td>Skin Temp - Hand</td>
<td>P = 0.643</td>
<td>P = 0.406</td>
<td>P = 0.512</td>
</tr>
<tr>
<td>Skin Temp - Ankle</td>
<td>P = 0.192</td>
<td>P = 0.050</td>
<td>P = 0.181</td>
</tr>
<tr>
<td>Occupied Room Temp @ 1.1m</td>
<td>P = 0.500</td>
<td>P = 0.091</td>
<td>P = 0.098</td>
</tr>
<tr>
<td>Abs Humidity</td>
<td>P = 0.465</td>
<td>P = 0.136</td>
<td>P = 0.023</td>
</tr>
<tr>
<td>Mean radiant Temperature</td>
<td>P = 0.214</td>
<td>P = 0.196</td>
<td>P = 0.261</td>
</tr>
</tbody>
</table>

For both these AB comparisons, the most significant contributor to the preferences is the Skin Temperature difference between Head and Ankle. Passive Chilled Beam system, through a combination of convective and radiant energy exchange at ceiling level, cools the head whilst allowing the ankle area to remain at a stable temperature. VAV and UFAD systems on the other hand have air circulation at lower body areas and hence the difference between the head and the ankle area is higher than that experienced under PCB.
For the PCB vs UFAD, the Head and Ankle skin temperatures also have an impact. This can be explained by the vastly different forms of energy exchanges involved with these two types of HVAC systems. In UFAD the energy exchange is via a low level air supply whilst for PCB the heat exchange is mainly convective from ceiling height.

There is no significant difference between Under Floor Air Distribution (UFAD) and Variable Air Volume (VAV) systems from comfort perspective. Humidity difference, due to dehumidification with lower supply air temperature of a VAV system compared to UFAD (which generally provide higher humidity levels), shows a significant impact but not sufficient to create a noticeable difference between these two systems from overall comfort viewpoint.

Following are graphs indicating the skin temperature differences for three clothing levels together with occupied zone temperature:

![Graphs showing skin temperature differences for three clothing levels](image)

Fig 6 – Skin Temperatures – TD = Mean Head minus Ankle Temperature Deg K and Occupied Zone Temperature Deg C for clo values = 0.4, 0.5 & 0.6

As can be seen the clothing levels have an impact on skin temperatures. As the level of clothing increases the mean head minus ankle temperature (TD) decreases. This is because the body temperature will remain higher around the ankle with increased clothing and vice versa.

The clothing value or the gender difference or the number of participants with bare ankles did not have significant impact on the thermal preferences.

A vital observation is the consistency of zone temperature during the operation of each of the HVAC system. Occupied zone temperature has a direct relation with number of complaints in buildings. Hence it was important to ensure that there were minimum variations (plus or minus 0.5 degrees of the set-point) in zone temperatures between the three systems. The occupied room temperatures at
0.1 m and 1.1 m did not have significant impact on the thermal preferences. This was one of the aims of the experiment.

It was also observed that there was a noticeable difference between the occupied zone temperatures at 1.1 m and the wall sensor at 1.7 m. Wall mounted thermostats / temperature sensors are typically located at 1.7 m in most commercial buildings. The results show that variation in the difference of these temperatures depended on the type of HVAC system in operation – for VAV the mean = 0.6 °K, for UFAD the mean = 0.4°K and for PCB, the mean = 0.2°K. This could be useful information for commissioning of these types of systems in setting the control set points and checking against occupied zone conditions.

CONCLUSION

There is no significant difference between Under Floor Air Distribution and Variable Air Volume systems with regards to indoor thermal comfort. This is mainly due to the fact that both are air based systems with similar air distribution characteristics.

Passive Chilled Beam (PCB) system offers a higher level of comfort when compared to both Variable Air Volume (VAV) and Under Floor Air Distribution (UFAD) systems. This is primarily due to the fact that Passive Chilled Beam system has the ability to cool the head without have a significant impact on the ankle area temperature. This confirms the adage of warm feet and cool head providing better comfort.

REFERENCES


