Experimental study on the performance evaluation of active chilled beams in cooling operation under varied boundary conditions

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Abstract. This study investigates the thermal comfort and indoor air quality performance of Active Chilled Beams (ACB) in cooling operation mode in an open office environment with asymmetrical loads. Many studies on thermal comfort using ACB in cooling mode have been conducted; most of the studies confirm that thermal comfort is satisfactory because the temperature gradient and the airspeeds are acceptable at the occupant level. However, these studies do not specifically address the local discomfort in cooling mode. Furthermore, these studies do not consider performance under different ACB configurations or varied boundary conditions such as those found in real offices. This paper reports the results of an experimental study that addresses the above issues. A laboratory experiment was designed to simulate a multi-occupant open office with an ACB subjected to asymmetric boundary conditions. The results demonstrate that discomfort draft risk at the ankle level is higher when the ACB is oriented parallel to the window. Furthermore, the results suggest that shape (the type of ACB) and throw of ACB affect air distribution. The results emphasize the importance of properly selecting, orienting, and designing ACB, not just to offset the room loads, but to match the proportions and boundary conditions of the office.

1. Introduction

Active Chilled Beams are high-induction terminal units inducing room air through a cooling and/or heating coil by supplying a low amount of primary air at high velocity through induction nozzles. The performance of ACB greatly depends on the attachment of an airstream to a surface (Coanda effect), which depends on the discharge angle of air from the beam. An inappropriate angle could cause poor air mixing and would turn the airflow from ACB to fall directly on the occupants. Therefore, to minimize the thermal discomfort and to have good air mixing, the angle of discharge of supply air is designed below 45° for ceiling mounted active chilled beams. The angle of discharge can be verified by a smoke test or PIV measurement. [1]

Active chilled beams (ACB) are known for their energy efficiency, due to their capacity to provide sufficient fresh air and uniform temperatures [2]. The usage of these devices is increasing around the world as they minimize the fan energy and ductwork size. Despite these advantages, there are some risks associated with usage of ACB that need to be taken into account for a good design. In 2015, REHVA and ASHRAE published the Active and Passive Beam Application Design Guide to help designers integrate ACBs in buildings [3]. However, this guide does not address asymmetric conditions directly. Many papers studied the draught risk [4, 5, 7, 8], the effect of asymmetric loads [8, 9], thermal comfort in the occupied zone [4, 5, 6, 7, 11] and ACB installation configuration [12] i.e. parallel/perpendicular
to the window in cooling mode. However, these studies are often not comparing different configurations and different load intensities including solar radiation as part of the load. This paper examines room airflow patterns for parallel/perpendicular configurations for different asymmetric load intensities, and impacts on thermal comfort and air change effectiveness. The experiment simulates environmental conditions in a multi-occupant office. The design, selection and installation of beams are critical in a multi-occupant office due to the presence of a number of heat sources, which influence the air distribution negatively.

2. Methods

2.1. Experimental facilities

The experiments were carried out in a controlled room environment (Figure 1) at PRICE Research Center North (PRCN) in Winnipeg, Manitoba, Canada. The room size of 6.2 x 4.9 x 2.8 m (20.3 x 16.1 x 9.2 ft.). The interior walls face south, east, and west. The north-facing enclosure consists of a fixed window on a wall underneath, connected to a climatic chamber that maintains simulated outdoor air temperature (OAT) conditions. The window dimensions are 4.5 m (14.8 ft.) wide by 1.7 m (5.6 ft.) high. The walls are highly insulated. Four ceiling-mounted lights illuminate the room. The room has been furnished to simulate office conditions for four occupants in cubicles at the centre of the room separated with partitions.

2.2. Air Distribution System

The cooling of the simulated office was realized by a 2-way Active Chilled Beam installed in the acoustic tile ceiling. The details of the ACB are presented in Table 2. A controlled volume of primary air was supplied at 55 °F by an air-handling unit. The flow and temperature of primary air were kept constant for each test and were recorded on the system. The duct connection to the ACB plenum is from the side of the unit and the static pressure at the nozzle is kept below 1.0 inWC (24.4 mmWC). The chosen unit is a linear ACB of 0.61 m (2.0 ft.) width and 1.83 m (6.0 ft.) nominal length, the induction face area is 0.55 m² (5.9 ft²), the nozzles have an 8.9 mm (0.35 in.) diameter and equipped with a heat exchanger with 2 different circuits for heating and cooling. The coil is connected to an independent heat pump that supplies hot and cold water to the coil at a rate of 0.095 l/s (1.5 GPM). The ACB unit has been selected based on the heating and cooling load requirement through PRICE ACB selection software. The coil temperature is kept above 12.7°C (55°F) to avoid any risk of condensation, thus the primary airflow is adjusted based on the load.

2.3. Room Layout / Load Layout

The rectangular room has four cubicles with a high-level partition (Figure 1). The ACB is installed either parallel or perpendicular to the window. Four ceiling-mounted lights are shown in the layout with their respective power input. Three heating panels were placed on the floor below the window to simulate solar gain on the floor. The heating panels can vary the power input to simulate varying solar loads in
different tests. Three vertical measuring stations ‘Trees’ T2, T3, T4 were equipped with RTD/air temperature sensor and air speed probes/anemometers at 4 different heights (0.1 m (4 inch), 0.6 m (2 ft.), 1.1 m (3.6 ft.), 1.7 m (5.5 ft.)). Trees were placed close to the occupants O#2, O#3 and O#4 but away from the ACB throw/airflow. Each cubicle/workstation has a thermal manikin, a monitor and a computer as heat sources.

2.4. Measurements
Room air temperatures and speeds were measured close to the manikins at three “trees”, at four heights per tree. The trees were carefully placed away from the direct throw from the ACB. Room operative temperatures and globe temperature were also measured close to the manikins. Discharge air temperatures were measured at the two ACB slots, as well as induced air temperatures and air speeds. Surface temperatures were measured for the window, walls, and ceiling. For the air change effectiveness test CO₂ samples were collected at three locations close to the occupants’ breathing zone. The instruments used are described in Table 1.

| Sensor                  | Application                                      | Type          | Range                | Accuracy                  |
|-------------------------|--------------------------------------------------|---------------|----------------------|---------------------------|
| Temperature             | ACB Supply / Induced Air Temperature             | HOBO MX1101   | -20° - 70°C           | ±0.21°C from 0° to 50°C    |
|                         |                                                   |               | (-4° - 158°F)        | ±0.38°F from 32° to 122°F |
| Temperature             | Surface                                          | RTD (Class A) | -30° - 300°C          | ±0.15° + 0.002* T         |
| Temperature             | Water/Room/ACB Supply and Return Temperature     | RTD (DIN 1/10)| -29° - 100°C          | ±1/10° (0.3 + 0.005*) °C |
|                         |                                                   |               | (-20° - 212°F)        |                           |
| Temperature             | Operative Temperatures                            | HOBO U12-013 with TMC6-HD | -40° - 100°C         | ±0.25°C from 0° to 50°C   |
|                         |                                                   |               | (-40° - 212°F)        | ±0.45°F from 32° to 122°F |
| Surface Temperature     | Wall / Window / Solar Panel Temperatures         | HOBO U12-013 with TMC6-HD | -40° - 100°C         | ±0.25°C from 0° to 50°C   |
|                         |                                                   |               | (-40° - 212°F)        | ±0.45°F from 32° to 122°F |
| Air Speed Transducer    | Room Air Speed ‘Trees’                           | SensoAnemo 5100LSF | 0.05 - 5 m/s         | ±0.02 m/s (3.93 fpm) ±1.5% of readings |
|                         |                                                   |               | (9.84 – 984 fpm)      |                           |
| Air Speed Transducer    | Room Air Speed ‘Trees’                           | TSI 8465      | 0 - 2.5 m/s          | ±3.0% of reading,         |
|                         |                                                   |               | (0 – 492 fpm)         |                           |
| Air Speed Transducer    | Room Air Speed ‘Trees’                           | TSI 8475      | 0.1 – 50.8 m/s       | ±2.0% of reading,         |
|                         |                                                   |               | (25 – 10000 fpm)     |                           |
| CO₂ Transmitter         | CO₂ Concentration                                | GMT220        | 0 – 5000 ppm         | ± (1.5% of range + 2.0% of reading) |

2.5. Experimental procedure
Three different tests were conducted. The workstation and lighting loads were the same across all the tests. Table 2 shows the parameters and their values for each test. For each test, the room load, solar load and environmental chamber temperature were adjusted to predetermined parameters. The data was recorded when the temperature of the room reaches a steady state. Steady state was assumed once the room temperature variation was smaller than ± 0.55°C (1°F). Measurements were then recorded in the system for a minimum of 1 hour for each test.

| Parameters               | Test #1 Parallel | Test #2 Parallel | Test #3 Perpendicular |
|-------------------------|------------------|------------------|-----------------------|
| ACB Orientation         |                  |                  |                       |
| Discharge Avg. Air Temp (°C/°F) | 18.8 (66.0) | 19.3 (66.7) | 18.0 (64.4)            |
| Room Temp. Set Point (°C/°F) | 23.8 (75.0) ± 0.55°C (±1°F) | 23.8 (75.0) ± 0.55°C (±1°F) | 23.8 (75.0) ± 0.55°C (±1°F) |
| ACB Induced Air Temp (°C/°F) | 24 (75.2) | 24 (75.2) | 23 (75.2)            |
| Primary Air Temperature (°C/°F) | 12.7 (55.0) ± 0.55°C (±1°F) | 12.7 (55.0) ± 0.55°C (±1°F) | 12.7 (55.0) ± 0.55°C (±1°F) |
| Primary Airflow Rate (l/s) / (CFM) | 70.8 (150) | 56.6 (120) | 56.6 (120)            |
| Entering CHW Temperature (°C/°F) | 13.8 (57.0) ± 0.55°C (±1°F) | 13.8 (57.0) ± 0.55°C (±1°F) | 13.8 (57.0) ± 0.55°C (±1°F) |
| CHW flow Rate (l/s) / (GPM) | 0.095 (1.5) |                  |                       |
Environmental Chamber Temperature (OAT) (°C/°F) | 34.1 (93.4) | 24.7 (76.4) | 24.7 (76.4)  
Avg. Window Temp. (°C/°F) | 26.3 (79.3) | 23.5 (74.3) | 24.2 (75.7)  
Heating Panel Loads (kW) | 0.22 / 0.23 / 0.22 | 0.27 / 0.29 / 0.27 | 0.27 / 0.29 / 0.27  
Manikin / Monitor / Computer (W) | 57 / 31 / 22 | 85 / 21 / 46 | 85 / 27 / 24  

*Loads associated with the heating panels on Figure 3 from left to right, †Loads associated with working stations 1 and 2 on Figure 3 respectively, ‡Loads associated with working station 3 and 4 on Figure 3 respectively

3. Results and Discussion

3.1. ACB in Parallel Configuration

Smoke tests show a symmetric air discharge from the ACB and infrared images show similar ceiling temperature patterns suggesting proper Coanda effects on both ACB outlets. As shown in Figure 2, Trees – T2 and T4, far from the window, show a small temperature stratification. Tree T3, close to the window, shows relatively constant temperatures from 0.1m (4 inch.) to 2.2m (7.2 ft.) heights, but lower temperatures at the 2.6m (8.5 ft) level, approximately 1°C (1.8°F) less than at 2.2m (7.2 ft.). It is interesting to see that temperature profiles are similar for primary air of 70.8 l/s (150 CFM) and 56.6 l/s (120 cfm).

![Figure 2](image1.png)

Figure 2. Air Temperature at Different Tree Heights near Occupants in Parallel Configuration.

Figure 3 shows different air-speed profiles with height, between T3 near the window, and T2 and T4 far from it. Tree T3 is the only one that did not measure a high air speed at the ankle level (i.e. 0.1m (4 inch.)) and was having his peak between 0.6 m (2 ft.) and 1.1m (3.6 ft.) instead. T4 has steady measurement from 0.6m (2 ft.) to 1.7m (5.5 ft.), while T2 has a higher speed at 0.6m (2 ft.) and it is accentuated with higher airflow.

![Figure 3](image2.png)

Figure 3. Air speed at Different Tree Heights near the occupants in Parallel Configuration.

At the south wall, opposite to the window, negative buoyancy drives the air down along the wall, which gains speed until it reaches the floor and occupant O/#2 and O/#4 at the ankle level. At the north wall, when the ceiling air reaches the window it is deflected (i.e. “pushed”) away from the window by the
rising plume created by the heating panels (simulating solar gain on the floor), and by the warm window. Thus, contrary to the air patterns at the interior south side of the room (T2 and T4); T3 measures higher air speeds at the middle levels, and lower air speeds at the ankle level.

3.2. ACB in Perpendicular Configuration

In comparison with the parallel configuration, this setup shows a large asymmetry in the discharge jet that is deflected (i.e. “pushed”) away from the window by the pressures exerted by the rising buoyant plumes due to the solar gains. Such pressures exerted by strong warm air rising streams “attach” to the ceiling and counter the Coanda effect. In the absence of a Coanda effect, the discharge jet falls short from the walls. Another observation from this configuration is that a large amount of ACB induction air seems to come from the strong rising buoyant plumes at the window side.

![Figure 4. Air Characteristics at Different Heights near the Occupants in Perpendicular Configuration.](image)

The above airflow patterns can be explained by the measurements as follows. Higher airspeeds are observed at higher levels in trees T2 and T4 (Figure 4a) compared to the parallel configuration (Figure 3b), and conversely, lower air speeds are observed at lower levels in the same trees for perpendicular configuration versus the parallel one. As a result, the risk of ankle draft is eliminated in the perpendicular configuration as seen in trees T2 and T4. Furthermore, the temperatures at higher levels in trees T2 and T4 are also cooler in the perpendicular configuration (Figure 4b) versus the parallel one (2b), which reflects the deflecting of the cool ACB discharge air in that direction. Thus, the low airspeeds at T3 (Figure 4) originate from the buoyant air at the window side of the room. In T3, higher speeds and lower temperatures at the ankle level seem to be caused by the air drawn from the opposite side of the room; and lower speeds and higher temperatures at higher levels in T3 is produced by the warm rising air at the window side of the room.

3.3. Thermal Comfort

Thermal comfort is assessed using ASHRAE Standard 55-2017 [13]. Whole-body thermal comfort (PMV) is evaluated first, including whole-body draft risk using the SET model; followed by verification of local thermal discomfort from ankle draft risk and radiant thermal asymmetry. Environmental variables for thermal comfort calculations are obtained from the tests. Occupant metabolic rate of 1.1 Met is assumed typical of sedentary office work. The clothing insulation value of 0.57 Clo is used for summer (cooling) indoor conditions. A new ankle draft-risk model considers that a person feels ankle draft only when her/his whole-body thermal sensation tends towards the cool (negative) side of the PMV. Air speeds fluctuate in short intervals were averaged. It can be concluded that the main risk for thermal discomfort results in parallel configuration from the high air speeds at the ankle level at Trees T2 and T4.

3.4. Air Change Effectiveness

The air change effectiveness has been evaluated for tests #2 and #3 using ASHRAE Standard 129 to calculate the air change efficiency using the mean age of air near the occupant. The results show for
both the tests an air change efficiency of 0.99 -1.01, this means the CO2 concentration is the same in the occupied zone than measured at the exhaust grille which further indicates that the air is in a fully mixed condition under cooling mode in a room with Active Chilled Beams.

4. Conclusion
This paper investigated the impacts on air quality and thermal comfort of two ACB orientations under varying boundary conditions. Results show that air change effectiveness is good for parallel and perpendicular ACB configuration in the cooling operation. It also shows that ACB achieve PMV in general, that follows the ASHRAE 55 standard. The perpendicular configuration does better at preventing local discomfort due to high airspeed at ankle level for occupants O#2 and O#4 as seen in parallel configuration but the Coanda effect was mostly disturbed due to the thermal load available in the room. The asymmetric load influences the air distribution pattern across the room, but seems to have a positive impact on the thermal comfort of occupant #3 without affecting the air quality at this workstation. Therefore, it is important that the interaction between the thermal load and the air distribution must be studied before designing and selecting an ACB for an office, which could affect the thermal comfort and air distribution in the room.

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References
[1] Upadhyay, R. K. 2018. Performance evaluation of active chilled beam in cooling and heating operation under actual field boundary conditions. British Columbia Institute of Technology.
[2] Rhee, K., Shin, M., & Choi, S. 2015. Thermal uniformity in an open-plan room with an active chilled beam system and conventional air distribution systems. Energy & Buildings, 93, 236–248. https://doi.org/10.1016/j.enbuild.2015.01.068
[3] ASHRAE/REHVA 2015. Active and Passive Beam Application Design Guide.
[4] J. L. Dréau, P. Heiselberg and R. L. Jensen, 2014 "A full-scale experimental set up for assessing the energy performance of radiant wall and active chilled beam for cooling buildings." Building Simulation 39-50
[5] J. L. Dréau and P. Heiselberg, 2014 "Sensitivity analysis of the thermal performance of radiant and convective terminals for cooling buildings," Energy and Buildings 82, 482–491
[6] P. Mustakallio, Z. Bolashikov, K. Kostov, A. Melikov and R. Kosonen, 2016 "Thermal environment in simulated offices with convective and radiant cooling systems under cooling (summer) mode of operation." Building and Environment 82-91
[7] K. N. Rhee, M. S. Shin and S. H. Choi, 2015 "Thermal uniformity in an open-plan room with an active chilled beam system and conventional air distribution systems."
[8] R. Kosonen, A. Melikov, B. Yordanova, and L. Bozhkov, 2007 "Impact of heat load distribution and strength on airflow pattern in rooms with exposed chilled beams,"
[9] H. Koskela, H. Häggblom, R. Kosonen, and M. Ruponen, 2010 "Air distribution in office environment with asymmetric workstation layout using chilled beams," Bldg. and Env., 45 1923-1931.
[10] H. Koskela, H. Häggblom, R. Kosonen, and M. Ruponen, 2012 "Flow pattern and thermal comfort in office environment with active chilled beams," HVAC & R Research, 18 723-736.
[11] A. Melikov, B. Yordanova, L. Bozhkov, V. Zboril, and R. Kosonen, 2007 “Impact of the airflow interaction on occupants’ thermal comfort in rooms with active chilled beams,” 6th Intl. Conf. on Indoor Air Quality, Ventilation & Energy Conservation IAQVEC, Sendai, Japan.
[12] J. True, V. Zboril, R. Kosonen, and A. Melikov, 2007 “Consideration for minimizing draught discomfort in rooms with active chilled beams,” Proc. of Clima Wellbeing Indoors.
[13] ASHRAE, ASHRAE/ANSI Standard 55-2017 Thermal environmental conditions for human occupancy, American Society of Heating, Refrigerating, and Air-Cond. Eng.: Atlanta, GA.
[14] Liu, S., S. Schiavon, A. Kabanshi, and W. Nazaroff. 2016. Predicted percentage of dissatisfied with ankle draft. Indoor Air 27(4):852–62.