Performance Evaluation of Active Chilled Beam in Real Office Conditions in a High-Performance Building in Heating

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ABSTRACT

Active Chilled Beams (ACB) units are air induction units that handle the cooling needs of spaces with a limited amount of primary air. These systems are energy-efficient and are widely adopted worldwide, however, in-depth investigations on the performance of ACB systems under real office conditions are still inadequate. The performance of ACB in heating mode has not been documented and deserves close investigation. The study investigated the operation of 4-pipe ACB under heating mode in a LEED Gold Building at British Columbia Institute of Technology in Vancouver climate under steady state conditions. The air velocity and temperature distribution inside an office under heating mode were studied and found that the ACB system is effective in heating. Surface temperature distribution was found close to the setpoint temperatures. The supply velocity and supply temperature at both slots of ACB were found different. It was concluded that the difference could be uneven pressure distribution in the primary air plenum and heat exchanger design of the ACB which need further research and investigation in a controlled environment.

INTRODUCTION

Many types of HVAC indoor terminal units are employed in HVAC applications including diffusers, fan coil units, unit ventilators, active and passive chilled beams, radiant ceiling, etc. Currently, Active Chilled Beam (ACB) terminal unit is considered as one of the leading energy-saving systems because energy is transferred through water instead of air. ACB was also listed as one of the 15 most promising HVAC related technologies by American Council for Energy-Efficient Economy (ACEEE) in 2009 [1]. Many laboratory experiments have claimed that ACB can offer improved Indoor Environment Quality (IEQ) with great energy savings potentials. The experience with such a unit is growing worldwide, therefore, it is necessary to research and analyze the performance of ACB under real conditions. ACB systems are employed commonly in North America for heating and cooling in commercial buildings especially in a high-performance building where ACB saves fan energy and helps to achieve the optimize energy performance credits under Energy and Atmosphere category for LEED certification. Although many studies have been done in past in cooling mode, but the experience of ACB under heating mode is still not studied and require detailed investigation. The purpose of this study was to assess the performance of Active Chilled Beam under real operating conditions in an academic building under heating mode. This study is an initial investigation of ACB performance under heating mode. The study was accomplished by investigating the air velocity and temperature distribution at the outlet of the ACB and inside the office environment under heating mode.

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WORKING PRINCIPLE OF ACTIVE CHILLED BEAM

Active Chilled Beam (ACB) is a device where a specific amount of primary air is supplied through an air handling unit or Dedicated Outdoor Air System (DOAS) to the plenum of the ACB unit. This air is then discharged through induction nozzles in the unit which induces indoor room air. The induced air flows through the integral water coil (heat exchanger), where it is either heated or cooled based on the water temperature. Then primary air (from air handling unit) and secondary air (induced through the coil) are mixed in the beam and diffused to the room space as supply air through slots located at the bottom of the beam [2]. Operation of an Active Chilled Beam is illustrated in Figure 1. It is to be noted that at the outlet of the nozzle, a low-pressure kernel is created as the pressure at the nozzle is reduced when air flows through the nozzle. All pressure reduction occurs at the primary air nozzle which results in a low-pressure region immediately at the nozzle outlet. This low-pressure area is slightly lower in pressure than the surrounding room air, therefore, this low-pressure area attracts the surrounding room air which is at a slightly higher pressure as illustrated in Figure 1. [3] The efficiency of the induction effect is dependent on the number, size, efficiency of the nozzles and the density and geometry of the secondary cooling coil. This secondary air from the conditioned space is moved across the heat exchanger without the need of any fan energy; therefore, the induction effect is a significant contributor to the energy reduction potential of active beams. Typically, an active beam can induce the secondary air of up to 2 - 5 times the primary air quantity. Usually, the temperature of the water is 14-18°C (57- 65°F) for cooling and 30-45°C (86 - 113°F) for heating application. The water flow rate is regulated for the control of indoor room temperature [4]. Modern ACB are equipped with both the coils, 2 pipe units are capable of either heating or cooling only and 4 pipe units are capable of both cooling and heating.

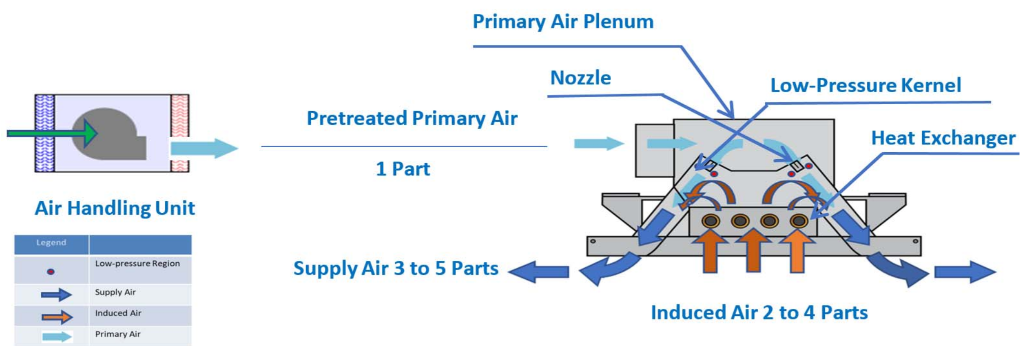


Figure 1 - Working Principle of Active Chilled Beam

METHODS

The study was carried out in a 3 story high-performance LEED Gold Building at British Columbia Institute of Technology in Burnaby City, province of British Columbia, Canada as shown in Figure 2. The building is located at 49° 14' N and 123° W, 20 km away from the Vancouver International Airport. The office selected for the study was second-floor perimeter office room with the size of 4.60 x 3.00 x 2.95 m (15.1 x 9.84 x 9.7 ft.) high, as shown in Figure 3. This perimeter office is covered by a double façade as shown in Figure 2 & 3. The west and north walls are exterior walls, and the east and south walls are the interiors. The exterior walls are made of reinforced concrete. The walls are highly insulated and calculated U values of walls and windows are shown in Table 1. The room is illuminated by two ceiling mounted lights. The cooling or heating in the office room is realized with 2 – way flush mounted Active Chilled Beam installed in the acoustic tile ceiling. The ACB details are presented in Table 2. The length of the inlet slot is equal to the length of the beam and it is located symmetrically in relation to the centerline of the room and parallel to the window as illustrated in Figure 3. The primary air is supplied by a central air handling unit and the flow and temperature of primary air are recorded in Building Automation System (BAS). The chilled beam is connected to a water source heat pump and both hot water and chilled water temperature supply to the chilled beam were recorded in BAS. The room is exposed to the outside environment only on the west side. The exposed wall has a fixed window of size 2.00 m (6.6 ft.) wide and 2.15 m (7.1 ft.) high wide with an operable sash of size 1.4 m (4.6 ft.) wide x 0.5 m (1.64 ft.) high.

Figure 2 - BCIT Building in Greater Vancouver, BC, Canada and the Perimeter Office on the Second Floor.

Table 1. Building Design Summary

Mechanical System	Central Air Handling Units with Water Source Heat Pump
Terminal Units	Active Chilled Beam – 4 pipe – Cooling & Heating
Interior Partitioned Wall	U Value – 0.73 W/m²K (0.13 Btu/hr-ft² °F)
Exposed Wall	U Value – 0.30 W/m²K (0.053 Btu/hr-ft² °F)
Interior Concrete Wall	U Value – 1.86 W/m²K (0.33 Btu/hr-ft² °F)
Slab (Top and Bottom)	U Value – 0.80 W/m²K (0.14 Btu/hr-ft² °F)
Overall Window	U Value – 2.61 W/m²K (0.46 Btu/hr-ft² °F)

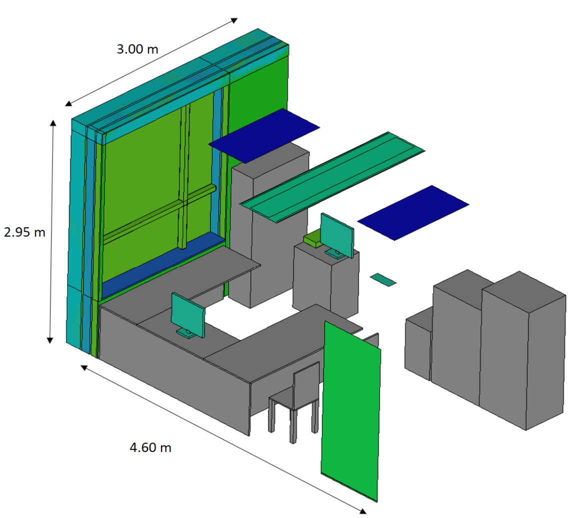


Figure 3 - Dimensions and Layout of the Office

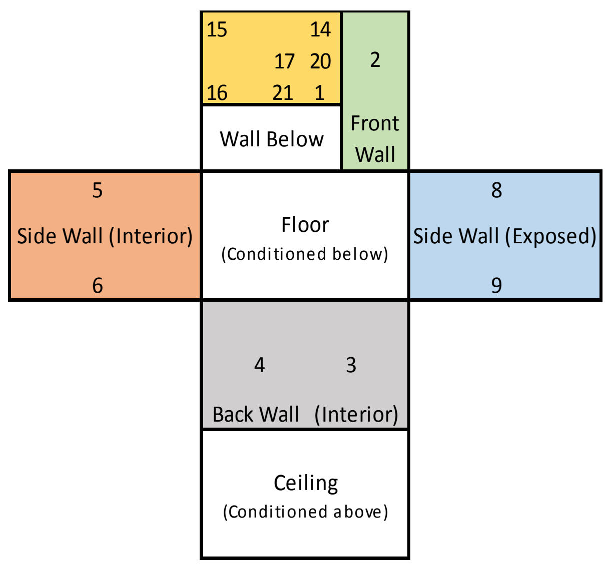


Figure 4 – Room Unfolded Surfaces with Temperature Sensors

MEASUREMENTS

Outdoor temperature, operating temperature and room temperature at different locations in the office, chilled beam supply temperatures at the two slots, chilled beam return air temperature, surface temperatures, local air velocity and air temperature at different points were recorded during the experiment which are described in Table 3.

Differential pressure (DP) at the ACB plenum, door and window were also recorded. The pressure difference across the door and window was found very low and is not reported in the paper.

Table 2. Specifications of the Active Chilled Beam

Overall Size	2.40 x 0.60 x 0.21 m (8.0 x 2.0 x 0.69 ft.)	
Number of Chilled Beam	1 unit	
Cooling Capacity	1154.0 W (3937.6 Btu/hr.)	
Heating Capacity	1422.0 W (4852.1 Btu/hr.)	
	Design	Actual Measured in Office
ACB Plenum Pressure Design	158.0 Pa (0.63 in.wg)	140.0 Pa (0.56 in.wg)
Supply Chilled Water Temperature	15.8°C (60.44°F)	16.0°C (60.8°F)
Supply Hot Water Temperature	48.9°C (120°F)	45.0°C (113°F)
Primary Air Flow	0.028 m3/s (59 CFM)	0.024 m3/s (50 CFM)
Primary Air Temperature	18.0°C / (64.4°F)	18.0°C (64.4°F)
Operation Schedule	5.00 AM – 10.00 PM	

Table 3. Sensor Specifications for Office Experiment

Sensor	Application	Type	Range	Accuracy
Temperature	ACB Supply / Return Air Temperature	HOBO MX1101	-20° - 70°C (-4° - 158°F)	±0.21°C from 0° to 50°C (±0.38°F from 32° to 122°F)
Temperature	Air Temperatures	HOBO U12-013	-20° - 70°C (-4° - 158°F)	±0.35°C from 0° to 50°C (±0.63°F from 32° to 122°F)
Temperature	Operative Temperatures	HOBO U12-013 with TMC6-HD	- 40° - 100°C (-40° - 212°F)	±0.25°C from 0° to 50°C (±0.45°F from 32° to 122°F)
Temperature	Outdoor Temperature	HOBO MX2302	-40 to 70°C (-40 to 158°F)	±0.2°C from 0 to 70°C (±0.36 from 32 to 158°F)
Surface Temperature	Wall & Window Temperatures	NXFT15XH103FA2B050 Thermistor	-40°C - 125°C (-40° - 257°F)	±0.2 °C (±0.36°F)
Air Velocity Transducer	Room Air Velocity	SensoAnemo 5100LSF	0.05 - 5 m/s (9.84 – 984 fpm)	±0.02 m/s (3.93 fpm) ±1.5% of readings
Air Velocity Transducer	ACB Supply & Return Velocity	TSI 8475	0 - 2.5 m/s (0 – 492 fpm)	±3.0% of reading,

Surface Temperature measurements

Wall and window surface temperatures were recorded by NTC thermistors. Figure 4 shows the surface labelling of the office and the location of temperature sensors placed on walls and window. The sensors were placed 0.3 m (1 ft.) below the ceiling for all walls while window temperatures were measured at various locations. Mean radiant temperature was measured by globe thermometer. Data from thermistors and globe were recorded by Agilent 34972A data logger at every 60 seconds. The details of the sensor used in the experiment are given in Table 3.

Room Air Temperature and Velocity measurements

The measurement of air temperatures and air velocities at different heights were carried out by omnidirectional calibrated anemometers SensoAnemo 5100LSF. The anemometers were placed on a manifold at 0.1 m (0.33 ft.), 0.6 m (2.0 ft.), 1.1 m (3.6 ft.) and 1.7 m (5.6 ft.) heights above the floor as shown in Figure 5, and moved manually at possible occupant's location in the room. The averaging time at each point was 180 seconds. The possible occupant's location is shown in Figure 12(b). The supply and return air velocity of the beam were measured by TSI 8475 anemometers as shown in Figure 6 and recorded on Agilent 34972A Data logger at every 60 seconds. The details about anemometers are given in Table 3.

Figure 5 - Local Air Velocity and Temperature Measurement

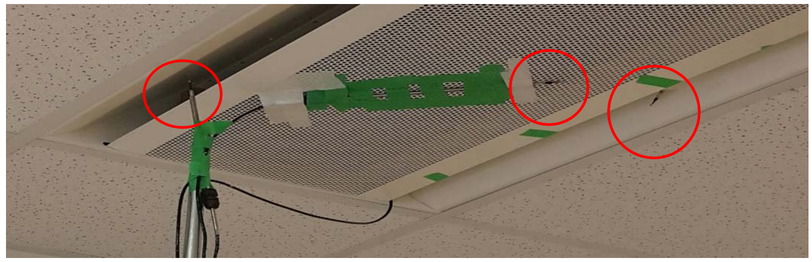


Figure 6 - Supply and Return Velocity Measurement of ACB

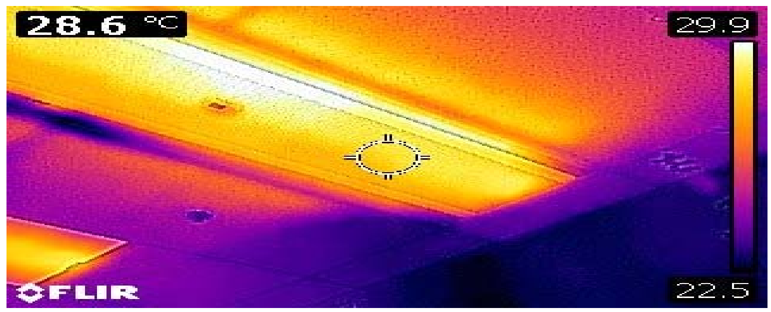


Figure 7 (a) Coanda Effect through Thermal Image Camera

Heat load

Two laptops, data logger and ceiling lights were used as heat sources inside the room. The window of the office at the external wall is shaded by the structure of double façade and partly by trees to protect the office from direct solar radiation and the room temperature is fairly stable at all time, therefore, solar radiation was not measured and considered under heating mode study of ACB. The details of heat load present during the test are detailed in Table 4. The monthly average outdoor air temperature during the experiment, recorded at the study building was 5.7°C (42°F).

Table 4. Internal Heat Load and Other Conditions

Lighting Load	10.8 W/m2 (3.43 Btu/hr-ft^2)
Equipment Load	200 W (682.6 Btu/hr.)
Occupancy	1 person - 130 W (443.58 Btu/hr.)

The measurements were taken with a real occupant working in the office under heating mode in the month of January 2018. The room temperature was varied between 20°C (68°F) to 24°C (75°F) and measurements were performed.

RESULTS & DISCUSSION

Coanda Effect

The temperature of the air jet discharged through the ACB is different from the ambient (room) air and therefore this experiment illustrated the case of a non-isothermal jet behavior in office. The Coanda effect was seen at the exit of ACB slots. Coanda effect is the tendency of the free jet attached to the ceiling. As soon as the high-velocity jet is discharged from the nozzles and further through the ACB system the air jet is seen attached to the ceiling due to low-pressure region creation above the jet. This attachment of air jet ensure good thermal comfort and avoid direct throw of cold or hot air to the occupied zone. This effect was visualized in the experiment through a thermal image camera which nicely captured the air jet attachment to the ceiling. The Coanda effect is shown in Figures 7(a) & (b).

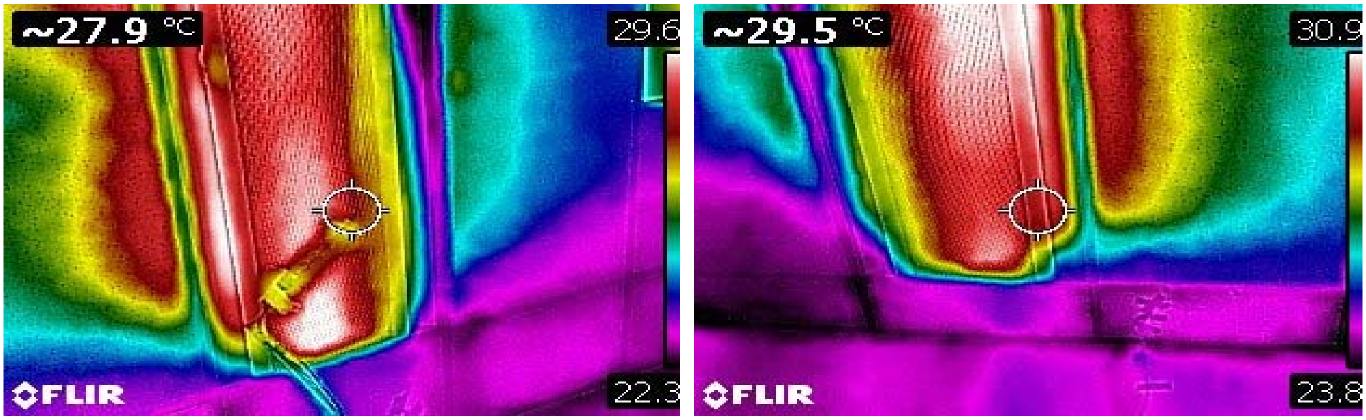
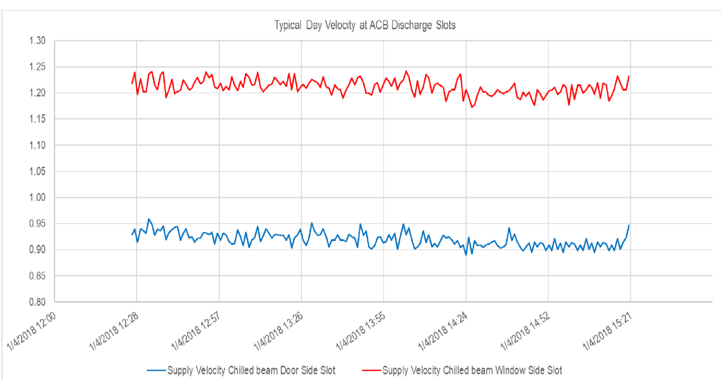


Figure 7 (b) - Coanda Effect through Thermal Image Camera

Difference in discharge air velocities at the two slots

The discharge air velocities were recorded during the test at both the supply slots. The velocity at one slot was found always higher than the air velocity at the other slot as shown in Figure 8(a). This phenomenon is due to the uneven pressure distribution at the nozzles in the ACB primary air plenum box as shown in Figure 8(b). The primary air supply is connected to the ACB plenum at one side and the airflow is directed towards the other end of the plenum which exerts more pressure at the nozzles at the other end. This causes the uneven air velocity distribution across the beam. The difference in velocities was also shown by Wu et al. [5] in their experiment and further in CFD modelling.



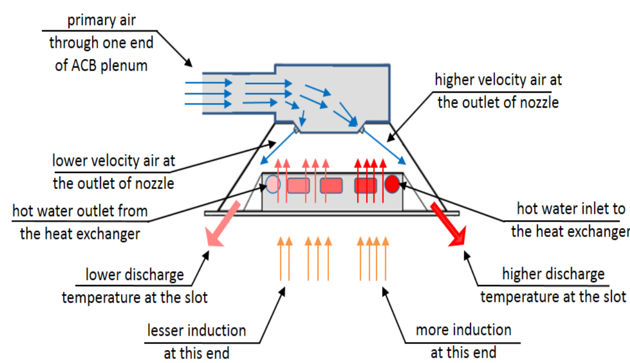


Figure 8 (a) – Discharge Air Velocity at the Two Slots

Figure 8 (b) – Discharge Velocity & Temperatures

Difference in discharge air temperatures at the two slots

The discharge air temperatures were recorded at both the slots and found unequal which can be seen in Figure 9. This could be due to the design and layout of the heat exchanger. The heat exchanger is placed horizontally in the ACB as shown in Figure 8(b). The water flowing into the heat exchanger gradually loses its heat while travelling; therefore, the temperature of the air passing through the heat exchanger is uneven, which in turn causes uneven discharge air temperatures. This effect is enhanced by the different discharge velocities at the two slots as explained above which enhances induction at one end and hence more heat transfer. The hot water inlet to the heat exchanger, higher discharge nozzle velocity (in turn higher induction) coincided at the same side of the tested beam in the experiment and therefore this phenomenon deserves further investigation in a controlled environment with ACB from different manufacturers to compare and analyze. When the room reaches steady state, the non-isothermal jet from ACB turns into an isothermal jet (water flow across the heat exchanger stops or reduced to minimum flow) this phenomenon is then minimized and temperature at both the discharged slots becomes nearly equal as shown in Figure 9.

Surface Temperature Distribution

Figures 11 (a) & (b) shows the surface temperature distribution of room surfaces after attaining the steady state. Each set of temperatures are an average of 15 minutes measured from 12.31 to 4.15 PM. The temperatures of all surfaces were found in line and within ±1°C (±1.8°F) range versus the room setpoint of 20°C (68°F) except the window which can be seen in Figure 11 (a). The window temperature at the top and center were recorded close to the room setpoint temperature but the bottom of the window was found within -2.5°C (-4.5°F) range of setpoint temperature as shown in Figure 11(b). The reason of such variation in temperature is the extended aluminum profile of size 0.1 m (0.33 ft.) depth attached to the window as shown in Figure 10 which causes the obstruction to the airflow down the window and destroys the momentum of hot air flowing down.

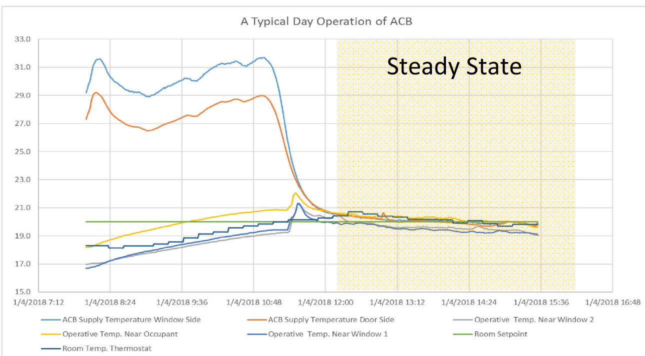


Figure 9 – Discharge Air Temperatures at the Two Slots

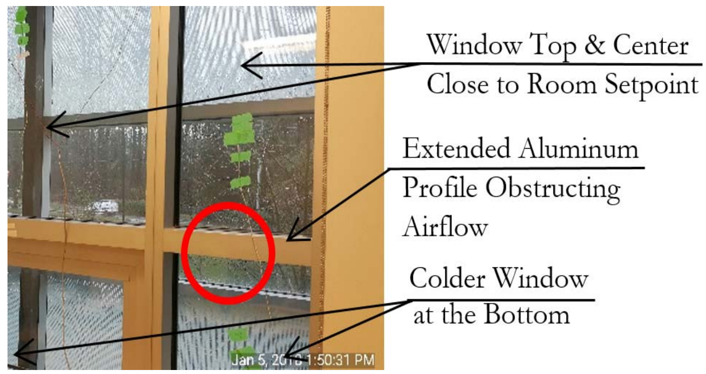


Figure 10 – Aluminum Extended Profile Obstructing Airflow at the Bottom Portion of the Window

Room Air Distribution

Figure 12(a) shows air velocity and air temperature distribution, when room setpoint was 20°C (68°F), at possible occupant's location as shown in Figure 12(b). The velocities were within the ASHRAE recommended limit in the occupied zone to avoid draft. It should be noted that this section presented data only for steady state condition. All measurements were done at the steady state condition with different room setpoints. With the setpoint of 20°C (68°F), the room air is almost uniform and the temperature at a height of 0.6 m (2.0 ft.) can be observed close to the setpoint. Figure 13 shows the temperature distribution at 4 different heights with different room setpoints near the occupant on different days during the experiment. It can be observed that when the setpoint was raised, to 24°C (75°F), thermal stratification starts to appear.

CONCLUSIONS

The intent of the paper was to obtain field data to help appreciate the real factors that affect the performance of ACB in the heating operation, for the benefit of manufacturers and designers. The temperature and air distribution were found satisfactory which concludes that the ACB is effective in providing cooling as well as heating. Coanda effect was realized which prevents direct throw of cold and hot air to the occupied zone. The velocity and temperature distribution at the supply slots of ACB were found uneven, this could be due to the heat exchanger design and duct connection to primary air plenum which requires a further investigation and CFD analyses to model the chilled beam. Surface temperature distribution was also found close to the setpoint temperatures, except for the window. Further study on the transient operation of ACB and CFD model is required to gain insight into the system and its limitations.

LIMITATIONS AND FURTHER WORK

The results reported in this paper correspond to a single office, which can be considered representative of many similar offices in this high-performance building. Other factors affecting the performance of ACB have been observed, such as the proximity of light fittings to ACB, the location of ceiling return grille relative to ACB, partition walls layout, and effect of cold or warm enclosure surfaces on ACB throw. A small sample of offices, some with different configurations, are being studied. Experiments in a controlled laboratory environment are being planned. CFD simulations are also being developed. The results will be reported in separate publications.

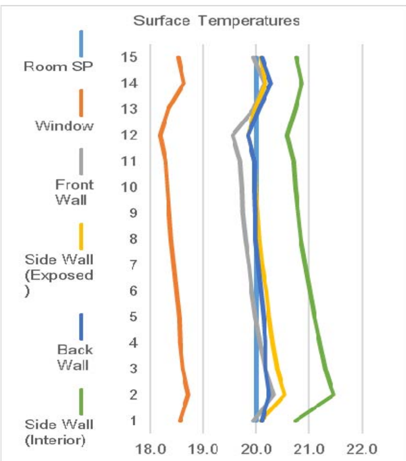


Figure 11 (a) Surface Temperatures

Figure 11 (b) Window Temperatures at the Top, Bottom and Center

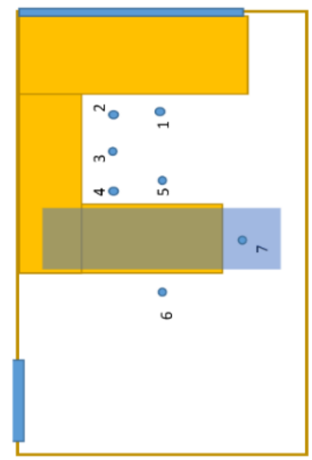


Figure 12 (b) Possible Occupant's Location

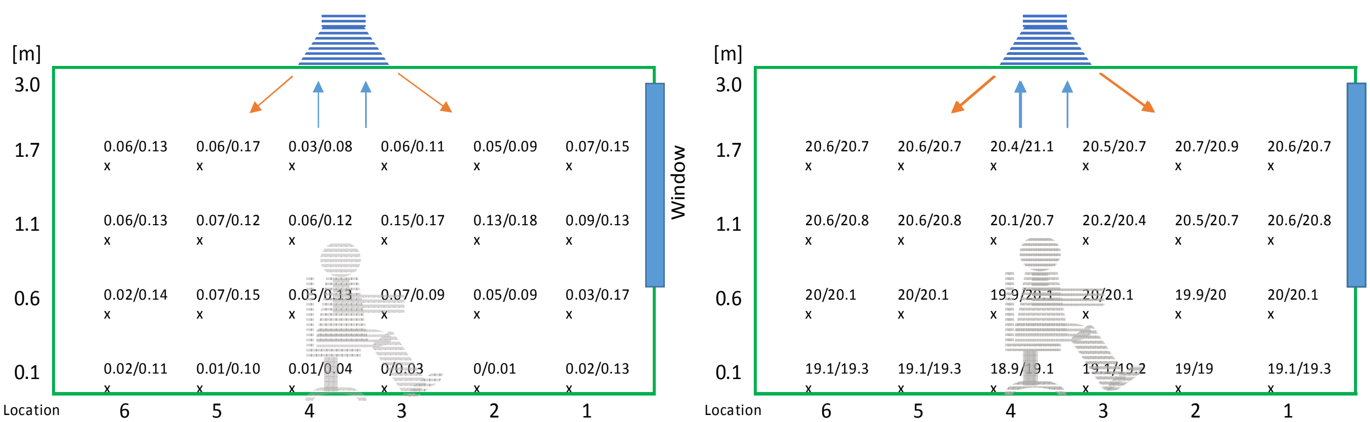


Figure 12 (a) Average / Maximum Air Velocity and Temperature Distribution (at Setpoint 20°C (68°F))

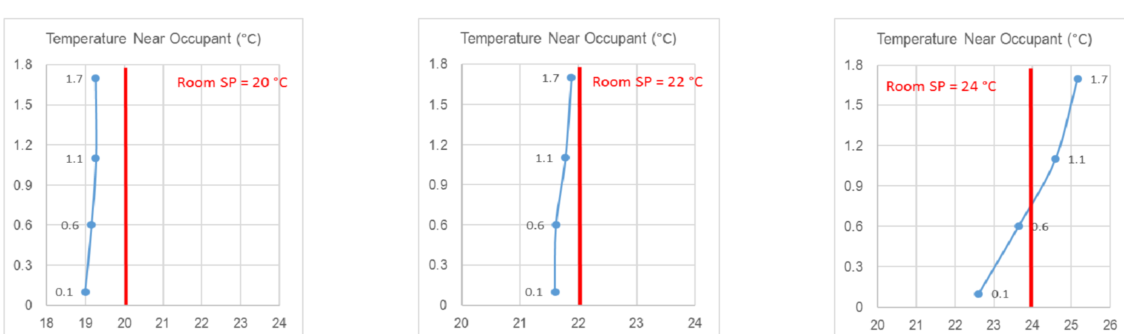


Figure 13 – Temperature Distribution at Different Heights and Different Setpoints near Occupant

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