Performance evaluation of Active Chilled Beam under cooling operation in real office conditions in a high-performance building

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Abstract. This study investigates the operation of Active Chilled Beam under cooling operation in single occupant office in a high-performance LEED Gold Building at the British Columbia Institute of Technology in Vancouver. The thermo-fluid phenomena of room air were studied inside a few offices under cooling operation in stable room temperature conditions. Active Chilled Beams were found performing effectively in cooling mode operation. Surface temperature distribution and the air temperature distribution in the occupied zone were found uniform at all heights and close to the room setpoint. The air velocities were within the recommended air velocity set by ASHRAE Standard for thermal comfort except at the colliding jet between two beams in some offices. The operative temperature measured near the occupant was found close to the room setpoint. The supply air velocity and supply air temperature at both the slots of the beam were found different. It was concluded that the difference in supply air velocity could be due to the uneven pressure distribution in the primary air plenum owing to the connection method of the duct to the primary plenum and the difference in temperature could be due to the circuit arrangement of heat exchanger inside the Active Chilled Beam, which needs further research and investigation of the beam characteristics in a controlled environment.

1. Introduction
HVAC systems provide appropriate indoor environmental conditions for human thermal comfort [1]. In recent decades, energy efficient HVAC systems have been developed at a very fast pace. Active Chilled Beam (ACB) is one of the leading energy-saving technologies where energy is transferred through the water instead of air and without the need for fan energy at the ACB terminal. Many studies have been done in past in a controlled laboratory environment [2, 3, 4]. The application of the ACB system is growing worldwide, therefore, it is necessary to research and analyze its performance under real conditions. The purpose of this study was to assess the performance of ACB under real operating conditions in an academic building under cooling 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 cooling mode.
Figure 1. Working Principle of Active Chilled Beam [6]

ACB is a type of terminal unit where a specific amount of air (primary) discharges through the induction nozzle, which induces room (secondary) air. The induced secondary air passes through the integrated heat exchanger, where it is either cooled or heated based on the water temperature [5]. Figure 1 shows the operation of an Active Chilled Beam [6]. A low-pressure region is created at the induction nozzle by the air leaving out of the beam plenum. This region is slightly lower in pressure than the surrounding room air, which attracts the air. The efficiency of the induction effect is dependent on the number, size, efficiency and discharge angle of the nozzle [7]. It also depends on the density and geometry of the integrated heat exchanger. Modern ACB units are equipped with both the coils, 2-pipe units are capable of either heating or cooling and 4-pipe units are capable of both heating and cooling.

2. Methods

2.1. Experimental facilities

The study was carried out in a 3-storey high-performance LEED Gold Building at British Columbia Institute of Technology (BCIT), British Columbia, Canada. The building is located at 49° 14' N and 123° W, 20 km away from the Vancouver International Airport. This paper discusses one of the perimeter offices on the ground floor with a room size of 4.85 x 3.07 x 3.55 m (15.1 x 9.84 x 9.7 ft.) as shown in Figure 2. The west exposed wall has a fixed window of size 2.90 m (9.67 ft.) wide and 1.75 m (5.74 ft.) high with an operable sash of size 1.4 m (4.6 ft.) wide x 0.5 m (1.64 ft.) high. The walls are highly insulated.

Figure 2. Perimeter Office at Ground Floor at BCIT

2.2. Office Air Distribution System

The cooling or heating in the office room is realized with two ceiling mounted Active Chilled Beams. A return ceiling grille of size 0.6 x 0.125 m facilitates the return from the room. Table 1 presents the details of the ACB unit.

| Table 1. Details 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                     | 2 units                                      |
| Cooling Capacity                           | 2308 W (7875.2 Btu/hr.)                     |
| ACB Plenum Pressure Design                 | 158.0 Pa (0.63 in.wg)                       |
| ACB Plenum Pressure Actual Measured in Office | 130.0 Pa (0.56 in.wg)                     |
Supply Chilled Water Temperature 15.8°C (60.44°F) 14.5°C (60.8°F) 
Primary Air Flow 0.028 m³/s (59 CFM) 0.023 m³/s (50 CFM) 
Primary Air Temperature 18.0°C (64.4°F) 18.0°C (64.4°F) 
Operation Schedule 5.0 M – 10.00 PM

Hourly analysis program calculated the cooling load of the office; the beams were selected to meet the cooling load with the desired noise level with the help of manufacturer-provided software with hydronic and primary air conditions as detailed in Table 1. A central air-handling unit supplies the primary air and water source heat pump supplies chilled water/heating water to the ACB respectively. The Building Automation System (BAS) records the flow and temperature parameters of supplied air and water.

2.3. Office Layout / Load Layout
The ACBs are located asymmetrically in relation to the centerline of the room. One ACB is close to the glass-partitioned wall and one above the occupant as illustrated in Figure 2(c). A suspended ceiling is at a room height of 2.95 m. The room is illuminated by two 80 W ceiling mounted lights. The window is shaded by the projected double façade base and partially by trees, which helps in suppressing the direct solar radiation most of the time during the day. Approximate office thermal internal load is described in Table 2.

| Table 2. Internal Heat Load |
|-----------------------------|
| Lighting Load | 160 W (545.9 Btu/hr) |
| Equipment Load | 200 W (682.6 Btu/hr.) |
| Occupancy | 1 person - 130 W (443.58 Btu/hr.) |

2.4. Measurements
A ‘Tree’ (thermo-anemometer stand) measured room air temperatures and velocity at various locations at four different heights 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.). The tree was placed carefully away from the direct throw from the ACB. Room operative temperatures and globe temperature were also measured close to the occupant. Discharge air temperatures were measured at the two ACB slots, as well as induced air temperatures and air velocities. Surface temperatures were measured for the window, walls, floor and ceiling. Differential pressure (DP) at the ACB plenum, door and window were also recorded. The instruments used for the study are mentioned in Table 3.

| Table 3. Sensor Specifications for Office Experiment |
|-----------------------------|
| Sensor | Application | Type | Range | Accuracy |
| Temperature | ACB Supply / Induced Air Temperature | HOBO MX1101 | -20°C - 70°C (-4°F - 158°F) | ±0.21°C from 0°C to 50°C (±0.38°F from 32°C to 122°F) |
| Temperature | Air Temperature / Operative Temperature | HOBO U12-013 | -20°C - 70°C (-4°F - 158°F) | ±0.35°C from 0°C to 50°C (±0.63°F from 32°C to 122°F) |
| Temperature | Outdoor Temperature | HOBO MX2302 | -40°C to 70°C (-40°F to 158°F) | ±0.2°C from 0 to 70°C |
| Surface Temperature | Wall, Floor, Window and Ceiling Temperatures | NXFT15XH103FA2B050 Thermistor | -40°C - 125°C (-40°F - 257°F) | ±0.2°C (±0.36°F) |
| Air Speed Transducer | Room Air Temp. & Speed ‘Tree’ | SensoAnemo 5100LSF | 0.05 - 5 m/s (9.84 – 984 fpm) | ±0.02 m/s (3.93 fpm) ±1.5% of readings |
| Air Speed Transducer | ACB Supply & Return Air Speed | TSI 8475 | 0.1 – 50.8 m/s (25 – 10000 fpm) | ±2.0% of reading, |

2.5. Experimental procedure
The measurements for the subjected office were recorded with a real occupant working in the office in the month of June and July 2018. The room temperature was varied between 20°C (68°F) to 24°C (75°F) and measurements were performed. The data was recorded when the temperature of the room reaches stability with a variation smaller than ± 0.55°C (1°F) from the room setpoint. Data from temperature
sensors (thermistors) and globe were recorded by Agilent 34972A data logger at every 60 seconds. Anemometer stand was moved manually by the occupant sitting in Office at different locations in the room. The averaging time at each point was about 180 seconds.

3. Results and Discussion

3.1. ACB Discharge Air Velocity

Discharge air velocities (supply) from both the slots of Active Beam were studied in detail and many observations were noted. The velocity measured at 3 equidistant points as shown in Figure 3(d) in one of the slots of the ACB was different in magnitude as shown in Figure 3(a), which could be due to the uneven pressure distribution between nozzles in the beam plenum, the effect of the room thermal load and subsequently the amount of induction takes place at the beam surface. However, the trend of velocities at these points was found almost the same. A similar difference was observed at the other slot of the ACB as shown in Figure 3(b). The average discharge air velocities at both the slots were plotted as shown in Figure 3(c) and found unequal similar to the experiment conducted in heating mode [7]. The same observations were noted in all the offices under study.

![Figure 3. ACB Discharge Air Velocities in Cooling mode](image)

3.2. ACB Discharge Air Temperature

The discharge air temperatures recorded at 3 equidistant points as shown in Figure 3(d) in one of the slots of the ACB were found uniform, similarly, a uniform temperature distribution was observed at the other slot as well, which indicates proper mixing of primary air and secondary (room) air throughout the individual slots. However, the average discharge air temperatures were found unequal at both the slots as shown in Figure 4(a). This difference in temperature could be due to the design and layout of the heat exchanger circuits as shown in Figure 4(b)). The heat exchanger is divided into 2 coil circuits, the chilled water entering into the heat exchanger at a lower temperature gradually absorb room heat while travelling. This makes the coil temperature higher at the leaving end. This effect is further enhanced by the different discharge velocities at the two slots and the subsequent difference in induction at both the ends of the heat exchanger/slots as shown in Figure 4(b). Higher induction at one end and hence more heat transfer and higher discharge temperature at this slot as compared to the other slot.
3.3. Office Surface Temperature Distribution

Figure 5 shows that the temperature of all surfaces follows the room setpoint temperature when varied between 20°C to 24°C to test the response of ACB. The surfaces are in line with the setpoint temperature within ±1°C. The response of ACB was found quick and close to the room setpoint for all surfaces. The operative temperature measured near 1.0 meter of occupant shows that the room operative temperature follows the varying room setpoint. The window temperature also follows the room setpoint except between 3 pm. to 4 pm. due to direct solar radiation on the window, however, the operative temperature near the occupant remains close to the setpoint.

3.4. Room Air Distribution & Thermal Comfort

Figure 6 shows the spatial distribution of air temperature and speed for a plane near the occupant for room setpoint of 22°C. The velocities were found within the ASHRAE Standard 55-2017 recommended
limit (0.2 m/s) [8] for thermal comfort in the occupied zone (points 26 to 6) to avoid drafts. Figure 6(b) shows that the air temperatures are almost equal to the setpoint. The air temperatures near the window (point 3) and the other end of the room (point 40) are lower than the setpoint due to the downdraft. CBE thermal comfort tool is used to assess the thermal comfort using ASHRAE Standard 55-2017. Whole-body thermal comfort (PMV) and local discomfort from the ankle draft are evaluated. The environment variables are obtained from the field tests. Occupant metabolic rate of 1.1 Met and clothing insulation value of 0.7 Clo are assumed for the calculations. The occupant is found thermally comfortable as a whole with neutral sensation. Ankle draft risk is not found due to minimum air speed at the ankle level.

4. Conclusion

The study shows that the discharge air velocity and discharge air temperature at the ACB slots are not equal, however, such differences do not affect the performance of ACB in cooling mode. The temperature distribution across the room was found uniform and close to the setpoint, which shows that ACB performs well in the cooling mode of operation. The air velocity was found within the ASHRAE recommended velocity of 0.2 m/s in the occupied zone. The occupant was found thermally comfortable as a whole and with a minimum risk of ankle draft due to lower air speeds at ankle level. Air movement was noticed across the room at different heights, which further proves that ACB is effective in ventilating the room uniformly with the primary air in cooling mode.

5. Limitations and Further Work

The results reported in this paper corresponds to a single perimeter office in Vancouver climate, which can be considered as representative of many similar perimeter offices in this high-performance building. A small sample of offices with different configurations and modes of operation were studied including CFD modelling and will be reported in separate publications.

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