An experimental investigation of a passive chilled beam system in sub-tropical conditions

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SUMMARY

Chilled beam systems are effective in providing good indoor environmental quality (IEQ) in an energy efficient manner. However, chilled beam systems are not common in sub-tropical climates where the requested cooling capacity is much higher than in temperate climates. This paper reports the findings of physical testing undertaken on a simulated office environment when the maximum cooling capacity was 122 W/m². Tests were also undertaken for higher theoretical heat gains (up to 164 W/m²). The mock up test environment included a 3.6m x 3.6m zone, representing a perimeter zone of an office building in a semi sub-tropical southern hemisphere climate. The purpose of the test was to measure the internal temperature distribution and air velocities for different heat gains and also for changes in internal layout. The test results are referenced to recognised standards for occupant comfort, particularly ISO7730. The conducted measures show that the air velocities in the occupied zone were below 0.25 m/s in all tests and the draft rates were below 20 % in nearly all measured points. The location of the workplace also did not have any effect on the air velocities within the space. This shows that passive beam system, including cooled mechanical ventilation, is possible to cover the requested cooling capacity in sub-tropical conditions without any draft.

BACKGROUND

Chilled Beam Application

The application of passive chilled beams in HVAC (Heating Ventilation and Air Conditioning) design for office spaces has been reasonably commonplace in Europe with examples of the application spanning over the last couple of decades. A common design encompasses a combination of ventilation air, distributed by mechanical means to a ceiling (or floor) mounted diffuser, and mechanical cooling via the passive chilled beam element located above a perforated ceiling. The passive beam element (battery type) itself is essentially a series of water tubes with fins attached to increase heat transfer to the air. Cooled water circulates through the beam. Airflow across the beam is driven by the natural buoyancy effects from air cooling through the beam element. Other solutions are active chilled beams where the room ventilation air is integrated into the room unit. This study is focussed on passive chilled beam systems.

Historically the majority of the application of passive chilled beams has been confined to certain room load densities (typically 50 to 80 w /m²). This is likely to be a symptom of the actual design loads encountered in such European regions. Much research has been undertaken in relation to the performance of various combinations and types of chilled beam products for these load scenarios. Zboril et al [1] investigated the air distribution for active beams with internal loads ranging from 50 to 80 w/m². A paper by Fredriksson et al [2] investigates the effect of the location of internal loads on the airflow and finds that the air plume under the beam can be affected by the placement of internal heat sources. It also identifies that air velocities under the beams can fluctuate. The study does not include the presence of mechanical ventilation air.

Other research, including information published by Rehva [3], recommends benchmark limits of capacity for passive chilled beams for "optimum heat loads" to 80 W/m² (watts per square metre of floor area) with a maximum of 120 W /m². These reports equate this to a specific chilled beam capacity of <150 W/m (Watts per linear metre of beam) when the beam is in an occupied zone, and up to < 250 W/m when installed in a non occupied zone. These limits have been established on the basis of air velocities and particularly draft within the space. The guide states that these values should be used as reference values and special attention should be given to room air velocities for higher heat loads. It is noted that these limits are based upon tests with no additional influences from room ventilation systems.

The performance of battery type passive chilled beam systems, in combination with cooled ventilation air and higher internal heat gains has limited research. This is of particular interest in semi tropical climates, including parts of Australia, where internal gains are higher than Europe due primarily to higher ambient temperatures and solar intensity. Perimeter office room sensible design gains can often reach 120 W/m² (or higher), even with relatively high performing double glazed facades.

The application of chilled beam HVAC design for office buildings is gaining popularity in Australia due to its potential of reduced energy consumption in comparison with traditional all-air variable air volume or constant air volume systems. Local regulation and market expectation is also increasing emphasis on energy efficiency in office building designs. Due to the limited application, the performance of chilled beams for higher heat loads (greater than 80 W/m²) is of great interest.

Of course the application of passive chilled beam systems for higher heat load spaces is not limited to spaces with higher fabric loads. Spaces with higher internal gains (e.g. call centres, TV studies etc) could make inference from this study.

Thermal Comfort

An assessment of thermal comfort includes consideration to a number of influences, which can be measured and quantified. These include Dry bulb temperature, humidity (or moisture), radiant temperatures (exposure) and air velocity (or draft). Much study has been undertaken on the interrelation of these items. This study aims to reference standard ISO 7730 standard (1990) which identifies a basic guideline for thermal comfort. This considers the temperature gradient in the room and also the room air velocities as follows (for summer cooling):

Draft rating (DR): < 20 (for category B space. For category C space this is <25)

Vertical air temperature difference: <3°C from foot to head when sitting or standing.

In general terms the differentiation between category B and C relates to the estimated Percentage of People Dissatisfied (PPD), with B targeting less than 10% and C targeting less than 15%. For general office type spaces category B is considered the appropriate target.

The equation for the determination of draft rating can be found later in this report. In general terms the draft rating takes consideration of both the local air turbulence and dry bulb temperature.

METHODS

The experiment was conducted at Halton Research Center. A test room (L *x* W *x* H = 3.6m *x* 3.6m *x* 3.3/2.8m) was used to simulate a real office. In the test room, two passive beams (CPT-105-605-2600/2400) were installed above the perforated false ceiling (3195 mm from the floor level). Three light fittings (each: 2x28 W/T5) and a swirl diffuser (TSR-160) were installed in the false ceiling at the level of 2800 mm from the floor level. The gross free area of the ceiling panels was 37 % and the perforation holes were 5mm. Close to the window wall, there was arranged an additional opening (300 mm) to improve the buoyancy effect, Fig. 1.

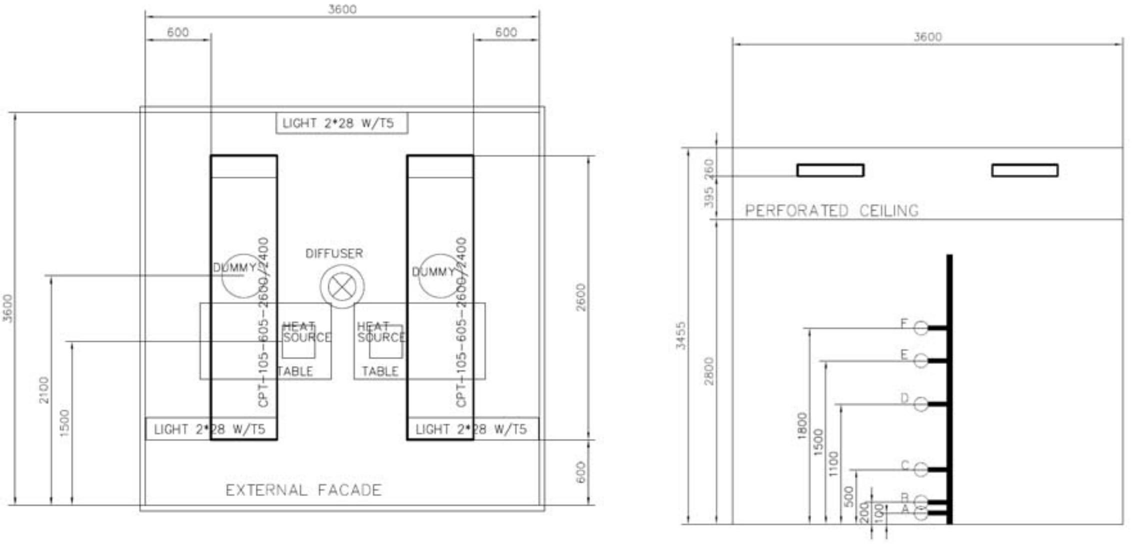

Figure 1. Simulated office (workplace layout 1) and the cross-section of the room space.

In the basic case of 122 W/m^2, the heat loads are: two computers (260 W), two dummies (150 W), light fittings (168 W), warm window surface (35.0 ^{o}C and ~ 600 W) and an electrical foil (400 W) (size of 3.6 m x 1.5 m close to the window) on the floor. The used airflow rate and supply air temperature of the swirl diffuser were 35 L/s (2.7 L/s per m^2) and 13 ^{o}C. The inlet water temperature of the chilled beams was 15 ^{o}C. The requested cooling capacity was arranged by modulating water flow rate of the chilled beams. The room air temperature was in the test cases between 23.5- 24.7 ^{o}C.

Two higher cooling capacity 153 W/m^2 and 164 W/m^2 were also studied. In the case of 153 W/m^2, two extra computers and dummies were installed. The highest cooling capacity (164 W/m^2) was arranged from the case of 153 W/m^2 by increasing the heat gain of the dummies. In this study, there was also analyzed the effect of the location of the workplaces on the performance of the passive chilled beam system. One additional case without false ceiling was measured to analyze the effect of the perforated ceiling panels on the air distribution. The studied cooling capacities and office layout cases are shown in Table 1.

Mean air velocity, air temperature and turbulence intensity were measured within the occupied zone at the locations of 0.1m, 0.2m, 0.5m, 1.1m, 1.5m and 1.8m above the floor. The measurement grid consists altogether 16 locations (altogether 96 points), Fig. 2.

Air flow velocities were measured with velocity sensor type Sensor HT 412 having accuracy ± 1 % of readings. The room air temperature, inlet water temperature, supply and exhaust air temperatures were measured with temperature sensors of type PT100 class A. The water flow rate was measured with Krohne Electromagnetic Flowmeter IFC010 with accuracy less than ± 1% of the readings. The airflow rate was measured with differential pressure transmitter Furness Controls FCO33 with accuracy less than ± 0.5% of the readings.

Table 1. Studied heat load and workplace layout cases.

Case	Room air (^oC)	Water flow rate (l/s)	Heat loads (W/m^2)	Workplace (WP) layout:
1	23.5	0.094	122	1:WP in the middle
2	24.1	0.094	122	2:WP close to the side wall
3	24.0	0.094	122	3:WP close to the window
4	23.4	0.094	122	1:WP in the middle (no ceiling panels)
5	24.7	0.196	153	1:WP in the middle
6	24.1	0.250	164	1:WP in the middle

For measuring of velocity, temperature and turbulence intensity 6-channel low-velocity anemometer HT 400 was used. The used 6 omni-directional velocity probes have spherical velocity sensor with a diameter of 2 mm, ensuring a fast response. The temperature sensor is shielded against radiation. Instantaneous values of velocity and temperature are measured simultaneously. Measurements of velocity and temperatures were time averaged over 180 s.

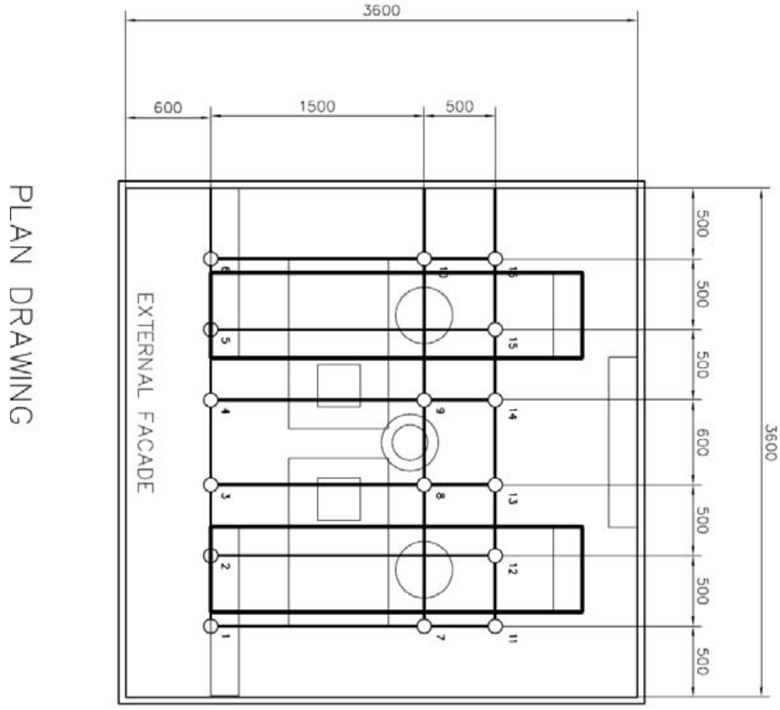

Figure 2. Measurement grid of the conducted experiment when workplaces are in the middle.

RESULTS

In Fig 3, there is presented the measured air velocity, temperature, turbulence intensity and draft rate profiles for test case 1. The measured velocity profile depicts that the air is well mixed over the whole occupied zone. Even with a heat gain of 122 W/m^2, the maximum air velocity was only 0.20 m/s. Also, the draft rate values were acceptable level.

	1				2				3				4				5				6			
Height (m)	v (m/s)	T_a (^{o}C)	Turb. (%)	DR %	v (m/s)	T_a (^{o}C)	Turb. (%)	DR %	v (m/s)	T_a (^{o}C)	Turb. (%)	DR %	v (m/s)	T_a (^{o}C)	Turb. (%)	DR %	v (m/s)	T_a (^{o}C)	Turb. (%)	DR %	v (m/s)	T_a (^{o}C)	Turb. (%)	DR %
1.80	0.09	22.7	41	7	0.07	22.8	41	4	0.06	23.0	45	3	0.06	23.0	60	3	0.07	22.9	46	4	0.09	22.8	53	7
1.50	0.10	22.6	32	8	0.09	22.7	31	6	0.06	22.8	48	3	0.07	22.8	53	4	0.09	22.8	43	7	0.09	22.7	38	7
1.10	0.12	22.6	28	10	0.12	22.6	28	10	0.09	22.6	37	7	0.09	22.7	48	7	0.10	22.7	35	8	0.12	22.7	35	10
0.50	0.09	22.6	39	7	0.13	22.4	33	11	0.12	22.4	35	10	0.12	22.4	35	10	0.11	22.6	40	9	0.10	22.7	45	8
0.20	0.11	22.8	43	10	0.12	22.7	33	10	0.13	22.6	33	11	0.13	22.6	27	11	0.12	22.8	35	10	0.12	22.8	38	10
0.10	0.16	23.1	29	13	0.15	23.0	28	12	0.15	23.0	26	12	0.16	23.0	22	12	0.18	23.2	23	14	0.17	23.2	26	14

	7				8				9				10			
Height (m)	v (m/s)	T_a (^{o}C)	Turb. (%)	DR %	v (m/s)	T_a (^{o}C)	Turb. (%)	DR %	v (m/s)	T_a (^{o}C)	Turb. (%)	DR %	v (m/s)	T_a (^{o}C)	Turb. (%)	DR %
1.80	0.15	22.2	40	15	0.10	22.4	41	8	0.11	22.2	40	10	0.14	22.1	46	15
1.50	0.13	22.2	40	12	0.12	22.3	35	11	0.13	22.1	35	12	0.14	22.1	43	14
1.10	0.10	22.5	46	9	0.14	22.3	34	13	0.14	22.1	38	14	0.15	22.1	38	15
0.50	0.13	22.4	38	12	0.19	22.1	22	16	0.17	22.1	30	16	0.16	22.0	33	16
0.20	0.16	22.1	28	15	0.16	22.1	21	13	0.13	22.2	30	11	0.14	22.1	28	12
0.10	0.20	22.1	22	18	0.18	22.1	22	15	0.15	22.2	31	14	0.15	22.1	29	14

	11				12				13				14				15				16			
Height (m)	v (m/s)	T_a (^{o}C)	Turb. (%)	DR %	v (m/s)	T_a (^{o}C)	Turb. (%)	DR %	v (m/s)	T_a (^{o}C)	Turb. (%)	DR %	v (m/s)	T_a (^{o}C)	Turb. (%)	DR %	v (m/s)	T_a (^{o}C)	Turb. (%)	DR %	v (m/s)	T_a (^{o}C)	Turb. (%)	DR %
1.80	0.14	22.0	43	14	0.09	22.0	49	8	0.09	22.3	44	7	0.10	22.2	44	9	0.17	21.8	47	20	0.19	21.8	38	21
1.50	0.12	22.0	47	12	0.10	22.0	36	8	0.08	22.2	46	6	0.13	22.1	45	13	0.15	21.8	40	16	0.15	21.8	43	16
1.10	0.14	22.0	40	14	0.12	22.0	39	11	0.09	22.1	42	7	0.14	22.0	35	13	0.14	21.9	38	14	0.15	21.8	47	17
0.50	0.13	22.0	39	13	0.13	22.1	38	12	0.12	22.1	34	11	0.13	22.2	37	12	0.14	21.9	34	13	0.12	21.9	40	11
0.20	0.09	22.1	42	7	0.09	22.2	39	7	0.10	22.1	38	8	0.11	22.1	34	9	0.11	22.0	42	10	0.09	22.1	41	7
0.10	0.11	22.1	36	10	0.09	22.2	36	7	0.11	22.2	37	10	0.11	22.1	33	9	0.10	22.0	37	8	0.08	22.1	41	6

Figure 3. Measured air velocity, temperature, turbulence intensity and draft rate in case 1.

Changes in office layout did not have any effect of the performance of the air distribution. This is seen in case 2 &3. The maximum air velocity was 0.20 m/s when the workplaces were located in the middle of the room , close to the side wall or close to the window. Also when the false ceiling was removed, the air velocities did not increased. In fact, the maximum velocity slightly reduced.

When the cooling capacity was increased from 122 W/m^2 to 153-164 W/m^2, the maximum air velocity was increased to value of 0.23 m/s. Also, the draft rate values were acceptable level: only in the couple of points DR- index was higher than 15 %. It should be noted that the typical limit of air velocity is set to 0.25 m/s during cooling season. Thus, the studied chilled beam concept fulfills this international standard threshold for the air velocity even when the cooling capacity was very high 150-160 W/m^2.

Table 2. Measured air velocities and draft rate (DR) in the test cases.

Case	**1**	**2**	**3**	**4**	**5**	**6**
Heat gain (W/m^2)	122	122	122	122	153	164
Workplace location	Middle	Side	Window	Middle	Middle	Middle
v_{max} (m/s)	0.20	0.20	0.20	0.17	0.23	0.23
v_{avg} (m/s)	0.12	0.10	0.09	0.12	0.13	0.13
Line number of the max. velocity	7	2	7	9	10	7
DR_{max} (%)	21	19	20	19	20	20
DR_{avg} (%)	11	8	8	11	11	11
Number of point DR> 15 %	8	2	7	6	16	15
Number of lines DR> 15 %	5	1	3	4	7	6

DISCUSSION AND CONCLUSIONS

Several tests were performed in order to establish the draft and heat gain performance of a mock up passive chilled beam installation under a number of scenarios. In summary these scenarios included:

- Adjustment of internal heat gains from 120 W/m² through to 164 W/m² (all cases);
- Adjustment to the internal layout of equipment, desks and people (case 2&3);
- Adjustment to the water flow rates delivered to the passive chilled beams in order test for increased capacity;
- Removal of perforated ceiling (case 4);

The results identify that within the range of these tests the draft rate (DR) could be maintained below 20 (with one reading at 21 for case 1) which would indicate compliance with ISO7730 For a category B building. More specifically the following was observed.

The removal of the perforated ceiling produced minimal difference to the draft and temperature performance for the internal heat gain loads at 120 W/m². Similarly, increasing the internal gains to 164 W/m² (case 6) resulted in broadly equivalent performance in terms of draft. At first glance this appears to be in contradiction to established limits of performance for battery type passive beam products. However further review indicates that the influence of the mechanically introduced air supply via swirl outlet diffusers has a profound effect on the air flow within the space. This can be illustrated by the smoke test demonstrations where it is apparent that the air movement is driven from these diffusers.

Similarly, adjustments to the internal layout of equipment produced little effect on the air movement. This could be attributed to the relatively small load as a percentage of the simulated fabric and lighting gains, which were fixed.

In all cases, the whole volume is fully-mixed as demonstrated by the measured velocities and from smoke tests. There is not any location in the occupied zone that exhibited excessively high velocities. Also the maximum velocity is approximately 2-times higher that average velocity in all cases.

Temperature distribution across the height of the room in all cases is significantly less than the 3°C target. Again the fully mixed environment is reason for this.

In conclusion it is apparent that the total performance is a combination of the influence of the cooling elements, air diffusion and thermal plumes of heat gains (although in this instance the affect of thermal plume was limited to changes in internal layout, which resulted in negligible affect). Focusing on the performance of a chilled beam element in empty space will not give the total view. All elements should be analysed concurrently. In cases where heat gains are high (> 80 W/m^2) , this is required. Analysis could be undertaken using full-scale mock-up or with CFD simulation. However special attention should be made to the boundary conditions and modelling of heat gains to achieve an accurate result.

These tests found that under certain conditions a combination of cooled air supply through swirl outlet diffusers, and battery type passive chilled beams can provide room sensible cooling capacities of 120 W/m^2 and potentially up to 164 W/m^2 without exceeding the requirements of ISO7730 for occupant comfort for category B office buildings. It is believed that the mechanically introduced air supply plays a significant role in the resultant air velocities within the space. The extent of influence of this is likely to be dependant upon the diffuser selection and airflow rate and this should be given due consideration. The tests presented did not compare different diffuser types so quantifying the effect of this may be the subject of further study.

REFERENCES

1. Zhoril, V., Melikov, A., Kosonen, R. (2006). Air flow distribution in rooms with chilled beams. 17th Air-Conditioning and Ventilation Conference. 17–19 May 2006 in Prague.
2. Fredriksson J, Sandberg M, Moshfegh B. Experimental investigation of the velocity field and airflow pattern generated by cooling ceiling beams. Building and Environment 36 (2001) pp. 891-899
3. Rehva. Guidebook no.5. Chilled Beam Cooling. Federation of European Heating and Air-conditioning Associations.