A case study on the application of underfloor air conditioning and ventilation system in a school assembly hall

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ABSTRACT

Floor return (FR) type underfloor ventilation system was installed in the assembly hall of a primary school in Hong Kong. Experimental investigations on the airflow and temperature characteristics were conducted. Pollutant distributions were also measured with different fresh air supply rates. Results reveal that the use of low momentum floor supply panels reduced the risk of draught discomfort and created a more significant temperature stratifications compared to those with fan boosted type floor air terminals. Ventilation of polluted air was localized up to the occupants' breathing level. The performances of the system indicated possibilities in reduction of energy consumption and improvements in indoor air quality over the traditional ceiling-based systems.

INDEX TERMS

Underfloor ventilation; Facility management; Temperature stratification; Thermal comfort; Floor return

INTRODUCTION

Providing air conditioning in large open plan premises with high headroom has been a major problem for HVAC designers. Examples of such premises include school assembly halls, manufacturing plants, atriums, airport/train station passenger terminals, convention centres, etc. Ventilation of such premises has been a hot topic for researchers (such as Nishioka *et al.*, 2000; Chow *et al.*, 2002) because these premises have several unique features that created many challenges in system designs. One major difference between these types of premises and typical office spaces is the ratio of the occupied volume to the total volume of the building. In those large open plan premises, this ratio is usually much smaller than that found in typical office spaces. The thermal buoyancy effect due to the internal heat load and temperature differences plays a more important role in determining the airflow and heat transfer in the space. Due to the smaller ratio of the occupied volume to the total volume, considerable amount of energy can be saved by keeping the occupied volume in the desirable temperature while leaving the upper space at higher temperature. This can be achieved by promoting temperature stratification in the space using vertical air distribution systems (Kim *et al.*, 2001). However, this temperature stratification must be balanced by thermal comfort considerations especially within the occupied area (Webster *et al.*, 2002).

Much of the recent research has been falling into the investigation of the performance of underfloor ventilation systems in such applications (Fisk *et al.*, 1991; Faulkner *et al.*, 1999). Underfloor ventilation systems are usually built with the raised floor systems, which create underfloor plenums for conditioned air distribution. The underfloor plenum can also be used for flexible facility managements. Therefore, it has been gaining popularity in modern office buildings, especially the so-called 'intelligent buildings'. These underfloor ventilation systems are found in two major configurations: top return (TR) type and floor return (FR) type.

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Conditioned air is supplied from the floor for both the TR and FR systems. Room air is returned near or at the ceiling level for the TR type system while room air is returned at the floor level for the FR system. Most of the previous studies focused on the TR system as it resembles some features of the displacement system (Faulkner *et al.*, 1999). Only a few studies have been reported for the FR system (Wan and Chao, 2002). This research aims at investigating the air velocity, temperature and pollutant distributions in a large open plan space ventilated by the FR type underfloor ventilation system.

METHODS

The primary school was located on a hill slope in the suburb area of Hong Kong. There was a secondary school next to this primary school and the nearby area was built with some low-density residential buildings. Experiments were carried out in the assembly hall, which was on the first floor of a separate two-storey building in the school campus. The ground floor of the assembly hall building was a fully open area. Inside the assembly hall, the usable floor area was about 347 m^2. The internal floor height measured from the finished surface of the raised floor to the ceiling was 3.8 m. The layout of the assembly hall is shown in Figure 1.

The ventilation system installed in the school hall was a floor supply FR type underfloor ventilation system. A layer of raised floor was built on the original wooden floor, which created a 250 mm deep underfloor plenum for conditioned air distributions and accommodations of other cable trunks. Since both supply and return air plenums were located underfloor, air baffles were installed to partition the floor plenum into supply zone and return zone. Two air-handling units (AHUs) were installed to condition the plenum air. Conditioned air was supplied to the occupied zone through 18 perforated floor panels. Each of these panels had 2304 air holes of 6 mm diameter for air diffusion. Another 18 perforated panels were installed in the return zone for room air return. The two AHUs had individual fresh air duct with variable air volume dampers to both sides of the hall for fresh air intake as indicated in Figure 1.

Experiments were carried out during the spring of 2003. Before the occupants went into the hall, the air conditioning systems were turned on for 1 h. The measurements were started an hour later and then the occupants got in. Each experiment lasted for about 1 h. During each experiment, there were about 70 occupants in the hall. The occupants were primary schools students aged from 10 to 12 years. The students were performing singing or reciting practices during the measurements and most of them were in standing posture at the positions indicated in Figure 1. Room air temperature set point of the AHUs was 20°C. Supply air volume of each AHU were 3120 m^3/h and the average supply air temperature was about 15°C. The supply air volume of each perforated floor panel was about 340 m^3/h. Two fresh air supply rates were set during the experiment. The higher one was 2000 m^3/h of fresh air that corresponded to about 8 l/s/person in the first experiment. This fresh supply rate was the same as that recommended by ASHRAE (2001). In the next test, the fresh air supply rate was lowered to 1600 m^3/h, which was about 6.35 l/s/person.

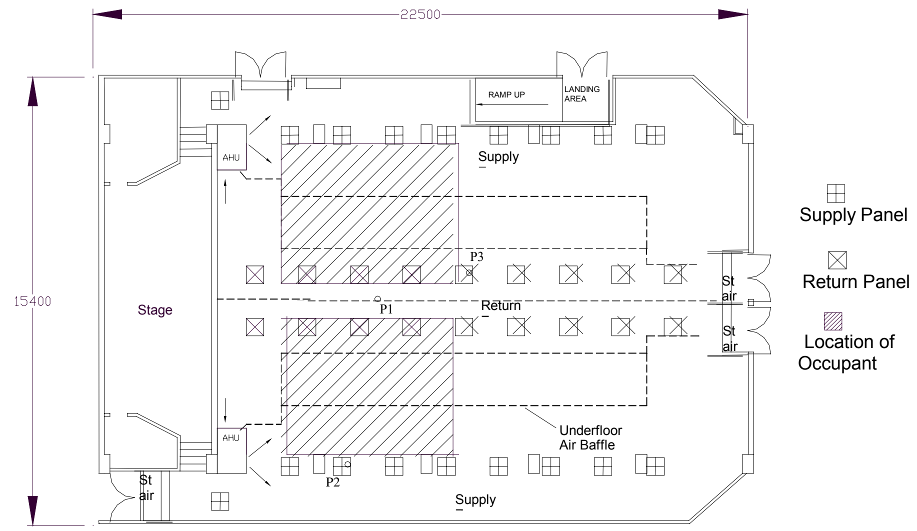

Figure. 1 Layout of the experimental school assembly hall.

Vertical distributions of air velocity and air temperature were measured at 10 height levels (0.1, 0.6, 1.1, 1.45, 1.7, 2, 2.5, 2.9, 3.3 and 3.75 m above the floor). Carbon dioxide concentrations were measured at six height levels (0.1, 0.6, 1.1, 1.7, 2.6 and 3.75 m above the floor). Due to the high activity level in the hall, installation of permanent measuring posts was not possible. A measurement cart installed with a measurement post of 3.8 m high was utilized as shown in Figure 2. Air velocity was measured by an omni-directional velocity transducer, which had an accuracy of ±0.01 m/s and a sensor response time of 5 s. Air temperature was measured by thermistor type temperature sensors with an accuracy of ±0.1°C and response time of 1 s. Air velocity and air temperature at every measurement point were measured for 3 min with a sampling frequency of 0.2 Hz. Carbon dioxide concentrations were measured by a non-dispersive infrared type sensor. The accuracy of the CO_2 sensor was ±5% of the reading. The response time of the CO_2 sensor was 60 s maximum for 90% of step change. Air sample was drawn to the carbon dioxide detector by using an air sampler pump. The pump was able to maintain a constant sampling airflow rate during air sampling. TYGON chemical resistant laboratory tubing was used for connecting the sampling system to the measurement points. Air samples were drawn for 3 min at each measurement point where the first minute was for flushing the 'old' air residues inside the sampling tube. The concentration reading was not recorded during flushing. A gas multiplexing system was developed for this multi-point measurement purpose. The gas multiplexer consisted of solenoid valves with variable time interval select switch. The internal gas pathways were also constructed by TYGON laboratory tubing. A PC-based data logging system was installed on the measurement cart for data acquisition.

RESULTS AND DISCUSSION

Air Velocity Characteristics

The measured air velocity profiles were plotted in Figure 3. The air velocity profile obtained in P1 shows that air velocities at different height levels were kept below 0.2 m/s. The result indicated that with the use of the floor supply ventilation system, there was no excessive air movement induced in the occupied area that could create high risk of draught. The velocity profile for P2 was obtained at the centre of a perforated supply panel. The profile shows that the air velocity at 0.1 m above the perforated panel was still high enough to create draught discomfort. However, the air velocity decayed much faster against the height than those more commonly used floor air terminals mounted with booster fans and supply air grilles such as that reported in some previous studies (Han *et al.*, 1999; De Carli *et al.*, 2000). These previous reports showed that the fan boosted supply terminals created a large column of draught discomfort zone above the supply vent up to the occupants' head level. The result indicated that the use of perforated panels was more suitable in premises like the experimental school hall where long-term exposure of the occupants right above or near the supply vent was unavoidable. The velocity profile showed that the supply air had very weak upward momentum and the supply jet turned into plume like flow characteristics after being released from the supply panel for a very short distance. The velocity profile for P3 was measured at above a return panel. The profile was very similar to that obtained at P1, which indicated that the presence of the return panel did not have significant effect on the air velocity at the space above it. The location of the return panel inside the occupied region did not create uncomfortable air draught to the occupants.

Figure 2 The measurement cart.

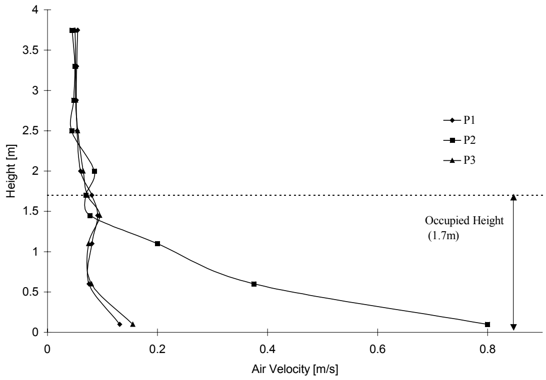

Figure 3 Air velocity distribution

Air Temperature Characteristics

Figure 4 shows the vertical temperature profiles obtained at different measurement positions. The figure indicated that significant temperature stratifications were created in the hall. The measured head (1.7 m) and foot (0.1 m) temperature difference in the occupied area, P1, were 2.8°C, which marginally met the comfort standard recommended by ASHRAE (1992) of 3°C. Air temperature kept increasing at higher height level. Near the ceiling level, the air temperature was about 23°C, which was about 3°C higher than the room temperature set point. The temperature profile obtained at P2 represents the temperature distribution above the supply floor panels. It can be observed that the air temperature increased sharply right after leaving the panel instead of maintaining a uniform temperature for a certain height. This indicated that the supply air jets from the perforated panel had very weak upward momentum. The supply jet air temperature became equalized at the height level of about 1.1 m and then followed the same distribution pattern as that in the occupied region at higher height levels. The vertical air temperature profile measured above the return panel, P3, showed similar pattern as that for the occupied region. This indicated that the presence of the return panel did not have significant impact on the temperature distribution in the space above it. Recalling the results of air velocity distributions, such high level of temperature stratification could be due to the weak supply air jet momentum with the use of perforated supply panels.

The above results indicated that with the use of underfloor ventilation system, the occupied area could be kept in desirable air temperature while leaving the upper space at higher temperatures. This feature is particularly favourable in buildings with high headrooms such as assembly halls or atriums as it reduces the volume of air that has to be kept at the comfort temperature. Energy saving can be achieved (Kim *et al.*, 2001). However, the system has to be carefully designed in order to prevent thermal discomfort due to draught near the supply terminals and excessive temperature stratifications.

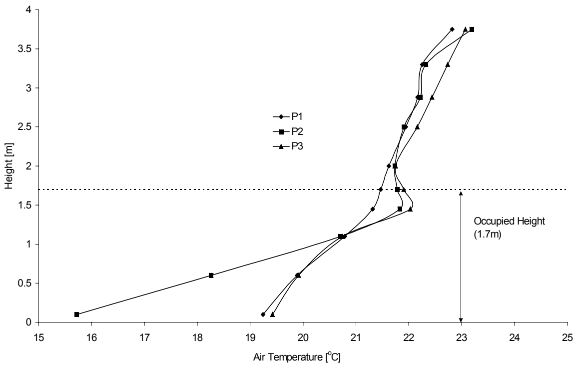

Figure 4 Vertical air temperature distributions.

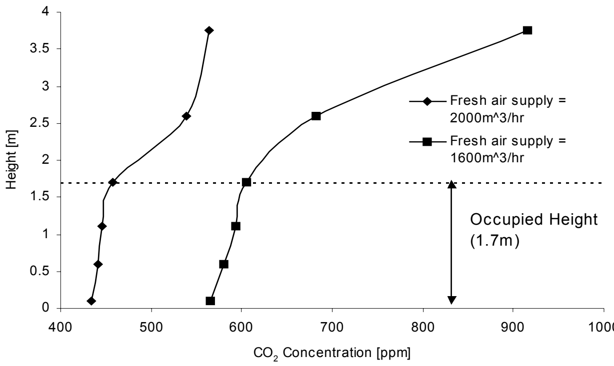

Figure 5 Vertical CO_2 concentration distribution.

Pollutant Distributions

Figure 5 shows the carbon dioxide concentration profile measured at P1 for the two different fresh air supply rates. Results from both the experiments show that the concentrations were kept relatively uniform from the floor level up to about 1.7 m above floor. At levels higher than this height, the concentration increased sharply until up to the ceiling level. The concentration profile indicated that a localized ventilation pattern was achieved. Sufficient ventilation was provided by the system limited to the height level of 1.7 m, which was high enough to cover the breathing levels of human beings, especially for primary school students. Higher pollutant concentrations were left in the upper space that was already outside the breathing heights. By comparing with the traditional ceiling-based mixing system, which usually creates a uniform pollutant distribution, the underfloor ventilation system improved the indoor air quality in the breathing zone by localizing the ventilation up to the occupied area only.

CONCLUSIONS AND IMPLICATIONS

Airflow and temperature characteristics were experimentally investigated in a 340 m^2 primary school assembly hall. The hall was ventilated by a FR type underfloor ventilation system. Pollutant distribution was also measured. Results indicated that with the use of low momentum perforated floor supply panels, significant temperature stratification was created in the occupied area and the upper space. The temperature stratification in the occupied area marginally met the international comfort requirement. High risk of draught discomfort could occur at space that was above the supply panel but the affected area was greatly reduced compared to those fan-boosted floor air terminals. Ventilation of polluted air was localized into the occupied area, which indicated possibilities in indoor air quality improvements over the traditional ceiling-based mixing system.

ACKNOWLEDGEMENTS

This research was conducted under the financial support from the Innovative Technology Fund of the Government of the Hong Kong SAR through grant no. UIM/7. Thanks must be given to C.C.C. Kei Wai Primary School for their support on this work. The contribution from

Mr S.C. Ho in part of the experiments is acknowledged. The ventilation system and other related engineering works in the experimental assembly hall were designed and built by Acron International Technology Ltd.

REFERENCES

ASHRAE (1992). *ANSI/ASHRAE Standard 55-1992. Thermal Environmental Conditions for Human Occupancy*. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE (2001). *ANSI/ASHRAE Standard 62-2001. Ventilation for Acceptable Indoor Air Quality*. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Chow, W.K., Fung, W.Y. and Wong, L.T. (2002). Preliminary studies on a new method for assessing ventilation in large spaces. *Building and Environment* **37** (2), 145–152.

De Carli, M., Peron, F., Romagnoni, P. and Zecchin, R. (2000). Analysis of air velocity and temperature distribution in furnished rooms with underfloor air diffusers. *Proceedings of the 7th International Conference on Air Distribution in Rooms—ROOMVENT 2000*, Reading, Vol. 2, pp. 687–692.

Faulkner, D., Fisk, W.J., Sullivan, D.P. and Wyon, D.P. (1999). Ventilation efficiencies of desk-mounted task/ambient conditioning systems. *Indoor Air* **9** (4), 273–281.

Fisk, W.J., Faulkner, D., Pih, D., McNeel, P.J., Bauman, F.S. and Arens, E.A. (1991). Indoor air flow and pollutant removal in a room with task ventilation. *Indoor Air* **3**, 247–262.

Han, H., Chung, K.S. and Jang, K.J. (1999). Thermal and ventilation characteristics in a room with underfloor air-conditioning system. *Proceedings of the 8th International Conference on Indoor Air Quality and Climate—Indoor Air ‘99*, Edinburgh, Vol. 2, 344–349.

Kim, K.H., Kang, S.Y., Lee, J.H. and Oh, M.D. (2001). Analysis of thermal environment in an airport passenger terminal. *Numerical Heat Transfer, Part A* **40** (5), 531–541.

Nishioka, T., Ohtaka, K., Hashimoto, N. *et al.* (2000). Measurement and evaluation of the indoor thermal environment in a large domed stadium. *Energy and Buildings* **32** (2), 217–223.

Wan, M.P. and Chao, C.Y.H. (2002). Experimental study of thermal comfort in an office environment with underfloor ventilation system. *Journal of Indoor + Built Environment* **11** (5), 250–265.

Webster, T., Bauman, F. and Reese, J. (2002). Underfloor air distribution: thermal stratification. *ASHRAE Journal* **May**, 28–36.