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A feasibility study of a ventilated beam system in the hot and humid climate: a case-study approach

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Abstract

The applications of ventilated beam systems in the hot and humid climate are limited. The main reason is the high risk of condensation. A case-study measurement was conducted in a typical office building in Singapore to investigate the feasibility of a ventilated beam system in the Tropics. The results show that the condensation in the beam system is possible to prevent and to reach dry cooling if infiltration is minimized, supply airflow rate is sufficient to extract humidity of people and tuning of the automation system has conducted probably.

Keywords: Ventilated beams; Air–water systems; Humidity control; Hot and humid climate

1. Introduction

Concerns over indoor environment have increased during recent years as a result of the knowledge on the significance of the thermal conditions and air quality on the health, comfort and productivity of the workers. Recent studies have shown that poor indoor air quality has a negative impact on thermal comfort, productivity and health issues [1,2]. Thus, it is possible to demonstrate that an investment for a better ventilation system is already profitable with modest productivity improvements in the workplace [3].

In the Tropical climate, it is important to control relative humidity concurrently with temperature. Many studies have been carried out to investigate the effect of humidity on human health and indoor pollution such as fungi, dust mites, particles, bacteria, viruses, pollutant emissions from building materials, respiratory and skin diseases. The effect of temperature and humidity on the perception of indoor air quality has been researched [4]. Decreasing the indoor air temperature and humidity could improve the perceived air quality significantly. The results have shown that the acceptability of indoor air increases linearly with decreasing enthalpy of air.

The majority of air conditioning systems installed in the Tropics are designed based on the mixing strategy. That is, e.g., variable and constant volume all-air systems. On correct design, these systems can offer high standards of comfort and air quality. It may however be that this happens at the expense of high running costs.

It should be noted that with the traditional mixing system about 85–90% of the supply airflow rate is circulated from the office spaces and only 10–15% of the total airflow rate is from outdoor. Hence, it is possible to reduce the cost of the ductwork significantly with the systems, which bring in only the required minimal outdoor airflow rate in the room spaces.

Ceiling-mounted ventilated beam system could be another attractive approach for improving energy and ventilation efficiency. These systems minimize the quantity of air handled and have the ability to provide a high-quality indoor environment. This means that the

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space requirement of ductworks and air-handling units are much smaller than the traditional mixing systems. This means savings in the structural and building services costs.

In the building process, the initial cost is still the main criterion when making choices between different systems. With life-cycle cost (LCC) calculations, it is possible to get a better overview of the total cost. The ventilated beam system was analyzed and compared to other typical systems. The LC cost of the ventilated beam was lower than the variable air–volume and fan–coil systems in the temperate climate [5].

In this paper, the feasibility of a ventilated beam system in the Tropical climate is studied using a case-study approach. Field measurements were conducted in two rooms of an office building, located in Singapore, served by a ventilated beam system. A comparative analysis on the infiltration during nights is carried out in a reference mixing-ventilated office to get more generic view of the air tightness of typical old office buildings.

2. Review of air–water systems

The development of ceiling mounted without fans-powered air–water systems has evolved three different branches: (1) radiation-ceiling panels, (2) passive convection-chilled beams and (3) active-ventilated beams. The differences between these systems are the principles of heat transfer. In the ceiling, the main heat transfer occurs by radiation. In the latter systems, it is either natural (passive beam) or forced (ventilated beam) convection.

There are some publications on the theoretical background of the radiation-ceiling system integration with displacement ventilation, e.g. [6] and passive beams, e.g. [7,8] in the temperate climate. To date, there is not much work done on the analysis relating to ventilated beams and no publication dealing with ventilated beams in the hot and humid climate.

Ventilated beams can be divided into two groups: freely installable without suspended ceiling and beams for installation in suspended ceilings. The beams in the ceiling can be divided into two subgroups: open beams and closed beams. In the open-beam system, the induction air circulates over the suspended ceiling. In a closed-beam system, air circulates only inside the device itself and is not permitted into it through the suspended ceiling. In this way, a closed-beam structure helps to improve the quality of the supplied air.

In the ventilated beam system, it is also possible to integrate all requested building services such as lighting and various detectors in a prefabricated room unit. This prefabrication improves quality control and reduces the installation time of the system. It also gives the flexibility for future layout changes and gives the possibility to create new solutions of interior design.

In the hot and humid climate with a small diurnal range and lack of seasonal variations, the risk of condensation with air–water systems is obvious. The main features of the Tropical climate are uniform temperature, high humidity and abundant rainfall throughout the year. In Singapore, the average dew point is about 24 °C and the humidity ratio of 18.5 g/kg during the nights and 19.5 g/kg in the daytime is almost constant throughout the year [9]. The rain will increase the humidity level of outdoor air and significantly reduces the heat gain through building walls [10]. It is found that the average reduction in heat gain for a total of 267 rain days is about 10%.

The risk of the condensation can be prevented with proper control strategy and minimize infiltration as found by Novoselac and Srebric [6] in the study of a radiation-ceiling and displacement ventilation system. Results show that the humidity ratio could be higher near the ceiling panels than the total mixing assumption due to the humidity gradient of the radiant-ceiling and displacement system. Thus, the surface temperature of the panel should be at least 1 °C higher to avoid condensation than with perfect mixing assumption indicates.

The condensation risk of the radiation-ceiling in hot and humid climate is also analysed with energy simulations studied by Zhang and Niu [11]. This study has shown that the room air needs to be dehumidified properly prior to the operation of radiant-ceiling system. In the study, the influence of the infiltration on indoor humidity for the morning start-up is negligible if dehumidification is implemented 1 h in advance. Using this control strategy, it is possible to have dry cooling during normal working hours.

The effect of infiltration through building envelope [12] and large openings [13] can be calculated if the characteristics of the building envelope and pressure difference over the outdoor and indoor air are known. The infiltration calculation requires data on local wind speed, pressure and air tightness of the structures, which are seldom available.

It should be also noted that the moisture absorption and desorption of building and interior materials should be taken into account particularly in the condensation risk analysis of early morning start-up period. It is estimated that one-third of the moisture generated in a room could be absorbed by the interior surfaces [14]. Theoretically, the moisture absorption and desorption can be computed [15] but the required information is rarely in place.

3. Experimental work

The feasibility of a ventilated beam system is evaluated using field measurement in an office building.

The condensation risk during the morning start-up period and operation hours is studied by monitoring room conditions. The night-time infiltration and the moisture absorption of the room building material are also analysed in another less air tight building to get a more generic view of the infiltration in old office buildings. In this paper, the limitations and design criterion for the ventilated beam systems in the hot and humid climate are also discussed.

3.1. The ventilated beam office

The measurements were conducted in a typical office building in Singapore. This three-storey building was initially a light factory. Recently, the floor that was used for study has been renovated.

In the renovation, all internal building materials were replaced and the present open space converted to partly open and partly personal room office layout. There was no retrofitting of the external walls and the windows that improves the air tightness of any part of the building envelope. The windows are non-openable one panel with metal frame and sealed gaskets (Fig. 1).

The total area of the office is 3970 m^2. In the office, two rooms were installed with a ventilated beam system. The rest of office rooms are served by the mixing system.

Fig. 1. The window structure of the ventilated beam office.

Fig. 2 shows the layout of the studied office and pointed out location of the studied ventilated beam rooms.

An office of 20 m^2 is located in the perimeter zone where possible air infiltration increase humidity level. The other room is a conference room of 56 m^2, which is located in the central area. This internal room is not affected by infiltration and the main humidity source is from the people. In the office room, four and six beams are installed in the conference room. The length of each beam is 2.1 m. Figs. 3 and 4 shows the layout of the studied rooms.

3.2. Ventilated beam system and measurement

The studied office and conference rooms are equipped with a ventilated beam system. In the beam system, there is a connection to the supply air ductwork from which the air enters in the plenum of the ventilated beam. Further in the ventilated beam, the air supplied from nozzles induces the room air through water coil. The mixture of the supply air and induced air is introduced into the room space through longitudinal slots along both the sides of the ventilated beam. Fig. 5 depicts the structure of the ventilated beam.

In temperate climate, the temperature of the supply air is typically 16–18 °C and the water inlet is 14–16 °C. In Tropical conditions, the supply air temperature should be designed to be lower and the temperature of the water inlet to be higher to prevent condensation. In Table 1, the values of the main design parameters of the system are shown.

The system is equipped with room controllers and two-way motor valves, which makes individual temperature control possible in the rooms.

To avoid possible damage due to condensation, ventilated beams are provided with a drainage system. Besides, the internal plenum of the beam is insulated to reduce possible condensates falling in the room. With these measures, it is possible to study different combinations of the set points without causing any problems in the normal use of the spaces.

In Fig. 6, the concept of the ventilated beam system and the measurement points is shown. The supply airflow rate is totally coming from outside and there is no re-circulation applied in the system. The designed specific airflow rate was 2.8 l/s per m^2 (19 l/s per person) in office and 2.5 l/s per m^2 (11 l/s per person) in the conference room. The return air is extracted to the other air-handling unit, which served the other part of the office. The used supply and return airflow rates are equal.

The three-way valve is used to rise up the water inlet temperature to the requested level (16–17 °C) from the normal supply temperature of the chiller (6–7 °C). With the design set points, the water-based cooling of the ventilated beam is about 2/3 of the total space cooling

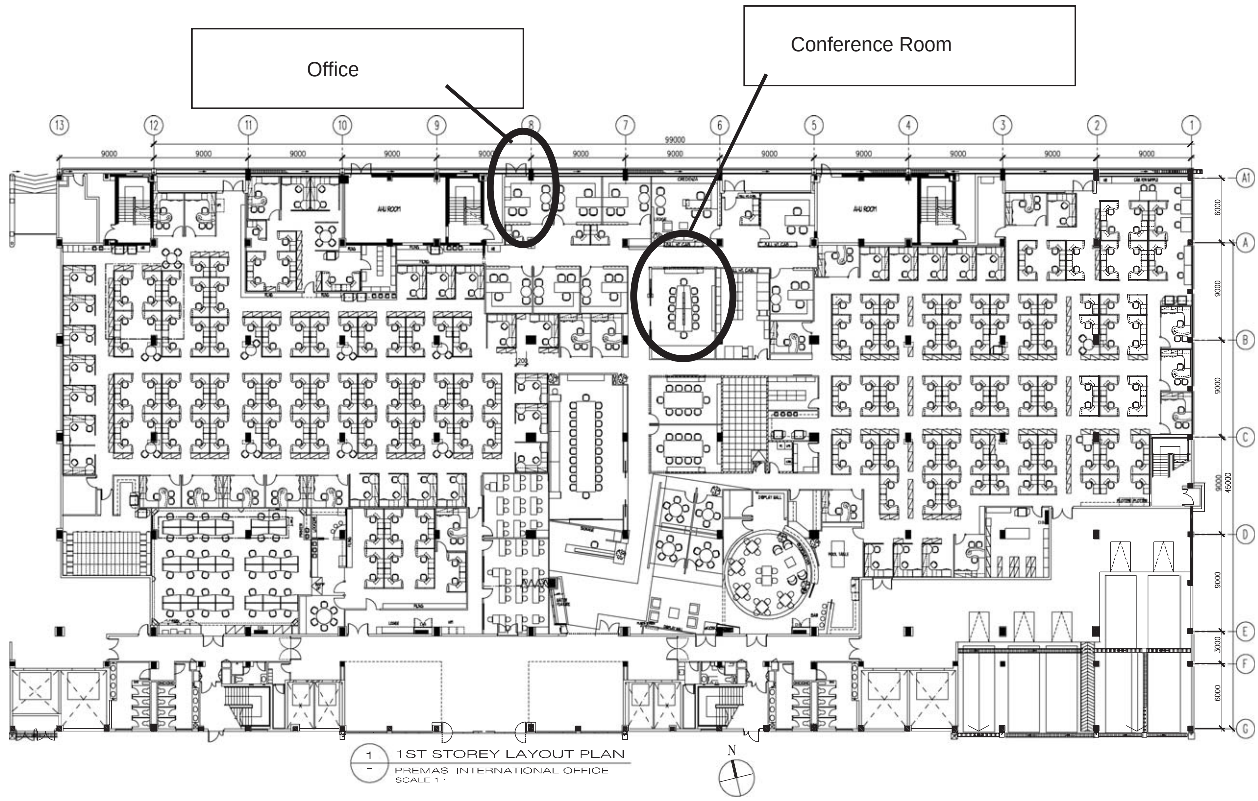

Fig. 2. The office layout and the locations of the ventilated beam office and conference rooms.

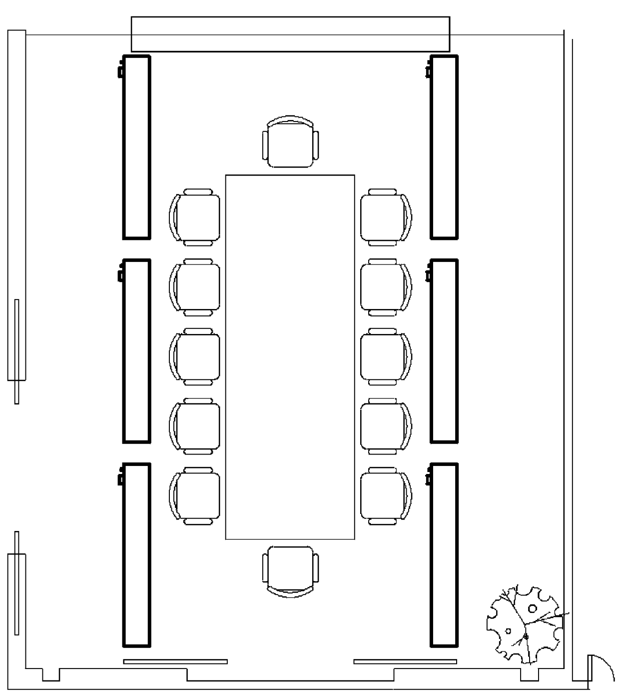

Fig. 3. The ventilated beam installation in a conference room.

capacity. Both the air-handling unit and the inlet water pump are running between 7:30 a.m. and 9:30 p.m. during weekdays.

For the humidity control point of view, it is an advance to start air cooling before the water-based cooling. In this test facility, there is still no special control strategy and the water-based and air-based cooling start at the same time.

In the measurement arrangement, the room temperature and humidity is measured with portable data logger. The same system is used to measure the supply air and outdoor conditions. The portable data logger calculates automatically all requested parameters of humid air, e.g., dew point and humidity ratio from the measured dry bulb temperature and relative humidity.

The supply airflow rate to the room spaces is measured using a pressure measurement tap of the ventilated beam. Using the technical specification of the product, the supply airflow rates are determined.

The water inlet and outlet temperatures were measured with the thermocouples installed on the water pipe. A proper contact of the thermocouples is secured using glue and covered the thermocouples with the insulation. Table 2 shows the measurement instrument used and the accuracy of the measurement arrangement.

3.3. Description of a reference building

The night-time infiltration and the moisture absorption of the room building material are analysed in a reference building to get more generic view of the

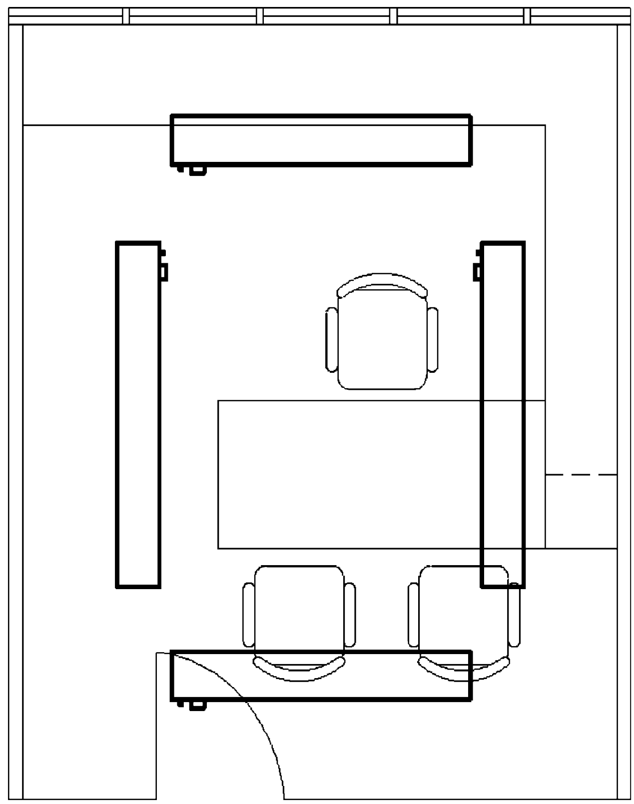

Fig. 4. The ventilated beam installation in an office room.

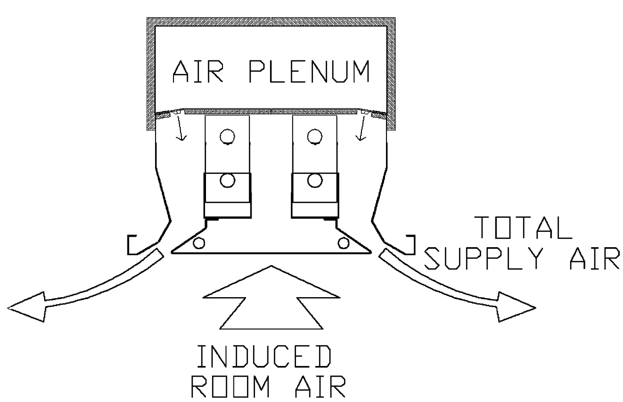

Fig. 5. In a ventilated beam, the supplied air from nozzles induces room air and the total supply air is introduced through longitudinal slots into the room space.

infiltration in older office buildings. The studied reference building is about 30 y old before energy crisis built institutional office building. In this building, there are obvious infiltration routes, e.g., in the window frame and cracks under doors.

In the reference building, two different offices were measured: (1) open layout office of 104 m^2 for five persons and (2) one person's office room of 14 m^2. In

Table 1
The design conditions of the ventilated beam system in the case-study office

Design conditions	Conference room	Office
Indoor temperature (°C)	23	23
Relative humidity (%)	60	60
Room area (m^2)	56	20
Sensible load (W)	2360	1780
Specific load (W/m^2)	42	89
Number of persons	20	3
Off-coil temperature (°C)	14	14
Air flow rate (l/s)	147	56
Water inlet (°C)	16	16
Water outlet (°C)	18	18

both of these spaces, there are openable windows and the doors of the offices lead to the corridor that is directly linked via non-airtight door to outdoor air. The open layout office is served with the normal constant air–volume system and the variable air–volume system is served to the person's open office.

The operation period of the chiller is from 7:30 a.m. to 10:00 p.m. during normal weekdays. Based on the conducted measurements, the air-handling units are started earlier and run longer to purge the room spaces. The operation time of one person's office is 7:20 a.m.–10:35 p.m. and 7:00 a.m.–10.45 p.m. in the open layout office. Room temperatures and outside air were measured using portable data logger (Table 2). The supply and the off-coil temperatures are measured using a calibrated hand meter with temperature accuracy of ±0.3 °C and humidity accuracy of ±3%. The supply airflow rate is measured from the diffuser (office room) with the hood and vane anemometer (accuracy ±5%) and from the grilles with the average face velocity method (estimated accuracy ±10%).

4. Results

4.1. Measurements in a ventilated beam office

In Figs. 7 and 8, the measurement results in the case-study building are shown. Fig. 7 depicts the operation of the system during one working day and Fig. 8 during 6 days, respectively. The room temperatures are 21–23 °C in the conference room and about 23 °C in the office room. The dew point of the conference room is about 17 °C and 14.5–16.5 °C in the office. The relative humidity is 65–70% in the office and 70–75% in the conference room. During this measurement period, the water inlet and the off-coil temperature were adjusted to be 17 and 13 °C. With these set points, the target was to prevent condensation in the beam unit and to get dry cooling.

The dew point of the conference and office rooms are quite close to the water inlet temperature. Anyhow only during a short time-slot, the water inlet temperature is higher than the dew point.

The humidity level is high in the room spaces because the supply airflow rate is much lower than the design values due to undersized fan capacity. In the conference room, the airflow rate is 39% lower than design value and in the office it is 42% lower. The actual airflow rate in the conference room is 1.4 l/s per m^2 (7 l/s per person) and 1.7 l/s per m^2 (11 l/s per person) in the office.

If the supply airflow rate is according to designed values, the dew point of the room spaces would be notably lower than that the inlet water temperature. This means that in this building, where the leakage is limited, it is possible to prevent condensation and to obtain dry cooling during working hours.

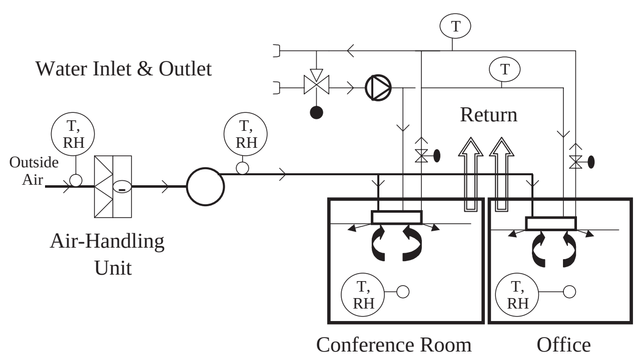

Fig. 6. The concept of the ventilated beam system and the measurement points in the case-study building.

It should be noted that the humidity level is not significantly increased during nights. The dew point raised up only by about 1 °C during the night-time from the day-time value. Also, during the weekend the humidity level will remain almost constant. This indicates that the infiltration is negligible. The estimated infiltration from the humidity measurement is less than 0.05 1/h.

The most critical time to reach dry cooling is to maintain requested humidity level during the morning start-up period. The condensation can be prevented with starting ventilation of dry air about 30 min earlier than the water-based cooling starts by adjusting operation hours of fans and the water pump of the beam system.

The surrounding spaces have an influence on the humidity level in the ventilated beam rooms. The air-handling unit is running between 7:30 a.m. and 9:30 p.m. during weekdays and between 8:00 a.m. and 1:00 p.m. during saturdays in this area.

The temperature in the mixing area is about 21 °C during working hours and relative humidity level is quite high (85%). The night temperature is slightly higher typically about 23 °C. The humidity ratio in the surrounding mixing area is over 13 g/kg while humidity

Table 2
Measurement instruments and accuracy

Parameter	Instrument	Accuracy
Water inlet and outlet temperature	Type T thermocouple wire	±0.2 °C
Room air relative humidity	Portable data logger	±5% RH
Room air drybulb temperature	Portable data logger	±0.3 °C

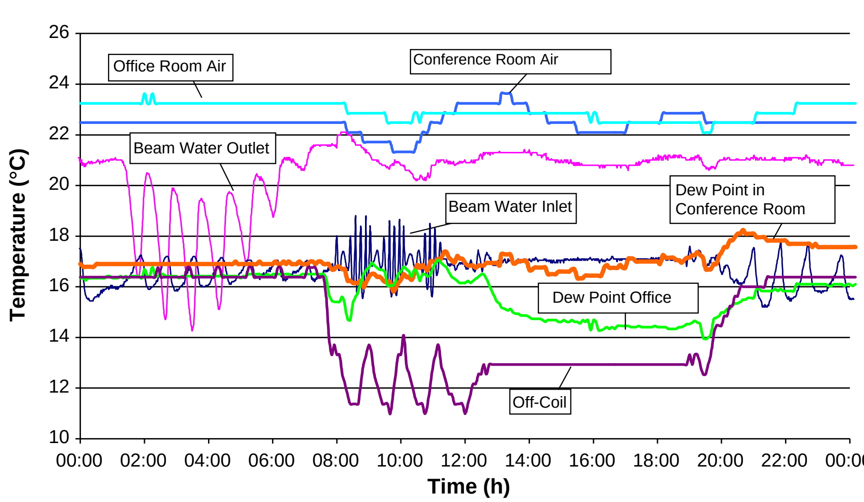

Fig. 7. The operation conditions in the ventilated beam system during one typical working day.

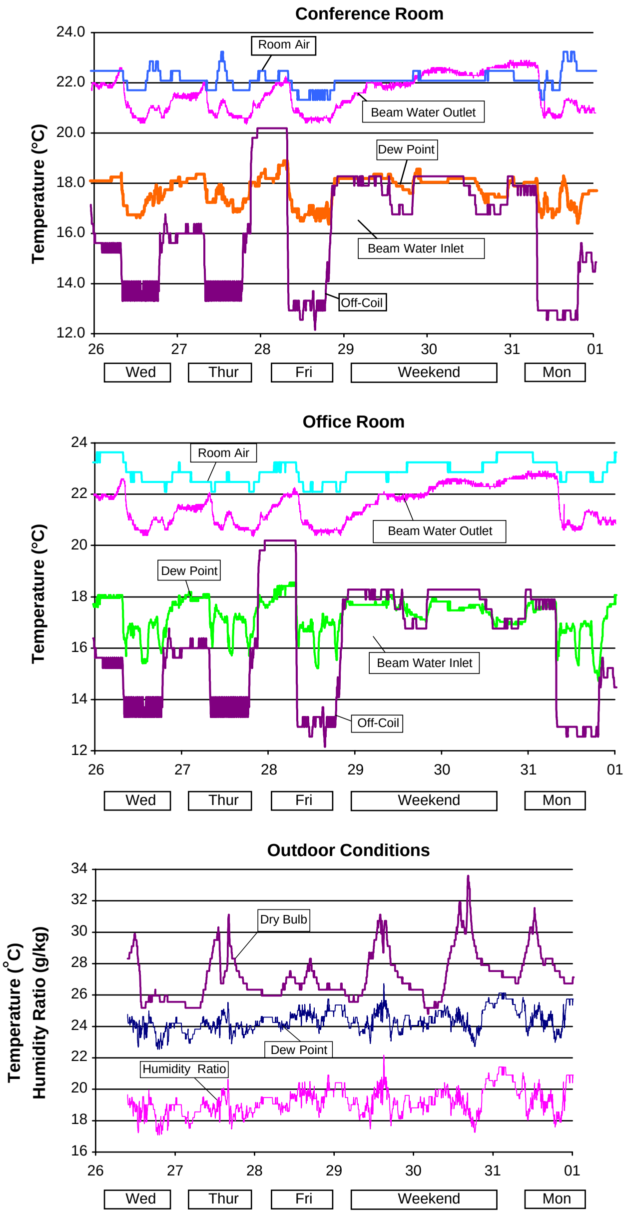

Fig. 8. The operation temperatures in the ventilated beam system and the conditions in the conference room, the office and outdoor air during 6 days.

is about 1 g/kg lower in the beam office humidity during the daytime (Fig. 9). This means that part of the humidity flow rate is attributable from the surrounding areas.

4.2. Measurements in a reference building

The leakage is studied in two less air tight offices to get an overview of the leakage level in old building stock. In this building, there are obvious infiltration routes, e.g., in the window frame and cracks under doors.

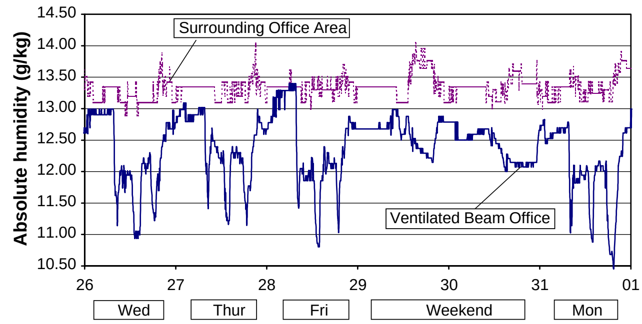

Fig. 9. The measured humidity ratio in the ventilated beam office and in a surrounding office that is served by mixing system.

The measured maximum and minimum airflow rates are 176 l/s (12.6 l/s per m^2) and 147 l/s (10.5 l/s per m^2) in the one person variable airflow rate office. In the open layout office, the constant airflow rate is 920 l/s (8.8 l/s per m^2). The supply temperature in the one person office is 15.5 °C and the off-coil of the air-handling unit is 14 °C. In the open layout office, the supply is 17.5 °C and the off-coil temperature is 16 °C, respectively.

In one person's office the operation hours of the air-handling unit is 7:20 a.m.–10:35 p.m. and in the open layout office 7:00 a.m.–10:45 p.m (see Fig. 10). The main idea of the early morning ventilation is to purge the room spaces. Because of missing design data, the exact design value of the operation hours is not known. The time setting of the chiller and air-handling units are not synchronized. Thus, the fans are running without any purpose after office hours and it increases humidity in the room space.

It should be noted that this unnecessary ventilation after office hours increase the dew point by about 2.5 °C in both offices. In morning purging, the dew point increase about 1 °C (from 21 to 22 °C) in the open layout office and 3 °C (19–22 °C) in the one person's office. After fans have been switched off for 2 days, the humidity level has not reached the steady-state conditions.

In the morning when the fans start to operate, the humidity level increases quite fast in the one person's office room and after 30 min the humidity level reached the normal conditions. In the open layout office, it will take about 2 h to reach normal day-time humidity level. The main explanation for it that is open doors of the open layout office in the early morning. In that space, it is common that the door to corridor and further the corridor door to outside are open.

The estimated maximum infiltration from the humidity measurement is less than 0.15 1/h in the room spaces where the one person room is more leaky than the open layout office. It should be noted that without the unnecessary purging, the humidity level would increase quite slowly. Still, these measurements indicate that if

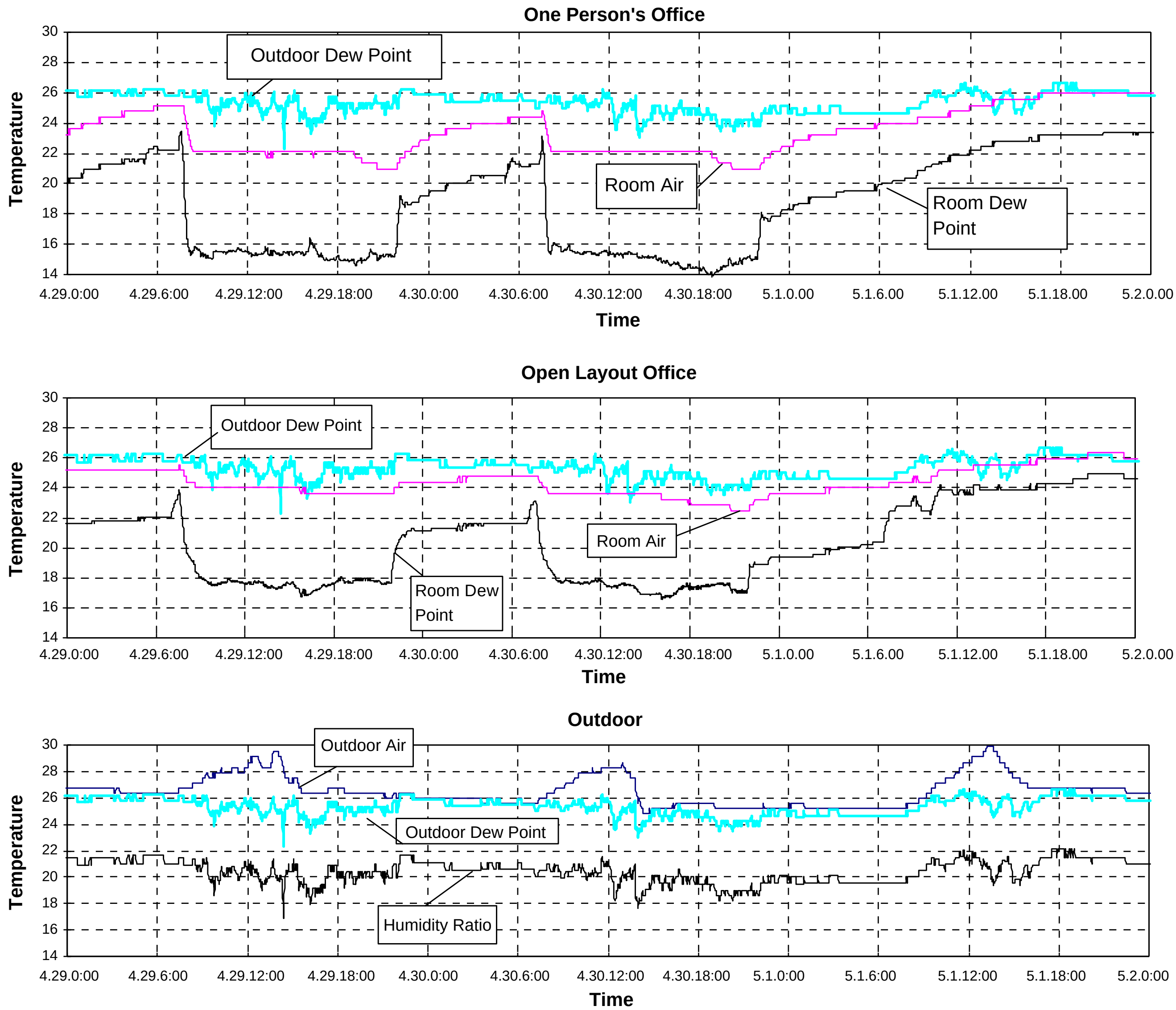

Fig. 10. The temperature and humidity in the one person's room, the open layout office and outside air during 3 days in a reference mixing ventilated office building. The third day is saturday.

the air tightness is at this level the room air needs to be dehumidified properly prior to the operation of the water-based cooling.

5. Discussion

The cooling loads of the room spaces are at the same level in the Tropical climate and in the temperate climate if the direct solar radiation is prevented. The main difference compared is the high outdoor humidity. In the Tropical climate where the humidity is always high, it is important to maintain the dew point of the room space lower than the water inlet to prevent condensation. The most challenging time period is mornings. In Scandinavia, the suitable water inlet is 14 °C and 15–16 °C in the central Europe. In the Tropics, the inlet temperature should be higher to prevent condensation in the ventilated beams.

The conducted measurements indicate that the infiltration could be quite small if the windows, frames and doors are airtight. Thus, the night-time generated humidity is possible to ventilate by starting the operation of fans about 30 min earlier than water-based cooling. Anyhow, the dehumidified period must be longer and the supply airflow rate should be higher if the buildings are less airtight.

The condensation risk is higher if rest rooms or staircases are located close to ventilated beam area. Thus, the air tightness of the internal doors together with the building envelope should be guaranteed during the design phase.

The target temperature and humidity level are the starting point for the system design. Typically, the target for the room temperature is 23–24 °C and 60–65% for the relative humidity as mentioned in the Singaporean guideline [16]. It should be that thermal comfort is not restricted to humidity limit in the indoor air. The humidity can be as high 75% if the air temperature is within the acceptable level [17,18]. Based on the study of Fang et al. [4], perceived indoor air quality is better if the room air is less humid. The latest research at National University of Singapore indicate that people in the Tropics can accept higher humidity [19]. Based on this study, the relative humidity can be as high as 65–70% with room temperature of 23 °C. It should be noted that mould growing should be taken account as a separate matter. The mould growing could be possible if the relative humidity is over 80% at the room temperature [20].

The selection of the design room conditions always compromise of the conditions of the supply air and the water inlet temperature. By reducing target humidity level, the required supply temperature is lower and airflow rate is higher. At the same time, the inlet water temperature could be lower and the cooling capacity of the beam is higher. On the contrary, higher target humidity reduces the required airflow rate but the inlet water temperature should be higher and this reduces the capacity of the ventilated beam.

Table 3 shows the dew point at some possible combinations of the room air temperature and relative humidity. The relative humidity of 65% means that the water inlet temperature can be about 16.5–17 °C at the temperature level of 23–24 °C.

The requested airflow rate per person is shown in Fig. 11 when the supply temperature is 14 °C. The humidity load of a person is used as a parameter. The shown range covers the moisture load in different conditions. The moisture load of 30 g/h per person describes relaxing person in the thermal balance situation. The moisture load of 40–60 g/h is during the light office work and 75 g/h during active office work [21,22].

The room design condition of 23 °C and 65% is attainable with the water inlet and the supply temperatures 17 and 14 °C when the specific supply airflow rate is 10 l/s per person. It should be noted that the supply

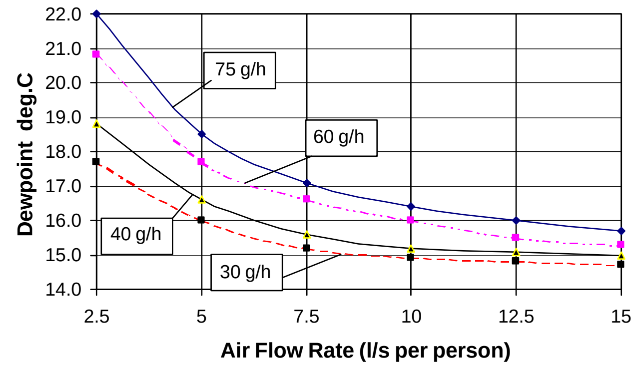

Fig. 11. Dew point as a function of airflow rate with different activity level of a person. The room temperature is 23 °C and the supply air temperature is 14 °C (humidity ratio of 10.1 g/kg).

airflow rate is not necessary need to be outside air. Depending of the application, part of the airflow is possible to take for return air side. The demand of the outdoor airflow rate is that most of building codes between 4–10 l/s per person.

In the mornings, the air-based cooling should start earlier and after a certain time when the humidity level will be at the design level water-based cooling should start. This means that control strategy should be designed taken into account the characteristic of the building. Also, the commissioning and the tuning of the automation system have to conduct probably. In the Tropical conditions, faults in the automation system are much more critical than in the temperate climate.

Table 3
Dew point temperature as a function of the target room temperature and relative humidity

Relative humidity (%)	Temperature (°C)	
	23	24
60	14.8	15.8
65	16.1	17.0
70	17.2	18.2

6. Conclusions

A case-study measurement was conducted in a typical Singaporean office building to investigate the feasibility of a ventilated beam system in hot and humid climate. Based on the measurements, the condensation in the beam system is possible to prevent and to reach dry cooling if infiltration is minimized, supply airflow rate is sufficient to extract humidity of people and tuning of the automation system has conducted probably.

The room design conditions of 23 °C and 65% is attainable with the water inlet and the supply temperatures of 17 and 14 °C when the specific supply airflow rate is 10 l/s per person. Together with the previous design parameter and with dehumidified the indoor air properly prior the operation of the water-based cooling, it is possible to maintain dry cooling without any condensation in the ventilated beam system.

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