Performance investigation of indoor thermal environment and air handling unit in a hub airport terminal

Lin Lin [a], Lingshan Li [a], Xiaochen Liu [a], Tao Zhang [a], Xiaohua Liu [a], Qingpeng Wei[a], Xiaohui Gao [b], Tao Wang [b], SiDong Tu [b], SiPing Zhu [b], WenBo Zou [b], Hong Qu [b]

[a] *Department of Building Science, Tsinghua University, Beijing 100084, China*

[b] *Beijing Capital Airport Energy-saving Technical Service Co., LTD, Beijing 100621, China*

Abstract: Airport terminal is a typical large space building with large high interspaces and multitudinous functional zones. The task of heating, ventilation and air conditioning (HVAC) system is to ensure the thermal environment of these zones with different functions. A typical terminal in cold region of China is investigated in present paper, where indoor environment and performance of air conditioning system in summer are emphasized. The results indicate that the indoor temperature and humidity parameters at a height of 1.5 m in each zone of the terminal can be effectively controlled. The indoor temperature at a height of 1.5 varies in the range of 24~27°C, and the temperature difference is 0.5~4.9°C in the vertical direction. The temperature at the top of the terminal is greatly affected by the outdoor temperature where is higher and fluctuates obviously, while the temperature at the height of the occupant area is lower and more stable under the control of the air-conditioning system. The indoor carbon dioxide concentration is also at a reasonable level, all below 900 ppm, indicating that the equivalent outdoor air volume per capita is greater than 35 m^3/h. Even in the case of high load caused by flight delays, the thermal environment in the terminal can be basically controlled at a comfortable level. As for the air handling unit, air handling process is tested to investigate the cooling capacity. The results show that the actual water supply of the AHU is relatively higher than the set value, but the air volume is almost equal to the set value which leads to an unsatisfactory energy efficiency. The tested energy efficiency ratio (EER) of AHU is only 5~7, almost approaching to that of the cooling plant. Reducing air flow rate could greatly improve the EER of the current air-conditioning system.

1 Introduction

In recent years, civil aviation industry is in the rapid development stage in China. With the development of the air transport industry, the scale and volume of the airport terminal is also growing rapidly [1]. Nowadays, airport terminals are usually designed as large space buildings with large floor heights (higher than 8 meters), complicated vertical connecting spaces across floors and massive surface areas of glazed envelopes for aesthetic reasons and lighting requirements. Meanwhile, the energy consumptions of airport terminals are extremely high, and there is a significant disparity among different airports in terms of energy consumption [2-5]. The average value of annual total energy consumption per unit terminal floor area in European airport terminals is 234 $kWh/m^2 \cdot a$, which is 1.3 times as high as that in office buildings, and air-conditioning energy consumption accounts for 40%-60% of building operation energy consumption [6-7].

Some scholars have tested the indoor environment of terminal buildings in summer. Wang et. al [8] investigated the IEQ of eight major Chinese large-hub airport terminal buildings using instrumental objective measurements and questionnaire subjective surveys, and the results showed that the average CO_2 concentration in each terminal was at a low level (about 400-700 ppm) with fresh air valves in air handling units (AHUs) almost shut off in actual operation process. Pichatwatana et. al [9] measured the indoor temperature of the terminal building with large glass enclosure at the top in summer, and the results show that the indoor temperature is still overheated even if the cooling capacity is increased. Consequently it is necessary to improve the large glass structure of the terminal building. Because of the large passenger flow of airport terminal, and the air

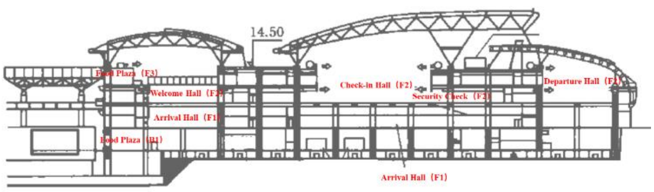
 https://doi.org/10.1051/e3sconf/201911101024

conditioning is provided indoors in summer, the temperature difference between indoor and outdoor is significant, causing the hot air outdoors infiltrating indoor through skylights due to the effect of thermal pressure [10]. In order to maintain a good indoor environment in summer, the air conditioning system needs to operate in a good condition. However, there are still limited tests on the actual performance of air-conditioning systems in terminals [11-15].

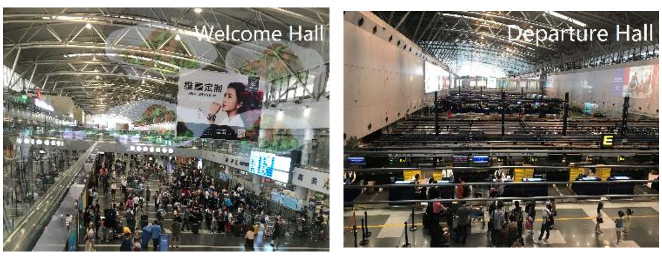
In the current study, on-site measurements in summer were performed in the large space building of a hub airport terminal in China (with annual passengers throughout of more than 68 million). Both indoor environment and performance of the air handling units are measured to reflect the actual situation in the typical summer condition.

2 Description of the airport terminal

The case airport for measurement is the Terminal 2 of a hub airport in the cold region of China, officially opened in 1999. As shown in Fig. 1, the floor area of the airport is about 336,000 m^2. Separated by the security check area, Terminal 2 can be divided into two typical zones: unsecured halls and secured piers. There are four floors available for passengers in the unsecured area: a food plaza (B1), arrival hall (F1), welcome hall and check-in hall (F2), and food plaza (F3). The welcome hall is about 16.0 meters high, and the check-in hall with a height of about 26.0 meters is the largest space of all the unsecured halls. The entrance gates and passages on different floors are almost always open and are connected with the outdoor environment directly.



(a)



(b)

Fig. 1 The case airport: (a) cross view of the airport; and (b) photos of the terminal building.

The air-conditioning system normally runs 24 hours every day in the cooling season with a design supply water temperature of 7 ºC. And the indoor design air temperature is 26 ºC. As shown in Fig. 2, chilled water from the cooling plant passes through the water separator inside the terminal directly and then is supplied to the AHUs and FCUs (fan coil units). FCUs are mainly used for cooling in office areas. There are 229 AHUs totally in this terminal 2, and there is no three-stage pump in the terminal building. In summer, the fresh air valves in AHUs are all shut off. The terminal devices of the all-air air-conditioning system in the terminal are mainly the nozzle and linear diffuser.

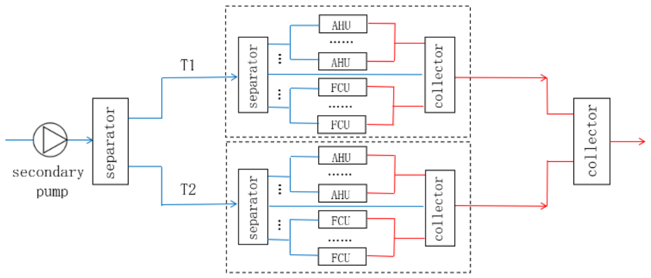


Fig. 2 Operating diagram of the air conditioning system in the terminal buildings.

The outdoor environmental conditions during on-site measurement (from Jul. 1st, 2018 to Jul. 30th, 2018) are shown in Fig. 3, including daily average outdoor air temperature, humidity ratio, and carbon dioxide concentration. It's indicated the outdoor air temperature and humidity ratio in this period vary from 22.5-30.5 ºC and 16.1-23.4 g/kg respectively, and the average carbon dioxide concentration is 446 ppm.

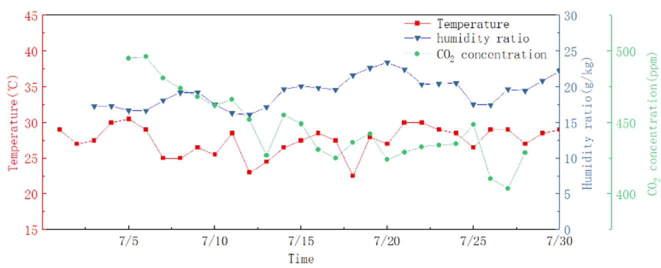


Fig. 3 Outdoor environment conditions during the test period including daily mean temperature, humidity ratio and CO_2 concentration.

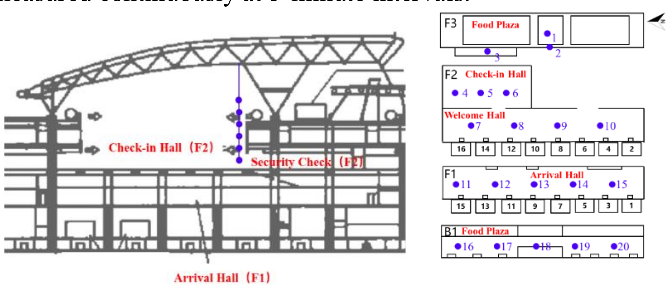
3 Test results of indoor environment

On-site measurements of the indoor environment in this airport terminal were carried out in July 2018, which could be regarded to represent typical summer conditions as shown in Fig. 3. The measured physical parameters consist of air and cold water parameters, which include the air temperature (*Ta*), relative humidity of the air (*φ*), air velocity, carbon dioxide concentration (*C*), water temperature and water flow rate. The measurement devices and their accuracies are shown in Table 1. The air temperature and relative humidity were measured using a combined resistance temperature detector (Pt RTD) and a lithium chloride relative humidity sensor (LiCl RHS) respectively.

Table.1 Specifications of the measurement devices.

Parameter	Device	Accuracy	Operational range
Air/water temperature	Pt PTD	0.2ºC	0-50ºC
Air relative humidity	LiCl RHS	3%	20-80%
Air velocity	Hot bulb anemoscope	0.03 m/s	0-10 m/s
CO_2 concentration	CO_2 concentration data logger	50 ppm	0-5000 ppm
Water flow rate	Ultrasonic flow meter	1%	0-3×10^6 m^3/h

All the indoor air sensors were non-uniformly arranged according to characteristics of the indoor environment in different zones as shown in Fig. 4. In the vertical direction, a series of testing points located at heights of 1.5 m, 3 m, 7 m, 10 m, 13 m, and 16 m were settled separately in the check-in hall as shown in Fig. 4(a), where T_a and *φ* were measured simultaneously. And every horizontal testing point (measuring *Ta, φ, C*) was located at the height of 1.5 meters above the floor in the occupant zones of different areas in the terminal as shown in Fig. 4(b). There were totally 25 testing points in this measurement, and the parameters were measured continuously at 5-minute intervals.



(a) (b)

Fig. 4 Testing points in the terminal building: (a) vertical testing points; and (b) horizontal testing points.

3.1 Temperature and humidity distribution

Fig. 5 illustrates the indoor temperature and humidity distribution in the unsecured area of the terminal building during 2:00 p.m. to 3:00 p.m. The temperature and humidity ratio differences between indoor and outdoor for all the horizontal testing points were within 5.2 to 10.2 ºC, -0.9 to 1.4 g/kg respectively. There was a relatively uniform temperature distribution in each floor. It's indicated the temperature of each floor is among 24.2-29.3 ºC, and the temperature decreases slightly with the decrease of the floor number. Further observation shows that the highest temperature occurs in the F3, which is due to the high quantity of heat production in the restaurant. And the temperature of other floors can be controlled within the set temperature of 26 ºC basically.

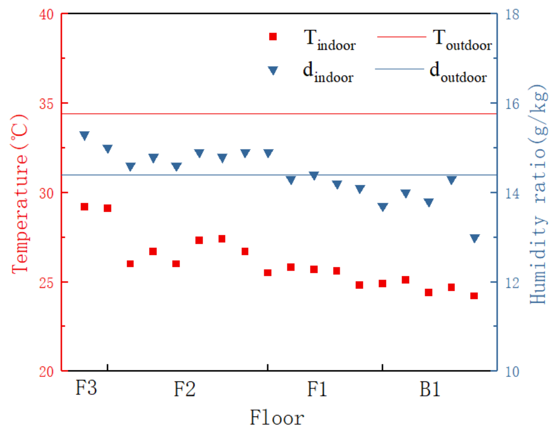


Fig. 5 Air temperature and humidity ratio of the unsecured area in the terminal building.

The vertical temperature distributions in the check-in hall is illustrated in Fig. 6. Due to thunderstorms on the day of the test, a large number of people are detained at night in the terminal building, so the temperature at night is higher than that during the day. However, the maximum temperature at night is only 25.2 ºC, lower than the set temperature of 26 ºC. This shows that the air conditioning system in the terminal can ensure that the temperature in all areas of the indoor area can be effectively controlled. In addition, as the end form of the check-in hall is double row nozzle (one located at the height of 3 m and the other at 9 m), except for the temperature at 16 m, there is no obvious temperature gradient in the vertical direction, which varies from 0.1 ºC to 2.1 ºC. At the same time, as the 16 m height is near the ceiling, the temperature almost changes with the outdoor temperature.

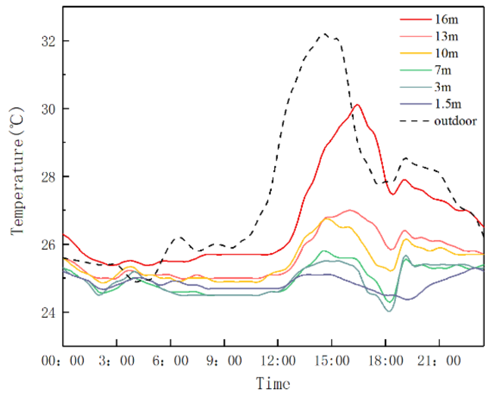


Fig. 6 Vertical air temperature distribution in the check-in hall.

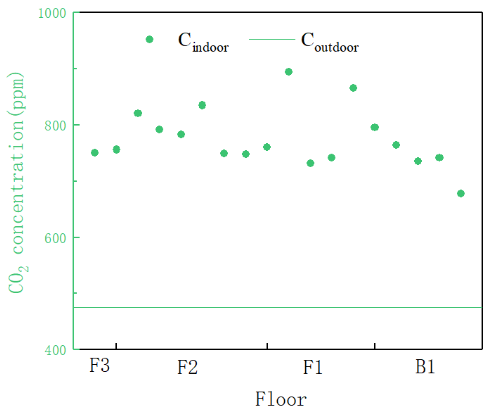


Fig. 7 CO_2 concentration outside the isolated area of the terminal building.

3.2 CO_2 concentration distribution

CO_2 is usually taken as a reference index of indoor environment in buildings [16-18]. The emissions of CO_2 are approximately proportional to the amount of CO_2 emitted by human respiration in terminal buildings. The concentration of indoor CO_2 are usually suggested to be lower than 1,000 ppm in many countries, which is beneficial to take the influence of both other pollutants and odors caused by human activities into consideration at the same time.

Fig. 7 shows the distribution of indoor CO_2 concentration in the unsecured area of the terminal building. There is no obvious stratification of the CO_2 concentration observed on different floors and the average values are 716 ppm, 806 ppm, 784 ppm and 756 ppm in B1, F1, F2 and F3 respectively with the outdoor concentration is 475 ppm. The results show that the indoor CO_2 concentration of the terminal building is significantly below the upper limit, indicating that there is excessive fresh air in the building, exceeding the actual demand of indoor occupants. The path of outdoor fresh air entering the building can be mechanically, and can also be infiltrated through the building envelope structure, indoor and outdoor connecting openings, door and window gaps, etc. As there is no mechanical fresh air supply in the terminal building in summer, it's indicated the excessive fresh air here is caused by the latter. Excessive fresh air leads to low indoor CO_2 concentration, and also leads to a substantial increase in cooling consumption of the air conditioning system. If the amount of fresh air in such buildings could be reduced by effective measures, and the amount of fresh air is controlled to a reasonable level for actual occupants, it would be reduced the energy consumption of the air conditioning system effectively based on ensuring the level of indoor environment.

4 Operation performance of the AHUs

4.1 Air handling process

Fig. 8 shows the principle diagram of an AHU in the T2 terminal building. It's indicated there are four air inlets and outlets of the AHU, i.e. return air inlet, fresh air inlet, exhaust air outlet and air supply outlet. However, there is no return air passage for the AHU, and air in the room setting the AHU is directly drawn as the return air for the return air inlet. This results in the return air parameters (such as CO_2 concentration) processed by the AHU being closer to the outdoor fresh air parameters, which is also an important reason for the low indoor CO_2 concentration. Fresh air and return air are firstly mixed in the inlet chamber, and then passes through the filter section and the cooling section in turn. Air with high temperature and humidity is cooled and dehumidified, and finally sent to the indoor space. The air volume of each draught and the air condition of each point are tested respectively. The measuring points are also illustrated in Fig. 8.

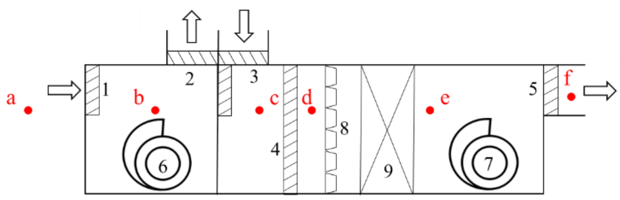
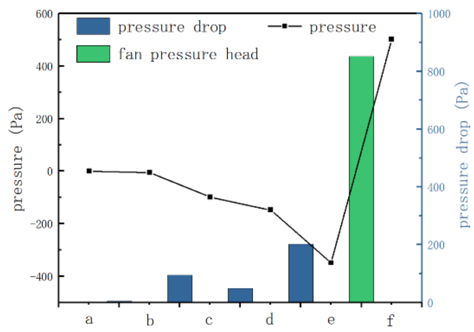


Fig. 8 Schematic diagram of AHU and measuring point: *1- return air damper; 2- exhaust air damper; 3-fresh air damper; 4-mixing damper; 5-supply air damper; 6-return fan; 7-supply fan; 8-air filter; 9-surface air cooler.*

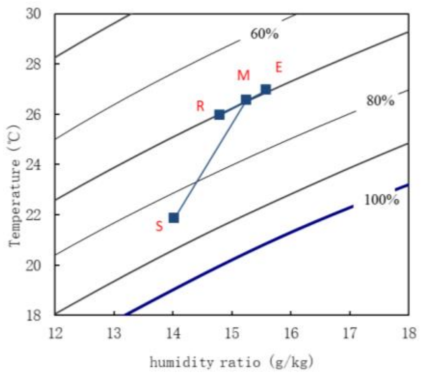
4.2 Energy performance of the AHU

Operating performance of a typical AHU is tested and a typical condition, 11:00 a.m. on July 12, is chosen to illustrate the results. The tested temperatures of supply and return water are 13.3 ºC and 19.2 ºC respectively, higher than the design temperatures of 7/12 ºC. The fresh air valve is always closed during the test. Due to closed of the return fan and the opener of the exhaust air damper, the pressure of the inlet chamber in the AHU is lower than the outside, which makes the air enter the AHU through the exhaust port instead. The test result shows that the return air volume is 27,200 m^3/h, and the return air (point *R*) temperature and humidity are 26 °C and 70%. The air volume of which entered from the exhaust port (point *E*) is 25,200 m^3/h, with the corresponding temperature and humidity of 27.2 ºC and 69% respectively. The supply air (point *S*) volume is 52,400 m^3/h, and the temperature and humidity are 21.9 ºC and 82%.

Fig. 9(a) shows the pressure drop in each component of the AHU. The total pressure drop of the filter and the surface cooler is 49 Pa, and the fan pressure head is 852 Pa. It can be seen that the largest part of the pressure drop is d-e, reaching 201Pa. The air handling process in the AHU is shown in Fig. 9(b). The fresh air which entered from the exhaust port is mixed with the return air in the inlet chamber to reach the mixed air state(point *M*), and then passed though the cooling section to reach the air supply state.



(a)



(b)

Fig. 9 Performance of the tested AHU: (a) pressure drop of each component; and (b) air handling process.

The cooling capacity of the AHU can be calculated as Eq. (1), and energy efficiency ratio (*EERt*) of the AHU is defined as Eq. (2):

$$Q_c = \frac{c_p \rho G(t_{out} - t_{in})}{3600} \tag{1}$$

$$EERt = \frac{Q_c}{W_t} \tag{2}$$

where subscripts *in* and *out* refer to the supply and return water respectively; Q_c is cooling capacity of the AHU, kW; G is the water flow rate, m^3/h; W_t is the power consumption of the AHU, kW.

The total heat exchange efficiency is the effective indicator for surface cooler which can be calculated as Eq. (3):

$$Eg = \frac{t_M - t_S}{t_M - t_{in}} \tag{3}$$

where subscripts *M* and *S* refer to the mixed air and supply air, respectively.

Table 2 shows the test and calculation results of AHU. The test results show that the fan power of the AHU is 25.3 kW, where the cooling capacity is 127 kW, and the *EERt* of this AHU is only 5.02, which is significantly lower than the rated value. Similarly, eight AHUs in the T1 and T2 buildings are tested and calculated, and the *EERt* are shown in Fig. 11. Generally, the rated *EERt* of the AHUs are higher than 10, while *EERt* of all the tested AHUs are lower than 10, far below the rated *EERt*. It is found that the air volume of the AHU is approximately equal to the rated air volume, but the water flow rate is smaller and the water temperature is higher, which leads to the lower cooling capacity and the low energy efficiency ratio.

Table. 2 Tested and calculation results of AHU

	Rated	**Measured**
Air volume (m^3/h)	60000	52400
Water flow rate (m^3/h)	63.9	16.8
Water supply/return temperature (ºC/ ºC)	7/12	13/19
Fan power (W)	30	25.3
Cooling capacity (kW)	373	127
EERt	12.4	5.0

Unbalance rate (%)	9.8
Total heat exchange efficiency (%)	34

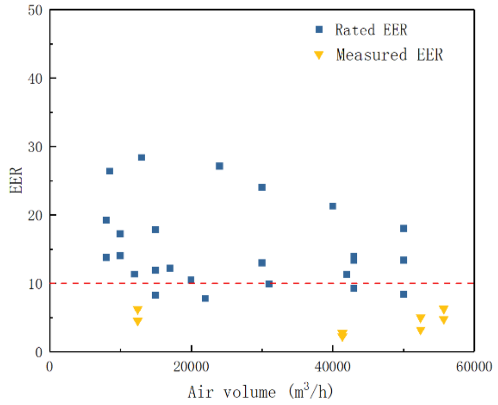


Fig. 11 Energy efficiency ratio of AHUs.

5 Conclusions

In this paper, on-site measurements of the indoor environment and air handling units were conducted in a typical Chinese hub airport. The main conclusions can be summarized as follows:

1) The indoor temperature and humidity parameters can be effectively controlled when the air conditioning system is running in summer. The horizontal temperatures in different areas are among 24 ℃~27 ℃. Even in the case of flight delays and high load of staying personnel, the environment in the terminal can still be basically controlled at a comfortable level.
2) There is no obvious stratification of CO_2 concentration observed on different floors. And the indoor CO_2 concentration of the terminal building is below the limit, indicating that there is excessive fresh air in the building, exceeding the actual demand of occupants. This will also lead to a significant increase in the requirement of the cooling capacity.
3) The test results for the AHUs show that the supply water temperature is high, and the actual water flow rate of the AHUs is lower than the set value. While the air volume is equal to the set value, resulting in the lower energy efficiency of the AHUs. As a result, the *EERt* of the AHU is only about 5~10, which is at a relatively low level and restricting the performance of the entire system.

Funding

The research described in this paper is supported by the National Key Research Program of China (No. 2018YFC0705001) and National Natural Science Foundation of China (No.51878369 and No. 51521005).

Nomenclature

c_p	specific heat capacity (kJ/(kg·ºC))
G	water flow rate (m³/h)
Q_c	cooling capacity of the AHU (kW)
W_t	power consumption of the AHU (kW)
t	temperature (ºC)
Greek symbols	
ρ	density (kg/m³)
Subscripts	
M	mixed air
S	supply air
in	supply water
out	return water

References

[1] International Air Transport Association (IATA). Annual Review 2017. 73rd Annual General Meeting, Cancun, June 2017, retrieved online from: http://www.iata.org/publications/pages/annual-review.aspx.
[2] Balaras CA, Dascalaki E, Gaglia A, Droutsa K. Energy conservation potential, HVAC installations and operational issues in Hellenic airports. Energy & Buildings, 2003, 35: 1105-1120.
[3] Zhao HT. A field study on energy consumption and indoor environment quality of terminals in China. Master Thesis, Tsinghua University, Beijing, 2015.
[4] 13-five year plan for the development of civil aviation in China, 2016.
[5] Rehault N, Ohr F, Maier R et al. Online Survey on European Airports Energy Operation (Project Cascade European FP7). released in 2016, retrieved online: http://www.cascade-eu.org/cms/index.php?id=publications.
[6] Alba SO, Manana M. Energy Research in Airports: A Review. Energies, 2016(9): 349.

[7] Pasa UM, Sogut MZ. An integrated research for architecture-based energy management in sustainable airports. Energy, 2017, 140: 1387-1397.
[8] Wang Z, Zhao HT, Lin BR. Investigation of indoor environment quality of Chinese large-hub airport terminal buildings through longitudinal field measurement and subjective survey. Building & Environment, 2015, 94: 593-605.
[9] Pichatwatana K, Wang F, Roaf S, et al. An integrative approach for indoor environment quality assessment of large glazed air-conditioned airport terminal in the tropics. Energy & Buildings, 2017, 148:37-55.
[10] Zhao K, Liu XH, Jiang Y. Application of radiant floor cooling in large space buildings-A review. Renewable Sustainable Energy Reviews, 2016, 55: 1083-1096.
[11] Song XL, Huang X, Xue Y. Running Cost Analysis of Evaporative Cooling Energy-saving and Purification Air-conditioning in Supermarket of Xi'an. Refrigeration and Air-conditioning, 2014(6):681-686.
[12] Liang XD. Energy saving and automation control design of HVAC system in BSCE new factory. Journal of HV&AC, 2014(5):83-86.
[13] Yi X, Luo Y, Zeng Y. A Damper control system for variable-air-volume air handling system of tobacco factory. Building Energy & Environment, 2005, 24(3):43-46.
[14] Zhu C X, Zhao X Y, Yang R L, et al. Diagnosis and Transformation of Air Conditioning and Refrigeration System for a Shopping Mall. Advanced Materials Research, 2013, 664:960-963.
[15] Zhao W U, Zhao X H, Chen L T, et al. Integrated Energy-saving Retrofitting of Heat Recovery for Air-conditioning System in a Factory of Shanghai. Building Energy Efficiency, 2014(4): 91-94.
[16] M.B. Schell, S.C. Turner, R.O. Shim. Application of CO_2-based demand-controlled ventilation using ASHRAE standard 62: optimizing energy use and ventilation. ASHRAE Transactions, 1998, 104:1213–1225.
[17] Y.P. Ke, S.A. Mumma. Using carbon dioxide measurements to determine occupancy for ventilation control. ASHRAE Transactions, 1997, 103 (1):365– 374.
[18] S.M.D. Giacomo. Differential CO_2 based demand control ventilation (maximum energy saving optimized IAQ). Energy Engineering, 1999, 96 (5):58– 76.

Dear Reviewers,

Thank you so much for your elaborate work with our paper. We are especially grateful for reviewers' time and effort for reviewing the previous version of the manuscript. These valuable comments and suggestions have considerably improved the clarity of the paper. The manuscript has been revised in response to the comments with the main modifications listed below.

- **Reviewer #1:**

The paper is focused on studying an air conditioning system of a large airport terminal in China. The paper is well structured but needs some minor revisions according to my comments below. (Accept)

1) The references in text must be changed from superscript to normal
2) The numbering in the References chapter must be size 10
3) Please replace "the-air conditioning" with "the air conditioning" (page 2)

Reply: Thank you so much for the suggestion. The references in text and the numbering in the References chapter have been adjusted to the correct format. And the spelling mistake in page 2 has been corrected.

- **Reviewer #2:**

1) In the article, some measurements of air temperature, humidity and CO2 in a Chinese terminal are presented during one day. The presented results are not so relevant. The main conclusions are that the temperature and CO2 are in the recommended ranges, and the energy efficiency ratio of the air handling units is only 5-7.

Reply: Thank you so much for the suggestion. Airport terminal is a typical large space building with large high interspaces and multitudinous functional zones. And a typical terminal in cold region of China is investigated in present paper, where indoor environment and performance of air conditioning system in summer are emphasized. Air temperature, humidity and CO_2 concentration are a comprehensive reflection of the indoor environment, which can reflect the operating effect of the air conditioning system. The test results can be used to understand the operation of the air conditioning system of the large space buildings in the airport, and at the same time have a certain guiding role in the design of air conditioning systems with up to space.

2) the paper is not respecting the format accordingly to E3S publication requests

Reply: Thank you so much for the suggestion. The format of the paper has been adjusted to meet the E3S publication requests.

3) there are many grammar mistakes
4) images quality is very poor

Reply: Thank you so much for the suggestion. The language has been polished in the revised manuscript.

- **Reviewer #3:**

1) English can be improved, especially in Chapter 4.1. and other chapters containing detailed explanations.

Reply: Thank you so much for the suggestion. The language has been polished in the revised manuscript.

2) Define FCU in Fig. 2.

Reply: Thank you so much for the suggestion. The FCU (fan coil units) has been defined in Chapter 2.

3) Chapter 3: The first paragraph declares measurements to have been done in typical summer conditions. Typical summer conditions as defined by which criteria/standard/etc.?

Reply: Thank you so much for the suggestion. Typical summer conditions refer to the outdoor parameters for summer are approximately the reference design parameter values for this area in the Practical Heating and Air Conditioning Design Manual (in Chinese).

4) Chapter 3.2. concerning CO2 concentration. It is stated that no mechanical supply of fresh air is available while Chapter 2 states that the entrance gates and passages are almost always

open and connected directly to the outdoor environment. Is this not a mechanical supply? Is it negligible? Further clarification required.

Reply: Thank you so much for the suggestion. The mechanical supply of fresh air in this article refers only to the part that is supplied to the room through MAUs (make-up air units) or AHUs, and the part that enters the room through the opened entrances is defined as air infiltration. It cannot be ignored, which is also the reason for the lower CO_2 concentration in the space without the mechanical fresh air supply.

5) Figure 9.b: Judging from the chart the supply air point is around the 85% RH curve. What is the impact on interior air quality in this case?

Reply: Thank you so much for the suggestion. It can be seen from Fig. 9(b) that the air is dehumidified and sent into the room after being treated by the AHU, and has no effect on the indoor air quality.