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Performance analysis of air-conditioning systems for high-tech cleanrooms under different climate conditions

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ABSTRACT

The air-conditioning systems served for high-tech cleanrooms, requiring strict space temperature, humidity and particle concentration controls, are usually energy-intensive, which consume the same magnitude of energy as that of data centers. Their system performance is strongly climate- and weather-dependent, which didn't receive enough attention as data centers. Therefore, this study has evaluated the year-round energy performance of high-tech cleanroom air-conditioning systems in different climate conditions. A typical high-tech cleanroom air-conditioning system, i.e., MAU (make-up air unit) +DCC (dry cooling coil) +FFU (fan filter unit) system, is selected to examine the system performance using the EnergyPlus/Matlab platform. The results show that the monthly energy performance of the system could be modeled as a function of the weather condition. The system has the lowest energy consumption during the transition seasons throughout the year. It also shows better energy performance in hot and mild zones. The studied results could provide a general understanding of the energy performance of high-tech cleanroom air-conditioning systems in different climate and weather conditions.

Keywords: high-tech cleanroom, air-conditioning system, energy performance, climate impact

NONMENCLATURE

Abbreviations	
AMC	Airborne molecular contaminant filter
CC	Cooling coil
COP	Overall coefficient of performance of cooling system
DCC	Dry cooling coil
E	Energy consumption (kW)
FF	Final efficiency particulate air filter
FFU	Fan filter unit
HEPA	High-efficiency particulate air filter
HU	Humidifier
MAU	Make-up air handling unit
MF	Medium efficiency particulate air filter
PF	Primary efficiency particulate air filter
PHC	Preheating coil
RAP	Return air plenum
RAS	Return air shaft
RHC	Reheating coil
SAP	Supply air plenum
Symbols	
h	Enthalpy (kJ/kg)
t	Temperature (°C)
w	Humidity ratio (kg/kg)

1. INTRODUCTION

High-tech cleanrooms have been growing very fast in terms of the total floor area and production quantity [1]. It also has large applications in today's industrial manufacturing, i.e., semiconductor manufacturing, TFT-LCD (thin-film transistor liquid-crystal display) panel manufacturing, microelectronics aerospace and other electronics. Such highly skilled and technology-intensive fabs basically require ultra-clean environment, which are highly energy-intensive [2]. The annual electricity

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consumption of a typical semiconductor fab is as high as 20,908 kWh/m^2 [3], which is around three times the average consumption of data centers worldwide [4] and even 100 times that of public buildings [5].

As the primary facility system to provide the novel production environment for manufacturing processes, the air-conditioning systems are also energy-intensive, which account for 30–35% of the total energy use in a high-tech industry [2, 3, 6, 7]. The main reasons are as follows. ***(i)*** High-tech cleanrooms need extensive supply air exchange rates to maintain the clean environment for high-precision manufacturing. ***(ii)*** High-tech cleanrooms need large outdoor air exchange rates to compensate for the large exhaust air generated from the manufacturing. ***(iii)*** The machines/equipment in high-tech cleanrooms generate a great amount of heat. Therefore, the high-tech cleanroom air-conditioning systems consume much energy, which could be up to 10,000 kWh/m^2 as ASHRAE Handbook shows [2].

However, such energy-intensive application has not gained sufficient attention [8, 9], and only a few studies have investigated and evaluated the energy performance of air-conditioning systems for high-tech cleanrooms. Hu [10] compared the summer-design-day energy consumption of five different air-conditioning systems, and pointed out that the MAU+FFU system exhibited the highest energy efficiency, followed by the MAU+axial fan system, for a typical 200mm dynamic-random-access-memory fabrication plant in Taiwan. Yin et al. [3] presented a calculation model to evaluate the hourly energy performance of the MAU+DCC+FFU system, and pointed out the obvious energy waste of cold-heat offset in summer and winter seasons [3, 11].

Although the above studies have investigated the operation performance of air-conditioning systems in high-tech cleanrooms, the system was evaluated in a single climate zone or a short-term operation period. The year-round performance analysis of air-conditioning systems serving high-tech cleanrooms in different climates is still missing. Therefore, this study would provide a general understanding on the energy performance of high-tech cleanroom air-conditioning systems in different climates. The V-shaped four-parameter relation is proposed to describe the system energy use considering the climate and weather impacts.

2. METHODS

2.1 A typical high-tech cleanroom air-conditioning system

A typical high-tech cleanroom air-conditioning system, i.e., MAU (make-up air handling unit) +DCC (dry cooling coil) +FFU (fan filter unit) system, is selected for performance assessment. The MAU+DCC+FFU system is the most updated and commonly-used air-conditioning system for high-tech cleanrooms today. The served cleanroom is designed according to Class 10/100 and thermal environment control requirements of 23±1°C and 45±5%. The air-conditioning system provides constant supply and outdoor airflow rates of 200 air exchange rates per hour (ACH) and 20 ACH, respectively. The system configuration and year-round operating principle are shown in Fig. 1.

The MAU and DCC separately condition outdoor air and return air, to fully-decoupled control the space relative humidity and dry-bulb temperature. The FFU cycles and pumps the overall supply air via an orifice plate air supply outlet facilitated with HEPAs, to maintain the ultra-clean and stable-thermal environment [3, 10-15] of high-tech cleanrooms.

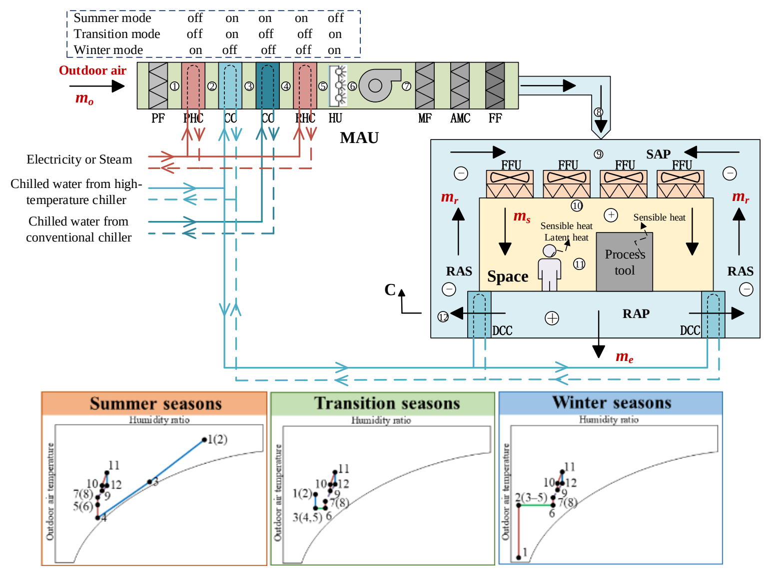


Fig. 1. A typical air-conditioning system for the high-tech cleanroom.

2.2 System energy model

Assuming that the indoor temperature and relative humidity in the high-tech cleanroom are perfectly controlled at 23°C and 45%, respectively, its annual cooling load profile (Q_{tot} W_{lat}) can be calculated by Energyplus. The required supply (h_s w_s t_s) and outdoor air (w_{ro}) states for offsetting the indoor total and latent cooling loads (Q_{tot} W_{lat}) are first determined based on the heat and mass balance equations of cleanroom (Eqs. (1–4)). Then the operating mode is identified by comparing the outdoor air condition with the required state. The loads of cooling coils ($Q_{cc,MAU}$ Q_{DCC}), heating coils ($Q_{he,MAU}$)

and humidifiers ($Q_{hu,MAU}$) can be thus calculated using Eqs. (5–9). Finally, the total energy consumption, including electricity for chillers (E_{cc}) and fans (E_f), and electricity or steam for heaters (E_{he}) and humidifiers (E_{hu}), can be computed using Eqs. (10–12). The above system energy model is developed in Matlab.

$$h_s = h_i - \frac{Q_{tot}}{m_s} \tag{1}$$

$$w_s = w_i - \frac{W_{lat}}{m_s} \tag{2}$$

$$t_s = \frac{h_s - 2501 w_s}{1.006 + 1.86 w_s} \tag{3}$$

$$w_{ro} = w_i - \frac{W_{lat}}{m_o} \tag{4}$$

$$Q_{fc,MAU} = \begin{cases} m_o(h_1 - h_3), & w_o > w_{fc} \\ 0, & w_{ro} < w_o \le w_{fc} \\ 0, & w_o \le w_{ro}, t_o < 17℃ \\ m_o(h_1 - h_3), & w_o \le w_{ro}, t_o \ge 17℃ \end{cases} \tag{5}$$

$$Q_{sc,MAU} = \begin{cases} m_o(h_3 - h_4), & w_o > w_{fc} \\ m_o(h_1 - h_4), & w_{ro} < w_o \le w_{fc} \\ 0, & w_o \le w_{ro} \end{cases} \tag{6}$$

$$Q_{DCC} = m_r(h_{11} - h_{12}) \tag{7}$$

$$Q_{he,MAU} = \begin{cases} m_o(h_5 - h_4), & w_o > w_{ro} \\ m_o(h_2 - h_1), & w_o \le w_{ro}, t_o < 17℃ \\ 0, & w_o \le w_{ro}, t_o \ge 17℃ \end{cases} \tag{8}$$

$$Q_{hu,MAU} = \begin{cases} 0, & w_o > w_{ro} \\ m_o h_{fg}(w_6 - w_5), & w_o \le w_{ro} \end{cases} \tag{9}$$

$$E_{tot} = E_{cc} + E_{he} + E_{hu} + E_f = \frac{Q_{fc,MAU} + Q_{DCC}}{COP_{hc}} + \frac{Q_{sc,MAU}}{COP_c} + Q_{he,MAU} + Q_{hu,MAU} + W_{f,MAU} + W_{f,FFU} \tag{10}$$

$$W_{f,MAU} = \frac{V_o \Delta P_{MAU}}{\eta_1 \eta_2} \tag{11}$$

$$W_{f,FFU} = \frac{V_s \Delta P_{FFU}}{\eta_1 \eta_2} \tag{12}$$

2.3 Climate/weather conditions

As China has a vast territory and climates show large diversities in different geographical regions, its typical climatic locations are selected in this study to assess the performance of high-tech cleanroom air-conditioning systems. Five typical cities, i.e., Harbin, Beijing, Shanghai, Guangzhou and Kunming in the five climate zones, are selected to locate the high-tech cleanroom. The TMY (typical meteorological year) [16] weather conditions of each city are used to identify the operation mode and calculate the load and energy consumption of the air-conditioning system.

3. RESULTS AND DISCUSSIONS

3.1 Monthly energy performance

Fig. 2 shows the monthly energy consumption of the MAU+DCC+FFU system for high-tech cleanrooms located in different climatic locations. It can be found that the high-tech cleanrooms located in the hot zones, i.e, Guangzhou and Shanghai, have higher monthly energy consumption in summer seasons, compared with that of cold and mild zones. However, the high-tech cleanrooms located in the cold zones, i.e, Harbin and Beijing, have much higher monthly energy consumption in winter seasons, compared with that of hot and mild zones. This is due to large preheating and humidifying demands of outdoor air. The cleanrooms in all five climates have the lowest energy consumption in transition months. It is worth noting that the high-tech cleanroom located in the mild zone, i.e., Kunming, has the relatively equal energy consumption in different seasons due to the mild climate throughout the year. When the high-tech cleanrooms locate in the cold and hot zones, the monthly energy consumption differs much in different seasons, due to the distinct climate difference throughout the year.

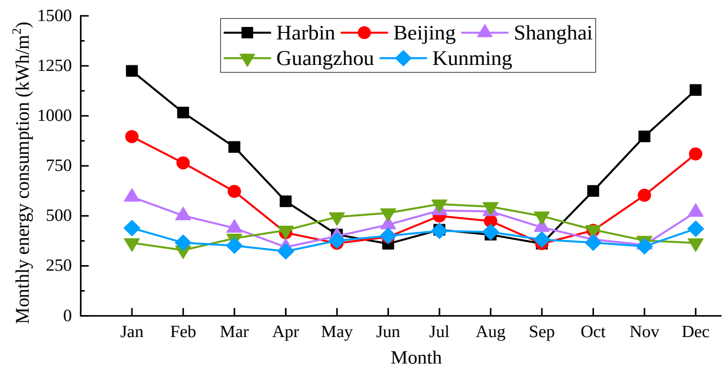


Fig. 2. Monthly energy performance.

In order to reflect the climatic and seasonal impacts on the energy performance of high-tech cleanroom air-conditioning systems, their monthly energy consumption is correlated with the monthly mean wet-bulb temperature of outdoor air for each city, as shown in Fig 3. It can be seen that the monthly energy consumption has a highly V-shaped relation with the outdoor air wet-bulb temperature whatever the cleanroom location. Four parameters are defined to describe this V-shaped relation, i.e., the change-point temperature t_c, the cooling&dehumidifying slope above the change point $k_{co\&dhu}$, the heating&humidifying slope below the change point $k_{he\&hu}$, and the base energy use associated with the change point E_0. The change-point temperature t_c could be used to divide the air-conditioning time throughout the year for high-tech cleanrooms. The $k_{co\&dhu}$ and $k_{he\&hu}$ could help identify how much increased or decreased energy use is required for the high-tech cleanroom air-conditioning system when the outdoor air wet-bulb temperature increases or decreases by 1°C in winter or summer seasons. Besides, this V-shaped relation could be used to estimate the possible energy consumption of high-tech cleanroom air-conditioning systems, as long as the outdoor air web-bulb temperature is available.

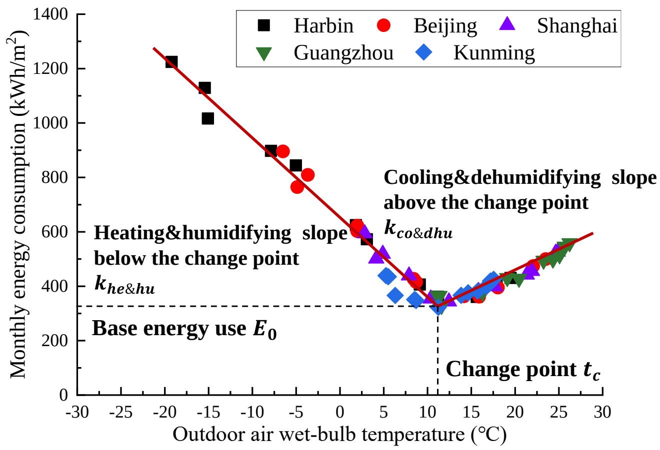
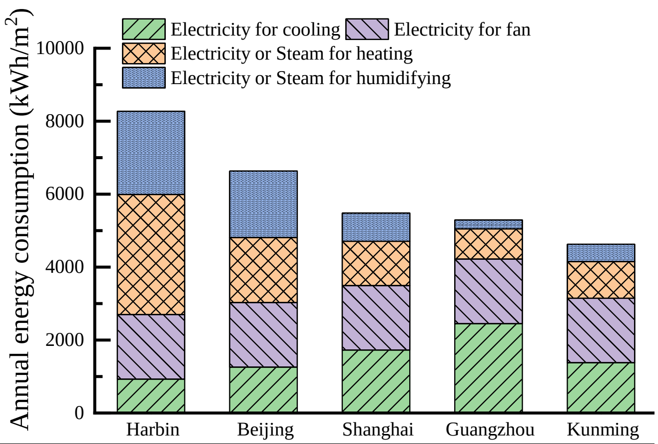


Fig. 3. The proposed V-shaped four-parameter relation.

3.2 *Annual energy performance*



Cooling	11.3%	19.0%	31.5%	46.3%	29.8%
Fan	21.4%	26.7%	32.3%	33.5%	38.3%
Heating	39.8%	26.9%	22.1%	15.6%	21.6%
Humidifying	27.6%	27.4%	14.1%	4.6%	10.4%

Fig. 4. Annual energy performance.

Fig. 4 shows the annual energy consumption and each item proportion of the MAU+DCC+FFU system for high-tech cleanrooms in different climates. It can be seen that the system annual energy consumption of high-tech cleanrooms located in cold zones is higher compared with that in hot/mild zones. This is due to the large energy consumption for heating and humidifying, which account for 39.8% and 27.6% in Harbin, and 26.9% and 27.4% in Beijing. When the high-tech cleanroom locates in hot/mild zones, the energy consumption of cooling accounts for a significant percentage, for example, 46.3% in Guangzhou. It is worth noting that the high-tech cleanroom located in the mild zone, i.e., Kunming, has the lowest energy consumption, as explained in Section 3.1.

4. CONCLUSIONS

In this study, the year-round energy performance of high-tech cleanroom air-conditioning systems is investigated in different climates. The major conclusions are as follows.

- The system annual energy consumption of high-tech cleanrooms located in cold zones is higher compared with that in hot and mild (the lowest) zones.
- The high-tech cleanroom located in the mild zone has relatively equal system energy consumption in different seasons. However, the high-tech cleanrooms located in the cold and hot zones, have much different monthly energy consumption in different seasons.
- The V-shaped four-parameter relation is proposed to describe the system energy use of high-tech cleanrooms in different climates. This relation could estimate the possible energy consumption for high-tech cleanroom air-conditioning systems.

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