Parameter analysis of air-conditioning systems for high-tech cleanrooms considering climate impact

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Abstract. The air-conditioning systems for high-tech cleanrooms are usually energy-intensive, due to strict temperature, humidity and particle concentration requirements. Their system performance strongly depends on the operation parameters and climate/weather conditions. But few studies have investigated such impacts for high-tech cleanrooms. Therefore, this study has quantified the impacts of operating parameters on the performance of high-tech cleanroom air-conditioning systems under different climate conditions via parametric and sensitivity analysis. A typical high-tech cleanroom located in Chinese five climate zones is selected to examine each parameter's impact using Energyplus/Matlab platform. Results indicate that the system annual energy consumption shows nearly linear changing trends when varying the operation parameters. The outdoor air exchange rate and MAU (make-up air handling unit) outlet air temperature are the most sensitive parameters in cold zones. The studied results can help practitioners improve air-conditioning system design and operational performance for high-tech cleanrooms through carefully determining parameters with heavy impacts.

Keywords. High-tech cleanroom, Air-conditioning system, Energy performance, Climate impact, Parameter sensitivity
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1. Introduction

High-tech cleanrooms have been growing very fast in terms of the total floor area and production quantity. It 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 [1]. The annual electricity consumption of a typical semiconductor fab is as high as 20,908 kWh/m^2 [2], which is around three times the average consumption of data centers worldwide [3] and even 100 times that of public buildings [4].

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 [1, 2, 5, 6]. The main reasons are as follows. (***i***) High-tech cleanrooms need extensive supply air exchange rate to maintain the clean environment for high-precision manufacturing. (***ii***) High-tech cleanrooms need large outdoor air exchange rate to compensate for the large exhaust air generated from the manufacturing. (***iii***) The machines/equipment in the high-tech cleanrooms generate a great amount of heat. Therefore, the energy performance of such energy-intensive applications strongly depends on the operation parameters (e.g. supply and outdoor air exchange rate). Improper determination of these operation parameters often occurs that much energy has been wasted [7].

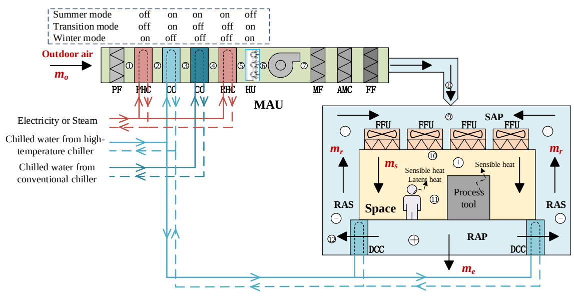
There are a few publications that have investigated the impacts of various operation parameters on the performance of high-tech cleanroom air-conditioning systems. Hu et al. [8] investigated the energy consumption of a Taiwanese semiconductor manufacturing fab, and indicated that lowering the dry-bulb temperature of the MAU (make-up air handling unit)-supplied air from 14°C to 11°C could result in 8.63% energy savings. Hu et al. [9] further quantified the corresponding reduced energy of 5.82% by reducing the MAU exit temperature of 1°C interval. Chang et al. [10] discussed the impacts of cleanroom dry bulb temperature and relative humidity setpoints, supply air volume flowrate and MAU exit temperature on the annual power consumption for a TFT-LCD fab by adjusting their values. The above researches focused on identifying the possible reduced energy use when changing the operation parameters (i.e. MAU exit temperature, supply air volume). The impacts of other important parameters, such as indoor cooling load, outdoor air volume, are still not clear. Meanwhile, very few studies are found concerning the parameter sensitivity analysis in air-conditioning system designs of high-tech cleanrooms considering the climate variety.

Therefore, this study conducts the parametric and sensitivity analysis to systematically investigate the impacts of key operation parameters on the energy performance of air-conditioning systems for high-tech cleanrooms under the full range of climate conditions. The climate-dependent sensitivity of each operation parameter on system performance is also identified and analyzed. This study aims to provide valuable information for parameter determination with expected energy savings, for high-tech cleanroom air-conditioning systems.

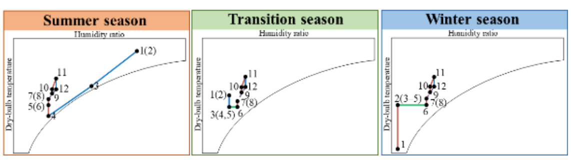
2. Methods

2.1 A typical high-tech cleanroom air-conditioning system and key operation parameters

A typical high-tech cleanroom air-conditioning system, i.e., MAU+DCC (dry cooling coil) +FFU (fan filter unit) system, is selected for parameter and sensitivity analysis. The MAU+DCC+FFU system is the most updated and commonly-used air-conditioning system for high-tech cleanrooms today [11, 12]. Its system configuration and year-round operating principle are shown in Fig. 1. The air-conditioning system provides constant supply and outdoor airflow rates to guarantee strict space temperature, relative humidity, cleanliness, static pressure controls. Specifically, the MAU and DCC separately condition outdoor air and return air, respectively, to fully-decoupled control the space relative humidity and dry-bulb temperature. The FFU cycles and delivers the supply air via the orifice plate air supply outlet facilitated with HEPAs (high-efficiency particulate air filter), to the high-tech cleanroom space.



(a) system configuration



(b) operating principle

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

Five key operation parameters are selected to evaluate their impacts, i.e., indoor design condition (t_i, w_i), indoor cooling load index (Q_{tot}), supply and outdoor air exchange rates (A_s, A_o), MAU outlet air temperature (t_{MAU}). Because they significantly influence the energy performance of high-tech cleanrooms, and they are primarily determined during the design stage and easy to adjust during the operation stage without any extra expenditure.

2.2 System energy model

Assuming that the indoor temperature and relative humidity in the high-tech cleanroom are perfectly controlled at the indoor design condition (t_i, w_i), its annual cooling load profile (Q_{tot}, W_{lat}) can be calculated by Energyplus. The required supply air (h_s, t_s, w_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 (w_{ro}). The loads of cooling coils ($Q_{fc,MAU}$, $Q_{sc,MAU}$, 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_c) and fans (E_f), and electricity or steam for heaters (E_{he}) and humidifiers (E_{hu}), can be computed and converted to the primary energy using Eqs. (10–12). The overall coefficients of performance (COPs) of the cooling systems (conventional: COP_{cc}, high-temperature: COP_{hc}) vary with the wet-bulb temperature of outdoor air [13-15]. The above system energy model is developed in the Matlab platform after validation.

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

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

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

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

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

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

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

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

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

$$\begin{aligned} E_{tot} &= E_c + E_{he} + E_{hu} + E_f \\ &= \frac{Q_{fc,MAU} + Q_{DCC}}{COP_{hc}\eta_p} + \frac{Q_{sc,MAU}}{COP_{cc}\eta_p} + \frac{Q_{he,MAU}}{\eta_s} \\ &\quad + \frac{Q_{hu,MAU}}{\eta_s} + \frac{W_{f,MAU}}{\eta_p} + \frac{W_{f,FFU}}{\eta_p} \end{aligned} \tag{10}$$

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

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

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 parameter impacts for high-tech cleanroom air-conditioning systems. Five typical cities, i.e., Harbin, Beijing, Shanghai, Guangzhou and Kunming in the five climate zones, i.e., severe cold, cold, hot summer cold winter, hot summer warm winter, as well as mild zones, are selected to locate the high-tech cleanroom [16]. The Typical Meteorological Year [17] weather conditions of each city are used to identify the operation mode and calculate the load and energy consumption of the air-conditioning system.

2.4 Sensitivity quantification

The sensitivity of each parameter is quantified and evaluated by the sensitivity factor *S(x)*, as shown in Eqs. (13).

$$S(x) = \frac{\Delta E_{tot}(x_r+\Delta x) - E_{tot}(x_r)}{E_{tot}(x_r)} \Big/ \frac{\Delta x}{x_r} \tag{13}$$

Where, *S(x)* is the sensitivity factor; x_r is the reference value of a certain parameter; Δx is the change of the parameter. A larger absolute value of *S(x)* represents a more sensitive relationship between the change of energy consumption and the change of parameter.

3. Results and discussions

3.1 Parameter impacts on system annual energy consumption

The individual impacts of the five key parameters (i.e., indoor design condition, indoor cooling load, supply and outdoor air exchange rates and MAU outlet air temperature) on the annual energy consumption of high-tech cleanroom air-conditioning systems are illustrated in Fig. 2.

It can be found that the system annual energy consumption varies nearly linearly with the changes of five operation parameters in all five climate zones. Either increasing the indoor cooling load, supply/outdoor air exchange rate and MAU outlet air temperature would increase the system annual energy consumption. However, the energy increasing rates are different when increasing the operation parameters in different climate zones. (***i***) As the indoor cooling load increases by 100W/m^2, the hot zones increase more annual energy consumption of 1.06 and 1.30GJ/m^2, compared with the cold zones and mild zone of 0.74, 0.87, and 0.98GJ/m^2, respectively. This is because the increment of indoor cooling load can be partially removed by the cold outdoor air in cold climates. (***ii***) As the outdoor air exchange rate increases by 1h^{-1}, the cold zones increase more annual energy consumption of 1.32 and 1.03GJ/m^2, compared with the hot zones and mild zone increase by 0.84, 0.88 and 0.63GJ/m^2, respectively. This is because more outdoor airflow rate requires more preheating energy demands in cold climates, which is larger than the increased outdoor air dehumidification demands in hot and mild climates. (***iii***) However, as the supply air exchange rate increases by 10h^{-1}, the five zones increase nearly the same annual energy consumption of 0.63, 0.64, 0.66, 0.67 and 0.65GJ/m^2, respectively. This is because the increased energy consumption is mainly used for fan power on delivering more supply airflow rate. (***iv***) Similarly, as the MAU outlet air temperature increases by 1°C, the five zones increase nearly the same annual energy consumption of 1.01, 1.01, 1.13, 1.16 and 1.05GJ/m^2, respectively. This is because the increased energy consumption is used to preheat and reheat outdoor air. (***v***) For the indoor design condition, higher indoor requirements of temperature and humidity are good to the hot and mild zones, where the hot and humid days occupy the most of year time and less cooling and dehumidification energy consumption is needed.

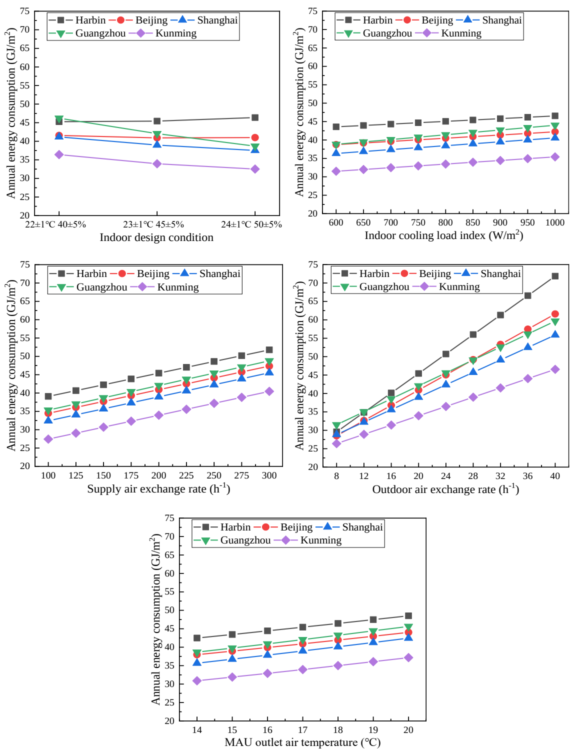


Fig. 2 - The impacts of five key operation parameters on the system annual energy consumption.

3.2 Parameter sensitivity on system annual energy consumption

In light of the impact differences of different operation parameters in the different climates, the sensitivity factors *S(x)* of five parameters in the five climate zones are shown in Fig. 3.

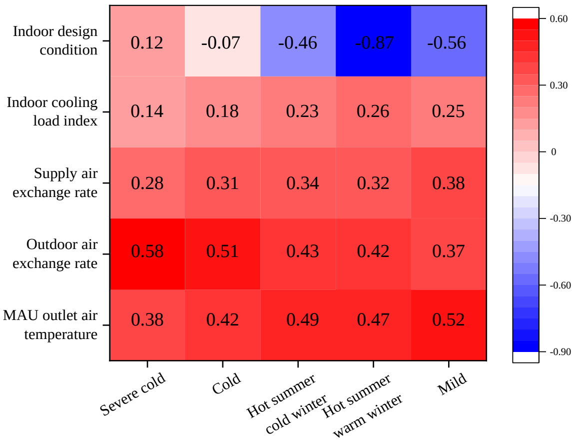


Fig. 3 - Sensitivity factors of five operation parameters under different climate zones.

For the severe cold and cold zones, the most sensitive parameter is the outdoor air exchange rate, followed by the MAU outlet air temperature. For the hot and mild zones, the most sensitive parameters are the MAU outlet air temperature and indoor design condition, followed by the outdoor air exchange rate. However, the indoor cooling load has the lowest contribution in all five climate zones. Therefore, the most energy-sensitive parameters in the specific climate zone should be well determined and adjusted during the design and operation stages, for considerable energy savings.

4. Conclusions

In this study, the quantitative impacts of operating parameters on the energy performance of high-tech cleanroom air-conditioning systems are investigated in different climates. The major conclusions are as follows.

- The annual energy consumption of high-tech cleanroom air-conditioning systems shows nearly linear changing trends when varying the operation parameters.

- As the supply air exchange rate and MAU outlet air temperature change, the energy consumption of high-tech cleanrooms in different climates changes nearly the same, i.e., 0.63–0.67GJ/m^2 per 10h^{-1} and 1.01–1.16GJ/m^2 per 1°C, respectively. However, as the indoor cooling load and outdoor air exchange rate change, the high-tech cleanrooms located in different climates show different performances.

- The outdoor air exchange rate and MAU outlet air temperature are the most sensitive parameters in cold zones, while the indoor cooling load index has the lowest contribution in all five climate zones.

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6. Nomenclature

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
h	Enthalpy (kJ/kg)
MAU	Make-up air handling unit
MF	Medium efficiency particulate air filter
m	Air mass flow rate (kg/s)
PF	Primary efficiency particulate air filter
PHC	Preheating coil
Q_{tot}	Space total cooling load (kW)
RAP	Return air plenum
RAS	Return air shaft
RHC	Reheating coil
SAP	Supply air plenum
t	Temperature (°C)
W_{lat}	Space latent cooling load (kg/s)
w	Humidity ratio (kg/kg)
Greek letters	
η_p	Power generation efficiency
η_s	Steam generation efficiency
η_1	Pressure efficiency
η_2	Motor efficiency
Subscripts	
c	Cooling system
cc	Conventional cooling system
f	Fan
fc	First cooling coil
hc	High-temperature cooling system
he	Heating system
hu	Humidification system
i	Indoor air
lat	Latent
o	Outdoor air
r	Return air
s	Supply air
sc	Second cooling coil
tot	Total

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