Applied Energy 204 (2017) 582–595

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Energy efficient design and control of cleanroom environment control systems in subtropical regions – A comparative analysis and on-site validation

Kui Shan, Shengwei Wang *

Department of Building Services Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong

HIGHLIGHTS

- Three typical air-conditioning system options are comparatively analyzed.
- The "partially decoupled option" is proposed for retrofit projects.
- Simulation and on-site test results show the proposed method performed properly.
- The annual cost saving is about 4.6 million HKD in the reported retrofit project.

ARTICLE INFO

Article history:
Received 13 February 2017
Received in revised form 21 June 2017
Accepted 15 July 2017

Keywords:
Cleanroom
Air-conditioning
Energy saving
Dehumidification
Humidity control

ABSTRACT

Compared with spaces air-conditioned for thermal comfort, cleanrooms often have special requirements on dry bulb temperature, relative humidity and particle concentrations. It is a challenging task to achieve those requirements with minimum energy consumption, especially when different parameters interfere with each other. A significant amount of energy would be wasted if the system is not properly designed and controlled. This paper firstly provides an overview and a discussion on the essentials for design and control of cleanroom air-conditioning systems. The existing systems and controls are categorized into three typical options and their performances are then analyzed based on different weather and load conditions. For new design, the "fully decoupled option" is the preferred option for humid sub-tropical regions. The analysis results are applied in a retrofit project for a pharmaceutical factory located in Hong Kong, a humid sub-tropical city, which employed the "interactive option". This system is proposed to operate as a "partially decoupled option" in this project since such retrofit requires no modification on the existing hardware. The retrofitted system option has been on-site tested in mild weather condition, which provided 69.6% and 87.8% reductions of cooling and heating consumptions respectively. More comprehensive comparison tests are also conducted on a dynamic platform built on Matlab/Simulink.

1. Introduction

Cleanrooms can be 30–50 times more energy intensive than the average US commercial buildings due to high ventilation rates required for maintaining low particle concentrations [1]. Cleanroom environment control systems or air-conditioning systems consume about 30–65% of the total energy use in a high-tech fabrication plant [2]. High energy consumptions often represent high operation costs: "A Class 10 environment typically costs about US $2000 per square foot to build and US$1 million a year to operate." [3,4]. It is essential to reduce energy use in cleanrooms for two main reasons. First, the cleanroom area has been growing fast, which increased from 4.2 million m^2 in 1993 to the estimated 15.5 million m^2 in 2015 in the US [5], and it increases even faster in South China. Second, the energy consumptions and their energy saving potentials are very high compared with many other air-conditioning systems.

Design and control of cleanroom environment control or air-conditioning systems are both essential for energy efficiency, which are closely interrelated concerning both the environmental control performance and the energy performance. Only when an air-conditioning system is properly designed, appropriate control can be implemented to achieve the desired environment control with high energy efficiency. In addition, control engineers should be involved in the design process so that all elements are considered [6].

* Corresponding author.
E-mail address: beswwang@polyu.edu.hk (S. Wang).

http://dx.doi.org/10.1016/j.apenergy.2017.07.050
0306-2619/

Many researchers have addressed the design of cleanroom air-conditioning systems. Hansz [7] provided five steps to collect required information for designing cleanrooms, i.e. establishing goals, analyzing facts, examining concepts, establishing needs, and stating problems. Yang and Eng Gan [4] analyzed the essential elements of cleanrooms design that significantly affect the construction costs. Tschudi et al. [8] provided strategies for designing and controlling of air change rates in cleanrooms, i.e. demand-controlled filtration (DCF) based on real-time monitoring of particle concentrations. Lin et al. [9] developed a fan dry coil unit return system for improving the energy efficiency of cleanrooms. Hu and Tsao [10] compared the energy efficiency of five different cleanroom air-conditioning systems made up of different combinations of recirculation air unit (RCU), make-up air unit (MAU), fan coil unit (FCU), dry cooling coil (DCC), fan-filter unit (FFU), etc. The results indicated that the system with combined MAU and FFU provided the highest energy efficiency. They also proposed a make-up air system for energy conservation [11]. Kircher et al. [1] compared energy efficiency methods through modeling and simulation on four systems, including a heat recovery system, solar preheating for dehumidification system, lighting control, and demand-controlled filtration. Some other studies addressed energy recovery from exhaust air using technologies like heat pipes or regenerative-desiccant wheel [12–16].

Though many studies for cleanroom design appear in literature, few studies have investigated the control of cleanroom air-conditioning systems. A well designed but not properly controlled cleanroom air-conditioning system may still consume a large amount of energy. Some studies discussed the control of cleanroom pressure. Wang et al. [17] provided an operation strategy to control pressure gradient in a multi-zone cleanroom. Their experimental investigation showed that the strategy achieved an energy saving of about 24.5%. Van den Brink et al. [18] also proposed an improved pressure control in cleanrooms with a focus on pressure deviations during the entry of cleanrooms.

However, very few published research works have addressed the control associated with design for energy efficiency in cleanrooms. Because of the special requirements, those approaches for thermal comfort air-conditioning systems, such as reducing outdoor air flow [19] and some complex control methods [20,21], may not be applicable for cleanroom applications. Only a few publications addressed local controls that aim at controlling process variables to follow their set-points in cleanrooms. For instance, Tan et al. [22] provided an automatic tuning approach for variable structure control of temperature in cleanrooms.

Since a majority of the cleanroom air-conditioning systems use cooling process for dehumidification, counteraction between heating and cooling for humidity and temperature control may waste a large amount of energy. Alternative approaches should be considered to enhance the energy efficiency of cleanroom air-conditioning systems. First, the system design should consider the climate conditions. Secondly, the control of the system in the year-round operation conditions should be properly considered at the design stage and the control design should consider the system energy use seriously.

This paper therefore provides an overview and discussion of the key issues of design and control of cleanroom air-conditioning systems. Three typical systems are then described and comparatively analyzed in different weather and load conditions. The analysis results are applied in a retrofit project for a pharmaceutical factory located in Hong Kong, a humid sub-tropical city, which originally employed an air-conditioning system of "interactive option". This system is retrofitted to operate as a system of "partially decoupled option" in this project since such retrofit is the most cost effective as it requires no modification of the existing hardware.

Though different cleanrooms may have different requirements, they have the same problem of high operation cost due to similar reasons. The results of comparative analysis of the systems of three categories as well as the case study presented in this paper provide very useful guidance for the design and control of environment control systems or air-conditioning systems in both retrofit and new projects.

The rest of this paper is organized as follows: Section 2 presents an overview and discussion on the key issues of design and control of cleanroom air-conditioning systems. Section 3 describes the configurations and control methods of three typical systems for cleanrooms. Section 4 shows the comparative analysis on these three systems. Section 5 introduces a retrofit project, including a description of the actual building air-conditioning, its retrofit on-site test plan, and the dynamic simulation platform for comprehensive tests and validation; Section 6 presents the on-site and simulation test results and analysis. On-site implementation results are also presented. Section 7 draws the conclusions.

2. Key issues of design and control of cleanroom air-conditioning systems

Compared with common purpose of air-conditioned spaces for thermal comfort, cleanrooms often have special requirements on dry bulb temperature (DBT), relative humidity (RH) and particle concentrations. A high supply air flow rate is often required in cleanrooms for removing airborne particle pollutants. Besides the large fan power consumption, the high supply air flow rate may also cause great power consumption for dehumidification and temperature control of cleanrooms. The conventional design and control methods directly cool down the supply air to its dew point for dehumidification and then reheat it to achieve the desired temperature in cleanrooms. Because of the high supply air flow rate, the required cooling and reheating energy for dehumidification would be extremely high even when the humidity load is low.

To solve the problem of high energy consumption caused by high supply air flow rate, some key issues should be addressed properly at design stage. First, it is essential to design the supply air ducts with low air flow resistance, so that the supply air fan power can be reduced. Second, conventional air handling processes have to be replaced by alternative approaches for controlling dry bulb temperature, relative humidity and particle concentration. Two common approaches can be summarized to address the problem of high energy consumption and the relative concepts are described as follows.

Approach 1: Dehumidify the outdoor air in primary air handling units (PAUs) to decouple humidity and temperature controls while the dried outdoor air is used to dehumidify air in the indoor spaces. This system is particularly suitable for cleanrooms of relatively low dehumidification load.

Approach 2: Decouple temperature and humidity controls using two parallel cooling coils besides heating. Supply air flow is separated into two streams. One stream goes through the wet coil for humidity control. Its flow rate is optimized so that the wet coil consumes minimum cooling energy for dehumidification. The other stream goes through the dry cooling coil for temperature control only. Moreover, the total flow rate of the two streams equals the required total supply air flow rate for the control of particle concentrations.

3. Three typical air-conditioning system options

Based on a survey of the existing systems and controls appearing in literature and real practice, cleanroom environment control systems or air-conditioning systems are categorized into three typ-