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Capturing energy-saving opportunities in make-up air systems for cleanrooms of high-technology fabrication plant in subtropical climate

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ABSTRACT

Operation of make-up air units (MAUs) for cleanrooms of high-technology fabrication plant in subtropical climates is very energy intensive, in that it is expected to deliver conditioned air at elevated airflow rates, compared to conventional commercial applications. Optimizing the design of MAU via reducing or displacing mechanical cooling or electrical heating processes can improve energy efficiency in cleanrooms since cleanroom air-conditioning systems typically use 30–65% of the total energy consumption in a high-tech fabrication plant [1]. This paper investigates the difference in energy efficiency performance of MAU systems with different pre-cooling and preheating/humidification schemes. Additionally, a comparative study was carried out for humidification schemes including wet media, directly atomized water, steam, and two-phase flow. The results show that energy recovery by DCC water return method exhibits the best energy efficiency among a total of eight schemes evaluated in this study. In addition, wet media scheme is the best humidification scheme in winter time, compared with the other three types of humidification schemes.

1. Introduction

High-technology industries such as semiconductors and opto-electronics manufacturing generate a variety of harmful gases in their manufacturing processes, and at the same time they have requirements of positive air-pressure for cleanroom operations. Make-up air units (MAUs) are typically designed to provide significant amounts of outside air that needs to be conditioned before it is mixed with recirculated air for use in cleanrooms. Because of the very high level of air circulation rates, energy required for cooling the outdoor air is significant. For example, cooling or heating energy required for conditioning outdoor air for a cleanroom can be more than half of electricity consumption of a cleanroom HVAC (heating, ventilating and air-conditioning) system. Identifying solutions to improve efficiency of MAU systems that condition outdoor air can reduce operations and manufacturing costs in such high-technology facility systems. While there are some published studies on MAU systems for conventional commercial buildings, literatures concerning energy savings in operating MAU systems in high-technology industries are rather limited. Brown [1] discussed the concept of energy recovery from make-up air-handling apparatus for commercial buildings in five different climatic regions in the United States. Suzuki et al. [2] reported that a 3% energy-saving on the overall performance of a MAU system can be achieved by improving the condensation performance of cooling coils in High-Tech fabrication plants in Japan. Mumma et al. [3] discussed an ultrasonic humidifier used in an AHU (air-handling unit) with volumetric flow rate of 15,000 scfm of outdoor air, for a VAV (variable air volume) system for humidification of outdoor air, and results indicate that its energy-efficiency would be higher than the traditional steam humidification. Roulet et al. [4] surveyed thirteen HVAC systems equipped with exhaust air heat recovery systems in Switzerland and Germany, and found that about 70% of these systems reach 80% efficiency. Bartholomew [5] indicated that the combination of heat pipe and regenerative-desiccant wheel can save up to 71% of cooling and dehumidification energy MAUs use in laboratory make-up air systems. Yau [6] reported a critical review of the status and potential application of heat pipe heat exchangers for recovery of coolness in HVAC systems, in tropical areas like Singapore, Malaysia, Thailand, Brunei and Indonesia, and concluded that double heat pipe heat exchanger systems for buildings with operating theatres, the fresh air should be first pre-cooled at the first heat pipe heat exchanger evaporator zone, through coolness recovered from the contaminated exhaust air. Subsequently, Yau [7] applied an eight-row thermal-siphon type heat pipe heat exchanger to recover waste energy from exhaust air to dehumidify and cool fresh outdoor air in hospital operating rooms in tropical

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areas. Recently, Hu and Tsao [8] compared energy efficiency performance of five different HVAC systems for cleanrooms and pointed out that the MAU, in combination with FFU (fan filter unit) systems exhibited the highest energy efficiency, in comparison with traditional "centralized" AHUs, for a typical 200 mm DRAM fabrication plant. In a subsequent article, Tsao and Hu [9] improved the energy performance of the MAU system by properly arranging components of a MAU. Westbrook [10] presented a practical example of using run-around coils for reheating of air in a MAU in a 300 mm wafer fabrication plant for Texas Instruments (United States), with a "two temperature" cooling coil system. However, no data was available to quantify the effects or benefits. Lovins [11] indicated that using high pressure humidification, instead of traditional steam humidification, can cut down 60% of NOx generation from steam generators, and 70% of energy can be recaptured for make-up air handler, when an enthalpy-wheel recovery device is installed in a typical laboratory exhaust system. Cohen [12] compared four cleanroom humidification systems to determine energy consumption per unit of water absorbed by makeup air required for the cleanroom. Niu and Zhang [13] investigated performance of the membrane type heat recovery device for make-up air-handling unit by the first law of thermodynamics, and found that latent heat recovery is more important than sensible heat recovery, and about 57.3% of the energy required for treatment of fresh air could be recovered. Hu and Chuah [14] benchmarked electricity consumption in nine semiconductor fabrication plants in Taiwan and found fan and pump in make-up air-handling accounted for approximately 2% of total energy consumption in fabrication plants.

None of the studies mentioned above have provided detailed theoretical analysis of energy consumption by MAU systems, considering the associated chilled water systems, along with heat recovery, cascade cooling during cooling/dehumidification in summer time, and reheating/humidification process during winter time, including wet media, direct water atomization, steam and two-phase flows.

2. Objectives

This paper aims at capturing energy-saving opportunities in make-up air systems for high-technology industries in subtropical climates. The specific objective of this study is to quantify the potential for energy saving via analyzing and comparing a series of MAU system designs and improvements in different cooling/dehumidification and preheating/humidification processes.

3. MAU design characteristics and methodology

3.1. MAU base design

In order to evaluate and compare performance of different designs in energy recovery from heating and humidification operations of make-up air-handling units, we use a draw-through type make-up air-handling unit as the base design in this study. The calculation base is the MAU for a typical semiconductor cleanroom in a subtropical region, with specifications of the MAU as shown in Table 1 and Fig. 1.

3.2. Alternative MAU design and operation

A previous study (Tsao and Hu [9]) indicated that the chilled water temperature for operating the primary/secondary cooling coil is a very important factor for energy consumption in MAUs. For example, chilled water temperature of 5–7 °C for cooling coil in MAU would correspond to a Coefficient of Performance (COP), for the chiller, of approximately 3.5, while an increase of chilled water temperature to 9 °C for primary cooling coil (e.g., with the help of pre-cooling of outdoor air) in MAU would correspond to an enhanced COP of 4.0. Often a chilled water system with "dual temperatures" – a higher temperature set for primary coil (e.g., 9 °C) and a lower temperature set for secondary cooling coil (e.g., 5 °C) – can satisfy dehumidification requirements and reduce electricity use for the chilled water system. If we consider air mass flow rate to be $\dot{m}_a$, the steady-state energy equation for any cooling process (Fig. 2), from status 1 to status 2, may be written as:

Table 1
Specification of MAU studied.

Outdoor air condition (OA)	
Summer	34 °C DB, RH = 80%
Winter	6 °C DB, RH = 30%
Indoor air condition	23 °C DB, RH = 45%
Air flow rate for MAU	100,000 m^3/h
Total pressure for MAU fan	1600 Pa
Fan mechanical efficiency	80%
Leaving air from primary cooling coil (LA1)	20 °C DB, 19.4 °C WB
Leaving air from secondary cooling coil (LA2)	10.4 °C DB, 10.4 °C WB
Supply air from MAU to the cleanroom (SA)	17 °C DB

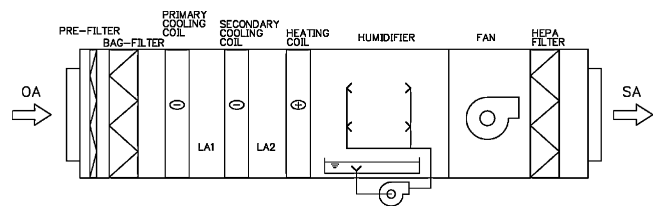

Fig. 1. HVAC apparatus layout of MAU (Case 1/Case 2).

$$\dot{m}_a h_1 = \dot{m}_a h_2 + \dot{m}_f h_{f,2} + \dot{Q}_c \quad (1)$$

where h_1 and h_2 are enthalpy at states 1 and 2, $h_{f,2}$ denotes the enthalpy of condensate, if any, assuming temperature at state 2, and $\dot{Q}_c$ means the total cooling capacity of the cooling coil.

The water balance equation is

$$\dot{m}_a w_1 = \dot{m}_a w_2 + \dot{m}_f. \quad (2)$$

where w_1 and w_2 are the specific humidity for states 1 and 2, respectively, and $\dot{m}_f$ is the mass flow rate for condensation.

If we substitute (1) into (2), we obtain

$$\dot{Q}_c = \dot{m}_a[(h_1 - h_2) - (w_1 - w_2)h_{f,2}] \quad (3)$$

Since capacity for primary and secondary stage cooling coils is $\dot{Q}_{CCP}$ and $\dot{Q}_{CCS}$, respectively, the total cooling coil capacity $\dot{Q}_c$ may be written as

$$\dot{Q}_c = \dot{Q}_{CCP} + \dot{Q}_{CCS} \quad (4)$$

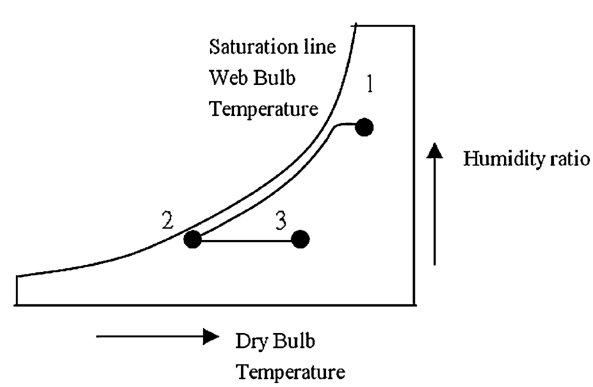

Fig. 2. Psychrometric process for outdoor air-handling during summer.