Energy Saving Potentials of a 100% Outdoor Air System Integrated with Indirect and Direct Evaporative Coolers for Clean Rooms

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Abstract

In general, HVAC systems for clean room facilities require significant energy to maintain the indoor environment. Due to high air change rates, reducing operating energy consumptions has been a critical issue. The purpose of this paper is to investigate the energy saving potentials of indirect and direct evaporative cooler assisted 100% outdoor air system (IDECOAS) serving a clean room. This research also provides a practical insight on how cooling and heating coil loads can be reduced and how to design the proposed system. In this study, it was assumed that a clean room is served by four different types of HVAC systems: a variable air volume system (VAV), an air washer system (AIRWASH), a dedicated outdoor air system (DOAS), and IDECOAS. It was found that DOAS and IDECOAS can reduce the annual cooling and heating coil loads by over 65.7% and 59.5%, respectively, compared with the VAV.

Keywords: clean room; air-washer; IDECOAS; DOAS; indirect evaporative cooler

1. Introduction

The purpose of an air handling system in a clean room is not only to control the indoor thermal environment but also to provide environmental conditions that fit a given industrial process¹⁾. However, a large amount of supply and exhaust air flows, and HEPA filters with high pressure drop are causing significant energy consumption. A significant energy penalty in clean room operation has not been the primary issue in resolving this problem, because the facility is generally used for high-end industrial products or processes²⁾. However, energy conservation is also a critical issue even in the industrial sector.

In the open literature, one may find that Hu *et al.* (2008)³⁾ experimentally showed that clean room energy consumption can be reduced by applying a new water circulating pump system in an air handling system. Olim (1998)⁴⁾ and Xu (2008)⁵⁾ suggested renovated fan-filter units (FFUs) to save fan energy compared with the conventional system. However, existing researches on energy conservation in a clean room facility is still rare.

In this study, the energy saving potentials of three different air handling systems applicable to the clean room are analyzed by comparing the energy performance of each system with that for a conventional VAV. The three systems considered in this research are as follows:

- AIRWASH: air washer system⁶⁻⁷⁾
- DOAS: dedicated outdoor air system⁸⁻¹⁰⁾
- IDECOAS: 100% outdoor air system integrated with indirect and direct evaporative coolers¹¹⁻¹²⁾

These systems are known as energy conservation air handling systems in conventional building applications. Given this, one may also expect that they can provide excellent energy saving in clean room applications, although this has not been studied yet. Therefore, in this research, the energy saving potentials of the above three air handling systems are investigated by estimating energy consumption based on the assumption that they serve an identical clean room facility.

2. System Outline

The definition of a clean room is to control floating particles in the air within a specific range of numbers and territory. It is largely divided into an industrial clean room (ICR) and a bio clean room (BCR).

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The ICR is a space to control the minute particles found in the air used in industrial facilities such as semiconductor plants. The BCR is used for the intercepting of microbe infections in the aseptic facilities of hospitals and biological laboratories or food manufacturing facilities. Due to recent progress in various super precision industrial technologies, the demand for clean room facilities is increasing.

2.1 Clean room air handling systems

Air handling systems applied to clean room facilities can be classified into two types:

- TYPE 1 is a 100% outdoor air system (Fig.1.) conditioning the clean room using the outdoor air (OA) only. The room air is exhausted to the outside without re-circulation. DOAS and IDECOAS can be used as TYPE 1 systems.

Fig.1. 100% Outdoor Air System (TYPE 1)

- TYPE 2 is a make-up air system (Fig.2.) which recirculates most room return air into the space after filtering return air using HEPA or ULPA filters to minimize airborne contamination in recirculated air. The make-up air system provides the minimum outdoor air required for ventilation purposes only. All three air handling systems are applicable as TYPE 2 systems.

In TYPE 2, the latent load and some of the sensible load are accommodated by the make-up air handler. And then, the pre-conditioned outdoor air is mixed with the room return air in the recirculation or main air handler. The supply air setpoint condition (i.e. temperature and humidity levels) is maintained by the main air handler.

3. Simulation

This study performed energy simulation for three different systems (Fig.3.) on the assumption that they serve an identical clean room. These systems can be used in the form of both TYPE 1 and TYPE 2 systems. However, DOAS is commonly used as a make-up air handler, so the simulation was performed by considering DOAS as a TYPE 2 system.

Fig.2. Make-up System (TYPE 2)

(a) Air Washer System (AIRWASH)

(b) Dedicated Outdoor Air System (DOAS)

(c) IDECOAS

Fig.3. Simulated Systems

The indoor air condition for the clean room was set to 24°C dry-bulb temperature (DBT) and 50% relative humidity (RH). The supply air (SA) flow rate was adjusted based on the air conditioning load of the space. The SA DBT was set to 20°C (i.e. neutral temperature) in all alternative systems. The SA dew point temperature (DPT) was set to 13°C. It was assumed that the facility was located in Seoul, South Korea.

Theoretical system models could be found in the open literature as presented in sections 3.1 to 3.4. In this research, simulations for application to cleanrooms were conducted using the EES commercial equation

solver program¹³⁾ which enables the mathematical modeling and analysis of various thermal systems.

3.1 Air washer system (AIRWASH)

AIRWASH is composed of an air washer and wet scrubber. The RA is discharged into the wet scrubber and then exhausted to the outside. The heat withdrawn from the RA is recovered by the water sprayed into the unit. The OA is cooled or heated by a cooling and heating coil (CH/C) installed in the air washer (Fig.3.a). The SA passed through the air washer is delivered into the clean room after the target condition of the SA is acquired by the coils downstream of the unit.

When AIRWASH is applied as both TYPE 1 and TYPE 2 systems, the DPT setpoint of the SA (i.e. 13°C) is met by the CH/C and cooling coil. In the case of TYPE 1 application, however, the reheat coil would be required to meet the SA DBT (i.e. neutral temperature). AIRWASH is simulated based on the theoretical analysis and experimental model suggested by Song *et al.* (2009)⁷⁾.

3.2 Dedicated outdoor air system (DOAS)

DOAS is composed of an enthalpy wheel, a cooling coil, and supply and exhaust air fans. The OA entering the DOAS unit is preconditioned by the enthalpy wheel. It provides pre-cooling and pre-dehumidification of the SA during the cooling season, and pre-heating/pre-humidification during the heating season. The cooling coil located at the enthalpy wheel downstream takes charge of additional dehumidification (Fig.3.b). DOAS is considered as a TYPE 2 system, and the system is simulated based on the system model suggested by Jeong and Mumma (2005)¹⁴⁾.

3.3 Evaporative cooling assisted 100% OA system (IDECOAS)

IDECOAS consists of an indirect evaporative cooler (IEC), a cooling coil (CC), and a direct evaporative cooler (DEC) at the SA side, and a heating coil (HC) and a sensible heat exchanger (SHE) at the scavenger air side (Fig.3.c). The SA volume is adjusted based on the air conditioning load variation similar to the VAV system. During the cooling season, the OA entering into the unit is primarily cooled by IEC. The SA DPT setpoint (i.e. 13°C) is met by the CC. During the intermediate season with relatively dry OA, the CC load can be reduced additionally by the DEC operation.

In both TYPE 1 and TYPE 2 applications, the SA passes through IEC and CC is reheated to the neutral temperature (i.e. 20°C) by recovering the sensible heat from the scavenger air side using the SHE. When the neutral temperature cannot be acquired by the sensible heat recovery, additional heat is supplied through the HC located at the scavenger air side.

3.4 Estimation of required OA flow

In order to avoid infiltration and maintain cleanliness in clean rooms, international standards, such as ISO 14644-7 (2004)¹⁵⁾ and IEST-RP-CC028. 1 (2002)¹⁶⁾, are generally applied. Maintaining positive or negative

pressure in the clean room is also an important role of the air handling system¹⁷⁾.

In both TYPE 1 and TYPE 2 applications, the required room pressure is maintained by modulating the SA and RA flows of the air handling unit. According to recent research¹⁸⁾, it is recommended to provide 1.2-1.5mmAq of positive pressure in order to prevent unnecessary infiltration. Generally, such level of pressure difference can be acquired when the SA volume is 15~20% higher than that of RA.

3.5 Humidity control

In the case of AIRWASH and DOAS, the required indoor humidity level is maintained by the conditioned SA. However, when the absolute humidity of SA is below 0.0092kg/kg (i.e. target condition), an additional humidifier should be used.

In IDECOAS, in order to meet the room humidity setpoint (i.e. 50% RH) during the intermediate season with dry OA, the SA is passed through IEC and CC which results in 36.24kJ/kg of SA enthalpy. And then, the SA is delivered to DEC for additional cooling and humidification. When the enthalpy of OA is below 36.24kJ/kg, an additional humidifier is required to maintain the target humidity level of the space.

4. Simulation Results

4.1 Comparison of cooling coil load

Monthly and annual comparisons of the CC load acquired from the energy simulation for each TYPE 1 system are shown in Figs.4. and 5.

In Fig.4., one can see that IDECOAS and AIRWASH are showing lower monthly CC loads compared with conventional VAV. In the case of the annual CC load (Fig.5.), both IDECOAS and AIRWASH consume less CC energy than the VAV. IDECOAS and AIRWASH reduce 38.5% and 36.6% of the annual CC load, respectively, with respect to the conventional VAV.

Fig.4. Monthly Cooling Coil Load (TYPE 1)

The monthly and annual CC loads for each TYPE 2 system are compared with those for the conventional VAV (Figs.6. and 7.). IDECOAS and AIRWASH show lower monthly and annual CC loads similar to the results observed in TYPE 1 cases. DOAS provides the lowest CC load for almost the entire operating period.

Fig.5. Annual Cooling Coil Load (TYPE 1)

Fig.6. Monthly Cooling Coil Load (TYPE 2)

Consequently, DOAS shows 46.8% less annual CC load compared with the conventional VAV. The benefit of DOAS comes from the total heat (i.e. both sensible and latent heat) recovery at the enthalpy wheel. The CC load reduction observed in IDECOAS and AIRWASH also results from the pre-conditioning of the OA entering upstream of the CC.

Fig.7. Annual Cooling Coil Load (TYPE 2)

4.2 Comparison of heating coil load

Monthly and annual HC (including reheat coil (RC)) loads for each TYPE 1 system are compared with those for the conventional VAV (Figs.8. and 9.). In Fig.8., all systems except IDECOAS show high HC and RC loads. In IDECOAS, the IEC and SHE reclaim the sensible heat from the scavenger air, so significant heating and RC load reductions can be obtained.

In Fig.9., IDECOAS shows 92% of heating and RC load savings with respect to the conventional VAV, and

Fig.8. Monthly HC and RC Loads (TYPE 1)

Fig.9. Annual HC and RC Loads (TYPE 1)

90.5% reduction over the AIRWASH system.

Figs.10. and Fig.11. present monthly and annual HC load comparison results, respectively, for each TYPE 2 system. DOAS shows the lowest monthly and annual HC load. This is the benefit of the enthalpy wheel recovering the sensible heat from the exhaust air side. DOAS could maintain the SA temperature by minimizing HC energy consumption.

Fig.10. Monthly HC Loads (TYPE 2)

On the other hand, in order to maintain an appropriate indoor humidity level during the heating season, additional humidification would be required in all the systems considered in this research.

From the simulation, it was found that TYPE 1 systems have identical annual humidification load (i.e. 29.4kg•h/kg). However, in TYPE 2 systems (Fig.12.), DOAS shows 25% reduction of the humidification load compared with other systems. It is caused by

Fig.11. Annual HC Loads (TYPE 2)

Fig.12. Monthly Humidifying Load (TYPE 2)

the enthalpy wheel used in DOAS, which recovers the latent heat from the exhaust air during the winter operation.

4.3 Comparison of annual total coil load

Annual total coil load (i.e. annual CC load + annual HC load) for each TYPE 1 and TYPE 2 system are presented in Figs.13. and 14., respectively.

In Fig.13., one may see that the annual total coil load of IDECOAS is 69.8% less than that of the conventional VAV, while the AIRWASH system shows 24.1% less annual total coil load. This means that IDECOAS can be the most energy-efficient system in TYPE 1 applications (i.e. 100% outdoor air systems).

Fig.13. Annual Total Coil Load (TYPE 1)

Fig.14. Annual Total Coil Load (TYPE 2)

In TYPE 2 applications (Fig.14.), one may see that DOAS provides the largest annual total coil load saving (i.e. 65.7%) with respect to the conventional VAV, while IDECOAS and AIRWASH provide 59.5% and 37.6% reduction, respectively. DOAS is the most effective solution to TYPE 2 applications.

5. Impact of Climate Conditions

In this research, the impact of climate conditions on the total coil load savings in each TYPE 1 and TYPE 2 system operation were estimated quantitatively via the energy simulation. In general, the climatic zone can be determined based on Köppen's climate classification or ASHRAE Std. 90.1-2007¹⁹⁾.

In this study, six cities which can represent six different climate zones classified by Köppen and ASHRAE Std. 90.1 were selected for the simulation (Table 1.). It was assumed that the clean room modeled in the research would be located at selected cities. And then, annual total coil loads were estimated for each TYPE 1 and TYPE 2 application. The results for each system were compared with those for the conventional VAV system case. The TMY2 meteorological data for each selected city was used for the energy simulation²⁰⁾.

The operating conditions of each TYPE 1 and TYPE 2 system were identical with those mentioned in the SIMULATION section.

5.1 Annual total coil load for each climate zone

The annual total coil loads of TYPE 1 systems in six different climate cities are presented in Fig.15. From Singapore (i.e. tropical climate) to Moscow (i.e. continental climate), the annual total coil load reduction of IDECOAS and AIRWASH with respect to the VAV are 53.5%~88.7% and 15.8~26.7%, respectively. Consequently, one may conclude that IDECOAS could be the most energy efficient solution in nearly all the climatic zones when it used as TYPE 1 application (i.e. 100% OA system).

Fig.16. presents the annual total coil load for each TYPE 2 system in six different climate cities. As expected, DOAS provides 58.4%~86.0% of annual total coil load savings compared with the conventional VAV in selected cities, while IDECOAS shows

Table 1. Selected Cities for Climate Zone

Location	Latitude (N+/S-)	Longitude (E+/W-)	Time Zone (+/- GMT)	Elevation (m)	Köppen classification	ASHRAE Std. 90.1-2007
Singapore	1.03	103.98	7	16	Af (Tropical wet)	1A (Very hot, Humid)
New Delhi	28.58	77.2	6	212	BSh (Hot subtropical)	1B (Very hot, Dry)
Hong Kong	22.3	114.17	8	62	Cfa (Humid subtropical)	2A (Hot, Humid)
Melbourne	-37.82	114.97	10	38	Csb (Mediterranean)	3C (Warm, Marine)
Seoul	37.57	126.97	9	86	Dfa (Humid continental)	4A (Mixed, Humid)
Moskva	55.83	37.62	3	156	Dwb (Moist continental)	6A (Cold, Humid)

Fig. 15. Annual Total Coil Load (TYPE 1)

Fig. 16. Annual Total Coil Load (TYPE 2)

46.4~78.0% reduction rates. It means DOAS could be the best alternative in any climatic zone when it is applied as a TYPE 2 system (i.e. make-up air system).

Interestingly, IDECOAS shows a higher energy saving ratio than DOAS in some dry climate cities (i.e. New Delhi, India and Melbourne, Australia). From this observation, one may conclude that IDECOAS, which is based on the evaporative cooling process is an energy efficient system in relatively dry climates.

6. Conclusion

In this study, air handling systems which can be applied to clean room facilities are classified in two categories: TYPE 1 (i.e. 100% OA system) and TYPE 2 (i.e. make-up air system). By performing energy simulation, the energy saving potentials of each TYPE 1 and TYPE 2 application over the conventional VAV system were estimated. From the results of this research work, the following conclusions were obtained:

(1) In TYPE 1 systems serving the clean room using 100% outdoor air only, IDECOAS provides 69.8% of annual total coil load saving with respect to the conventional VAV. One may also see that IDECOAS achieves 53.5%~88.7% of annual coil load reduction in any climate zone.

(2) In TYPE 2 applications pre-conditioning the entering make-up OA for ventilation, DOAS shows the highest annual coil load saving (i.e. 65.7%) compared with other systems. Simulation results for the six different climate cities also show that DOAS would be the best alternative in any climatic zone and save 58.4%~86.0% of the annual coil load. However, IDECOAS would be a better solution than DOAS in some dry or Mediterranean climatic zones.

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