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Energy Performance and Applicability Comparison of Two Different Types of Liquid Desiccant Assisted Evaporative Cooling Systems

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Abstract

A desiccant enhanced evaporative (DEVap) cooling system has been introduced recently using at least vapor compression technology. The main components of the DEVap cooling system are a DEVap unit, a regenerator, a cooling coil and a reheating coil. This system is based on variable air volume system to deal with space load and it requires specific outdoor air intake strategies according to the outdoor air condition. The DEVap unit cools and dehumidifies the process air to control the room condition and cooling coil conducts extra cooling when the humidity ratio of the air is extremely high. A liquid desiccant and evaporative cooling-assisted 100% outdoor air system (LD-IDECOAS) which uses non vapor compression technology consists of a liquid desiccant, an indirect and a direct evaporative cooler and a sensible heat exchanger. The purpose of this research is to compare energy performance of the DEVap cooling system and applicability with those of the LD-IDECOAS system by simulation in cooling season. The operating energy consumption will be estimated using TRNSYS 17 integrated with commercial equation solver (EES). In terms of fan energy consumption, LD-IDECOAS consumed 19% more energy because of pressure drop caused from each component compared with the VAV system. The DEVap cooling system consumed 46% more fan energy according to increased pressure drop and additional fans. For the regeneration of solution, the LD-IDECOAS required 4 times more natural gas because it introduces 100% outdoor air in cooling season compared with the DEVap cooling system. As a results, the DEVap cooling system saved 84% and the LD-IDECOAS saved 71% of primary energy compared with the conventional VAV system.

Keywords – DEVap; LD-IDECOAS; liquid desiccant; non-vapor compression; evaporative cooling;

1. Introduction

Realizing non-vapor compression heating, ventilating, and air conditioning (HVAC) systems are one of the most attractive issues. Compared with conventional variable air volume (VAV) systems, the non-vapor compression technologies have been studied recently. Among non-vapor compression technologies, the combination of a desiccant dehumidifier and an evaporative cooler has been focused to realize the non-vapor compression HVAC system.

A desiccant-enhanced evaporative (DEVap) air conditioner is suggested by Kozubal et al.[1]. It controls latent and sensible cooling separately without the vapor compression technology. To enhance its applicability in terms of multi zone conditioning, the DEVap cooling system and its operation strategies are proposed and it has a potential to save primary energy compared to the conventional VAV system [2]. For the sensible cooling, the DEVap cooling system introduces more outdoor air compared with the VAV system because of the exhausted air in the dew point indirect evaporative cooler.

A liquid desiccant and evaporative cooling-assisted 100% outdoor air system (LD-IDECOAS) has been introduced by Kim et al [3]. This system is also one of the non-vapor compression system and uses 100% outdoor air without recirculation air which is more than the conventional VAV system.

In this study, annual energy consumption of the DEVap cooling system and the LD-IDECOAS are estimated through simulation.

2. DEVap Cooling System

The DEVap cooling system controls room conditions with modulating its supply air flow rate like conventional variable air volume (VAV) systems. Unlike conventional VAV systems, the DEVap cooling system dehumidifies and cools the process air with an internally cooled liquid desiccant (LD) and a dew-point indirect evaporative cooler (DP-IEC) which are components of the DEVap cooler [1]. A regenerator is indispensable to restore the solution concentration which is not shown in Fig. 1. The DP-IEC controls sensible cooling in dry channels with introducing a portion of cooled and dried air to wet channels for evaporative cooling. Because of this exhausted air, in a previous study, the outdoor air (OA) intake strategies are proposed to satisfy the air mass balance of the system [4].

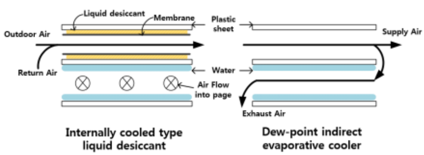

Fig. 1 Illustration of a DEVap cooler

The DEVap cooling system consists of a DEVap cooler, a cooling coil (CC), and an electric reheating coil (RHC) at a terminal VAV box which is represented in Fig.2. Because the DEVap cooler is not able to control supply air (SA) setpoint temperature with modulating the efficiency of the LD and the DP-IEC, a CC and a terminal RHC are necessary to meet the SA setpoint. If the operation of a DEVap cooler is not required, the MA passes through bypass duct to avoid pressure drop caused from a DEVap cooler. In winter season, this system is operated like a conventional VAV system with parallel electric heating equipment.

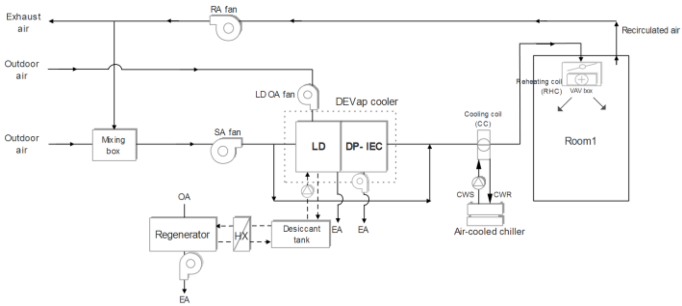

Fig. 2 Schematic diagram of the DEVap cooling system

For maintaining the air mass balance of the system, OA intake strategies are suggested in the previous study [4] and presented in Fig.3. OA intake strategies are similar to the enthalpy based economizer in conventional VAV systems. Depends on conditions of OA and room air (RA), the amount of OA intake is determined. Introducing more OA to compensate the amount of exhausted air in the DP-IEC is a fundamental concept. If enthalpy or dry-bulb temperature of OA is higher than that of RA, the amount of OA intake is equal to the sum of minimum ventilation rate and exhausted air rate in the DP-IEC (Region 1). If enthalpy of OA is lower than that of RA and dry-bulb temperature of OA is lower than that of RA and higher than SA setpoint temperature, the DEVap cooling system should operate as 100% OA mode to prevent the increase of cooling load with mixing OA with RA (Region 2). If the dry-bulb temperature of OA is higher than the lower limit temperature and lower than the SA setpoint, the DEVap cooling system mixes OA and RA with specific ratio which can meet the SA setpoint (Region 3). When OA dry-bulb temperature is lower than the lower limit temperature, OA intake rate is equal to the minimum ventilation rate (Region 4).

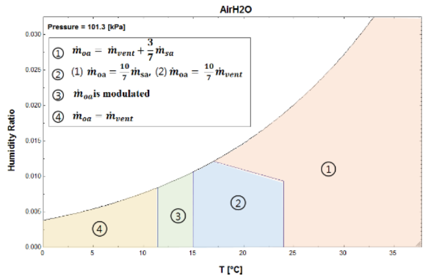

Fig. 3 Outdoor air intake strategies of the DEVap cooling system

Fig.4 shows operation strategies for the DEVap cooling system [4]. Each component of the DEVap cooling system is operated depends on the conditions of the mixed air (MA). As presented in Fig.4, operation modes of the DEVap cooling system are divided into 4 different modes. When the MA is required to be dehumidified and sensibly cooled, the DEVap cooler is activated with CC and RHC operation to meet SA setpoint (Region A). If the MA is dry, the DP-IEC is operated with CC and RHC when those are required (Region B). If the MA dry-bulb temperature and humidity ratio are lower than SA setpoint, RHC is activated alone (Region C). If dehumidification and heating are required, the LD and RHC are operated (Region D).

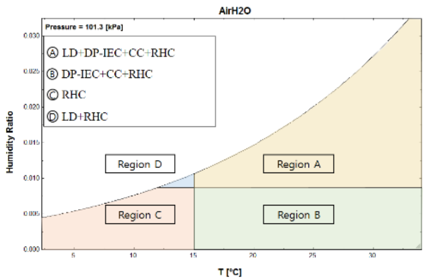

Fig. 4 Operation strategies of the DEVap cooling system

3. LD-IDECOAS

As an alternative to the vapor compression technology, a LD-IDECOAS was proposed which uses only OA to condition the space [5]. It is composed of a LD, indirect and direct evaporative coolers (IEC and DEC) and sensible heat exchanger (SHX). The LD enhances cooling capacity of indirect and direct evaporative coolers by dehumidifying the process air with decreasing the dew point temperature of the air simultaneously. In cooling season, the process air passes through LD for dehumidification, IEC and DEC for sensible cooling. In the IEC, RA or OA is used for the evaporative cooling in wet channels of IEC. SHX is used for reheating of the air to meet the SA setpoint. In heating season, LD is deactivated and the process air passes through the bypass duct and enters IEC. IEC acts like a SHX by exchanging heat with RA or heated RA if necessary.

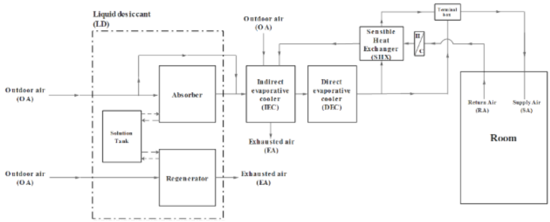

Fig. 5 Schematic diagram of the LD-IDECOAS

Operations of each components are decided by sensors located at the outlet of each component and the conditions of OA. It is described on psychrometric chart in Fig. 5. Operation modes are classified into 4 different modes. Boundary A represents upper limit humidity ratio which can be cooled by IEC and DEC to SA setpoint (e.g., 15 ˚C). Boundary B means the wet-bulb temperature of the SA, and Boundary C represents the SA dry-bulb temperature. Boundaries are determined depends on designed SA setpoint based on building thermal loads.

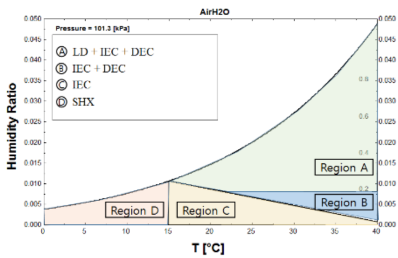

Fig. 6 Operation modes of the LD-IDECOAS

In the Mode A, the OA is too humid to cool the air using IEC and DEC. As a results, LD is activated for dehumidification and sensible cooling is conducted by IEC and DEC. If the OA is dry enough to cool with IEC and DEC, LD is deactivated and evaporative coolers cool the air (Mode B). In Mode C, only IEC runs for sensible cooling of the air. If the OA dry-bulb temperature is lower than the SA setpoint, the process air passes through the bypass duct and IEC performs as a heat exchanger between the process air and RA. In this case, if the OA dry-bulb temperature is too low to heat the air with double heat exchange between OA and RA, heating coil runs to heat RA to increase heating capacity of the RA.

4. Variable Air Volume System

In this study, the conventional variable air volume (VAV) system was set as a contrast system to compare the energy consumption with the DEVap cooling system and the LD-IDECOAS. The energy consumption of the VAV system with air-side economizer (Fig. 7) was estimated [2,6]. An electric heating coil was considered as reheating coil at terminal box of the system.

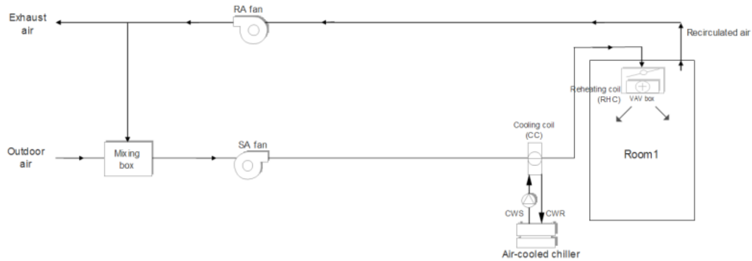

Fig. 7 Schematic diagram of the VAV system

5. Simulation

The simulations were conducted to compare the annual energy consumption of three different types of HVAC systems with TRNSYS 17 [7] and a commercial equation solver (i.e., EES). Annual thermal loads of the modeled office space were extracted using TRNSYS 17. Based on the hourly thermal loads and weather data, annual energy consumption of each system was estimated with models of each component integrated with the EES program. Simulation conditions are described in Table 1.

Table 1. Simulation condition outlines

Location	Seoul, Republic of Korea	
Climate	TMY2 weather data	
Building type and volume	Office building single zone (10 × 10 × 3 m^3 (width × depth × height))	
U-values	0.630 $W/m^2 \cdot K$ (Roof), 0.468 $W/m^2 \cdot K$ (Wall), 0.952 $W/m^2 \cdot K$ (Floor)	
Internal heat gain	Electronics	140 W / people (PC with monitor)
Occupants	Loads	75 W (sensible), 75 W (latent) / person
	Density	5 people / 100 m^2

6. Simulation Models

Simulation models of the DEVap cooling system and the LD-IDECOAS were set based on open literature [8,9]. In the LD-IDECOAS, energy is required to operate fans and pumps and to restore the solution concentration. For the internally cooled liquid desiccant, the linear regression model was used in (1). A simplified ε-NTU (effectiveness-number of transfer units) model [10–12] was used to predict the heat and mass transfer performances of the DP-IEC in (2). The DOE-2 air-cooled electric chiller model [13] is used to estimate chiller energy consumption represented in (3). CAPFT represents the available capacity of a chiller. EIRFT means the full-load efficiency of a chiller. EIRFPLR demonstrates the part-load efficiency of a chiller.

$$w_{LD,out} = 0.00768991 - 0.00012487 \cdot X_{in} + 0.00008797 \cdot T_{air,inlet} + 0.39009 \cdot w_{air,inlet} - 0.013782 \cdot R_{LG} \quad (1)$$

$$\varepsilon_{IEC} = \frac{1-\exp[-\mathrm{NTU}(1-C^*)]}{1-C^*\exp[-\mathrm{NTU}(1-C^*)]} \quad (2)$$

$$\mathrm{P} = P_{ref} \cdot CAPFT \cdot EIRFT \cdot EIRFPLR \quad (3)$$

Regeneration heat is a main energy consumption component for liquid desiccant assisted systems. To estimate the regeneration heat for both systems, some assumptions were set. With following assumptions, the regeneration heat can be estimated in (4)

- Regeneration rate is equal to dehumidification rate.
- Solution inlet temperature of regenerator remains constant (55˚C)
- Regeneration effectiveness is equal to the heat exchange effectiveness between solution and air in regenerator [14].

$$\mathrm{Q_{regen}} = \mathrm{m_{sol.in}} \cdot \mathrm{h_{sol.in}} - \mathrm{m_{sol.out}} \mathrm{h_{sol.out}} \quad (4)$$

In case of a packed-type liquid desiccant which is used in the LD-IDECOAS, an absorber performance is estimated with (5) [15]. The desired dehumidification rate of process air passed through the LD is known to meet the SA setpoint with evaporative coolers. The amount of solution sprayed into the absorber can be calculated with (5).

$$\mathrm{E_{abs}} = \frac{1-\frac{0.024\cdot \mathrm{GL}^{0.6}\cdot \exp\left(1.057\cdot \frac{DBT_{G.in}}{T_{L.in}}\right)}{aZ^{-0.185}\cdot pi^{0.638}}}{1-\frac{0.192\cdot \exp\left(0.615\cdot \frac{DBT_{G.in}}{T_{L.in}}\right)}{pi^{-21.498}}} \quad (5)$$

To estimate a fan energy consumption of both systems, a general VAV fan model was used considering the part-load ratio of fans in (6).

$$P_{fan,present} = (\ 0.0013 + 0.1470 \cdot PLR_{fan} + 0.9506 \cdot PLR_{fan}^2 - 0.0998 \cdot PLR_{fan}^3) \cdot P_{fan,design} \quad (6)$$

7. Simulation Results

Fig. 8 represents the comparison of the primary energy consumption of three HVAC systems in cooling season. In terms of fan energy consumption, the DEVap cooling system spends 46% more energy in comparison of the VAV system. It is mainly resulted from increased pressure drop of system components and additional fans in the LD and the DP-IEC. Moreover, the LD-IDECOAS consumes 19% more fan energy compared with the VAV system because of additional fans and pressure drop caused from additional components.

As expected, the DEVap cooling system saves 97% of electric chiller energy because this system condition the process air based on the non-vapor compression technologies (e.g. Liquid desiccant dehumidifier, Dew-point evaporative cooler). However, this system requires cooling coil for the additional cooling when the humidity ratio of the MA is extremely high. It results that only 3% of electric energy for chiller is required in comparison of the chiller energy consumption of the VAV system. The LD-IDECOAS saves 100% of chiller energy compared with the VAV system because this system cool the process air mainly with non-vapor compression units.

Even though the electric heating coils are required at the terminal boxes of the DEVap cooling and the VAV systems to reheat the process air to meet the SA setpoint, the DEVap cooling system saves 96% of heating energy. However, in the LD-IDECOAS, because this system is designed to cool the air till the SA setpoint, the electric heating coil is not required (saves 100% of heating energy).

Both system require natural gas consumption for the regeneration of desiccant solution which is not required in the VAV system. The DEVap cooling system consumes 81% less natural gas because of the difference between the required liquid to gas ratio of the internally cooled type and the packed bed type liquid desiccant unit.

As a result, compared with the VAV system, the DEVap cooling system saves 84% of primary energy and the LD-IDECOAS saves 71% of primary energy.

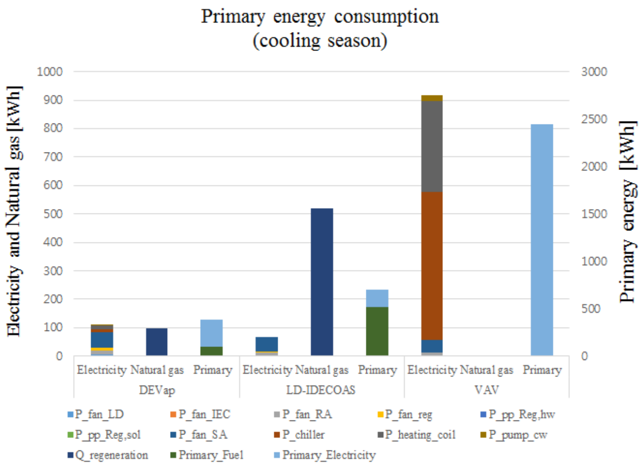

Fig. 8 Primary energy consumption of three systems in cooling season

8. Conclusion

In this study, the energy consumption of three different types of HVAC systems was estimated by simulation in the case of cooling system operation. From the simulation for the DEVap cooling system and the LD-IDECOAS, both systems showed significant energy saving in chiller energy (i.e., 97% and 100% respectively). Additionally, the LD-IDECOAS saved electric heating energy remarkably (i.e., 100%). However, increased fan energy and additional natural gas consumption was observed in both non-vapor compression based systems. One can notice that electric energy of chiller and heating coil were remarkably reduced even though fan energy of both system were increased because of complicated system composition and increased pressure drop. It is that the DEVap cooling system and the LD-IDECOAS showed the possibility of realizing a non-vapor compression HVAC system without penalty in terms of operation energy. Moreover, even if the LD-IDECOAS uses 100% of outdoor air without recirculated air, it saved primary energy compared with the VAV system. It is recognized that the LD-IDECOAS has a possibility to enhance indoor air quality without energy penalty.

Acknowledgment

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