UNDERFLOOR AIR DISTRIBUTION INTEGRATED WITH AN INDIRECT AND DIRECT EVAPORATIVE COOLING ASSISTED 100% OUTDOOR AIR SYSTEM

YJ Seok, HJ Cho, SK Han and JW Jeong
Department of Architectural Engineering, Sejong University, Seoul, 143-747, Korea
jjwarc@sejong.ac.kr

ABSTRACT

The purpose of this paper is to evaluate the energy conservation potential of an underfloor air distribution (UFAD) system integrated with an indirect and direct evaporative cooling assisted 100% outdoor air system (IDECOAS) in hot and humid climate. It is assumed that an office space is served by five different HVAC systems. Energy simulation for each system was performed using a commercial equation solver program, and the operating energy consumption in each system is compared. The results show that the UFAD system integrated with IDEC OAS reduces the cooling coil load by 47~63%, heating coil load by 89~94% and the total annual operating energy consumption by 47% with respect to the conventional overhead and the UFAD systems.

INTRODUCTION

According to the open literature, the underfloor air distribution (UFAD) system improves not only indoor air quality and energy performance, but also architectural flexibility and maintenance costs with respect to the conventional overhead (OH) system (Bauman,2003). Design guide or standards for the UFAD system have also be established and updated continuously for the last decade (ASHRAE, 2003).

However, insufficient humidity control problems are still indicated for the UFAD applications used in hot and humid climate zones. This problem may be caused by relatively high supply air (SA) temperature required in the UFAD system (Dickens, 2007).

If the SA were not dehumidified sufficiently, the control of the indoor humidity level would be difficult in hot and humid areas. This problem could be solved by cooling and reheating the SA for getting a required SA condition (i.e. relatively high SA dry bulb temperature with low humidity ratio), although it may increase energy consumption.

In addition, remarkable attention is required to prevent the cross contamination among spaces in the current UFAD system re-circulating a large amount of room air to save air conditioning energy consumption (Woods,2004).

Recently, an indirect and direct evaporative cooling assisted 100% outdoor air system (IDECOAS) attracts much attention because it can provide the wide spectrum of SA temperatures and humidity control without cross contamination problems (Gasparella, 2003).

In this research, the energy saving potential of an UFAD system integrated with IDECOAS is estimated quantitatively by energy simulation. It also provides the insight for overcoming existing limitations of the conventional UFAD system in terms of indoor air quality.

SYSTEM OVERVIEW

UFAD System

The UFAD system delivers the SA to the occupied zone through the underfloor plenum and floor diffusers. A conventional air handling unit (AHU) used in general OH system can also be applied to the UFAD system. The OH system serves the room through ducts in the ceiling plenum and the SA is mixed with the room air.after discharged through the ceiling diffusers.

However, in the UFAD system, the SA is delivered to the conditioned space via the underfloor plenum, and discharged by swirl diffusers installed on the floor. The room air temperature is stratified vertically, so the sensible heat and air contaminants are concentrated near the ceiling (i.e. unoccupied zone). Consequently, when the room air is exhausted through the ceiling plenum, the excessive heat and air contaminants in the unoccupied zone are extracted together with the exhaust air (EA).

On the other hand, in case of the UFAD system applied to the perimeter zone, fan terminal units (FTU) are commonly used for accommodating solar and skin loads. In this case, one cannot expect vertical stratification of the room air observed in the interior zone.

IDECOAS

The IDECOAS (Kim,et al. 2010) is a variable air volume system adjusting the SA flow based on the air conditioning load of the space, but uses 100% OA without re-circulating the room return air (RA) (Figure 1). This system is composed of an indirect evaporative cooler (IEC), a cooling coil (C/C) and a direct evaporative cooler (DEC) at the SA side, and a heating coil (H/C) and a sensible heat exchanger

(SHE) at the EA side. When the IDECOAS is applied to an OH system, a double duct or multi-zone system is commonly used.

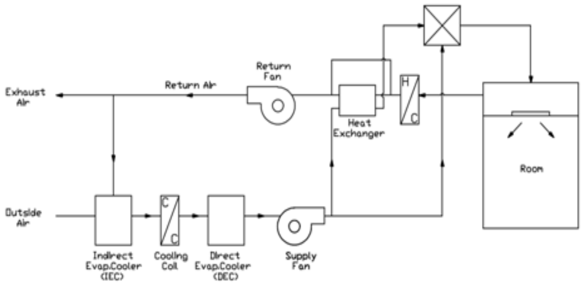


Figure 1. IDECOAS

This system can provide the economical air conditioning even in the hot and humid area by sharing cooling and heating coil loads with IEC, DEC, and SHE.

UFAD system integrated with IDECOAS

The main problem of the UFAD application in the hot and humid area is the insufficient control of the space latent load due to relatively high SA temperature. The cross contamination among conditioned spaces caused by the large re-circulation air is also a problem.

As a solution to these indicated problems, a UFAD system integrated with the IDECOAS is proposed. The inherent characteristic of the IDECOAS; that is, the wide spectrum of SA temperatures and humidity control without cross contamination would be desirable to the UFAD system.

ENERGY SIMULATION

In order to investigate the energy conservation potential of the proposed system, energy simulations for the five different air conditioning systems (Table 1) serving an identical space have been performed in this research and compared each other.

Table 1. Systems for the comparison

NAME	DISCRIPTION
SYSTEM 1	UFAD integrated with IDECOAS
SYSTEM 2	OH system integrated with IDECOAS
SYSTEM 3	conventional UFAD
SYSTEM 4	UFAD system with RA bypass
SYSTEM 5	Conventional OH system

Model space

The selected model space is the typical floor of an office building located at Seoul, Korea. This space consists of two interior zones and a perimeter zone (Figure 2).

The perimeter zone is set to the space within 5m-zone from the exterior wall (Kim et al. 2007). The solar and envelope loads are considered as the perimeter zone loads.

As for the interior zone, occupants, equipment and illumination loads are considered as interior zone loads in two OH systems (i.e. SYSTEMs 2 and 5). However, in three UFAD systems including the proposed system (SYSTEMs 1, 3, and 4), 40% of the illumination load is considered as the occupied zone load, while remaining 60% of the illumination load is set to the unoccupied zone load (Yu et al. 2007). The minimum OA intake rates in each system for ventilation follows ASHRAE Standard 62.1-2007. Design conditions for each system are summarized in Table 2.

Figure 2. Model space

Operating scenario - SYSTEM 1

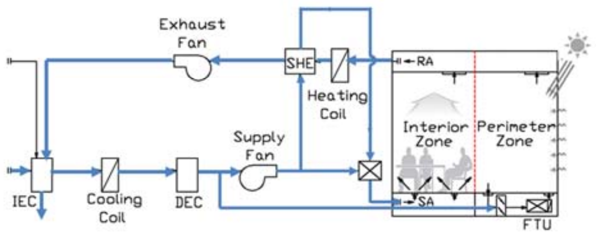
Cooling season: The hot and humid OA is cooled and dehumidified to reach the setpoint (e.g. 13℃ saturated) by the C/C after pre-cooling the entering OA at the IEC. The IEC is operated at maximum efficiency to reduce the C/C load as much as possible. If the humidity ratio (HR) at the C/C inlet is higher than 9.37g/kg (i.e. 13℃ saturated condition), the C/C leaving air temperature is maintained at 13℃. When the HR at the C/C inlet is less than 9.37g/kg and the enthalpy is over 36.7kJ/kg, the enthalpy of the C/C leaving air should be 36.7kJ/kg. If the C/C leaving air temperature is higher than 13℃ and the enthalpy is less than 36.7kJ/kg, the C/C load is reduced by operating the DEC, otherwise, the DEC does not operate. The conditioned SA is delivered to the perimeter zone without reheating, while some of the air is supplied to the interior zone through the neutral deck at the temperature of 18℃ by reheating at the SHE. (Figure 3a)

Intermediate season: When the OA enthalpy is less than 36.7kJ/kg and the temperature is over than 13℃, the SA setpoint temperature 13℃ is met by operating the DEC. The waste heat recovery through the SHE reduces C/C and reheating coil loads

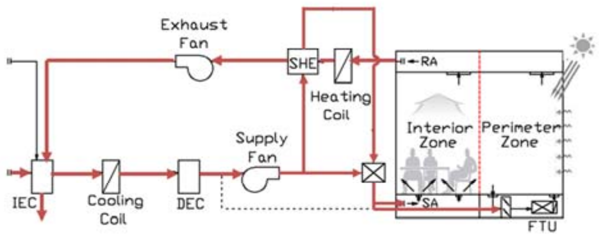
Table 2. Design Condition of each system

		SYSTEM 1	SYSTEM 2	SYSTEM 3	SYSTEM 4	SYSTEM 5
Area $[m^2]$	Perimeter zone	412.5				
	Interior zone	379.7				
Ceiling Height [m]		2.0	2.7	2.0	2.0	2.7
Indoor design condition (Dry bulb temp./Relative Humidity) [℃/%]	Cooling season	26/ 50				
	Intermediate season	24/50				
	Heating season	22/50				
Coefficient of overall heat transmission $[W/m^2K]$	Exterior wall	0.47				
	Interior wall	0.35				
	Window	3.84				
	Roof	0.29				
Indoor heat generation (in occupied zone) [W]	Illumination	3037.6	7594	3037.6	3037.6	7594
	Human	9872.2				
	Equipment	11391				
	TOTAL	24300.8	28857.2	24300.8	24300.8	28857.2
SA temperature [℃]		18	16	18	18	16
Minimum outdoor air flow [L/s]		638.5	638.5	638.5	638.5	638.5

Heating season: The OA is pre-heated by the IEC and heated to the setpoint temperature (i.e. 22℃) by the sensible heat recoverd at the SHE. The HC should operate if the SA temperature after the SHE is less than 22℃. The envelope load of perimeter zone is accommodated by the FTU after heating up to appropriate temperature (e.g. 35℃) (Figure 3b).



(a) cooling season



(b) heating season

Figure 3 Operating mode of SYSTEM 1

Operating scenario - SYSTEM 2

Cooling and Intermediate seasons: The way of operating this system is similar to SYSTEM 1, but its SA temperature is set to 16℃.

Heating season: The system operates in the same way of SYSTEM 1.

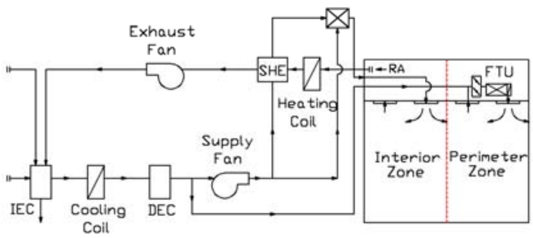


Figure 4 Operating mode of SYSTEM 2

Operating scenario - SYSTEM 3

Cooling season: The RA is mixed with the OA and cooled by the C/C at 13℃ saturated condition. The SA leaving the C/C is supplied to the perimeter zone via the FTU, and accomodates the solar radiation and the envelope load. The SA to the interior zone is delivered through the underfloor plenum after reheating by the H/C up to the appropriate SA temperature (i.e. 18℃).

The room air is stratified vertically and the sensible heat inside the room is concentrated near the ceiling (i.e. unoccupied zone). In general, the air temperature exhausted from the space is 2℃ higher than that of the conventional OH system.

On the other hand, when the OA enthalpy is lower than that of EA and the OA DBT is higher than 18℃, the economizer control is activated. If OA temperature is less than 18℃, the SA temperature setpoint is maintained by modulating OA and RA dampers.

Intermediate season: The system operates at the economizer mode.

Heating season: The minimum OA flow is supplied to the interior zone after heating up to the appropriate temperature (e.g. 22℃) at the H/C. The air to the perimeter zone is additinally conditioned by the FTU. The FTU discharges 35℃ air to accomodate the heating load in the perimeter zone.

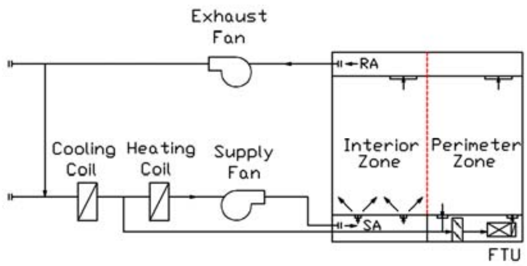


Figure 5 Operating mode of SYSTEM 3

Operating scenario - SYSTEM 4

Cooling season: A portion of the RA is bypassed the C/C for reheating SA after the C/C. It may reduce the reheat coil load. The basic operating strategy is similar to SYSTEM 3. However, the SA leaving the C/C should be cooled more (i.e. 10℃ saturated condition) than that of SYSTEM 3 (i.e. 13℃ saturated condition) in order to satisfy the setpoint condition after mixing with the bypassed RA.

Intermediate and heating seasons: The system operation modes are identical to SYSTEM 3.

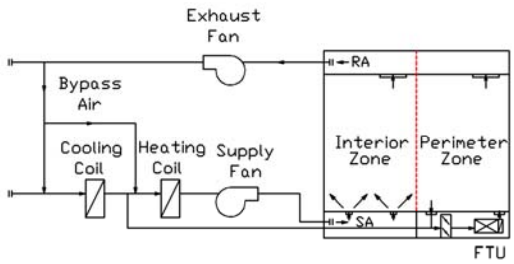


Figure 6 Operation mode of SYSTEM 4

Operating scenario - SYSTEM 5

Cooling season: The SA is cooled and dehumidified to meet 13℃ saturated condition at the C/C. The air leaving the C/C is supplied to the perimeter zone via FTU without reheating, while it is delivered to the interior zone at the temperature of 16℃ through the reheating process. The economizer mode is activated when the enthalpy of OA is lower than that of the EA.

Intermediate season: The system operates in the economizer mode.

Heating season: The minimum OA is delivered to the interior zone after heating to the setpoint temperature (i.e. 22℃). The air is provided to the perimeter zone after heating (e.g. 35℃) in FTU to accomodate the perimeter zone heating load.

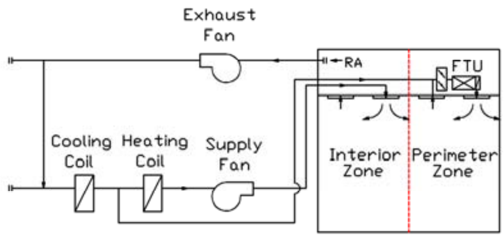


Figure 7 Operation mode of SYSTEM 5

The energy simulation was performed by modeling each system using a commercial equation solver program (f-Chart Software, 2010). The BIN method was applied to estimate the annual energy consumption in each system. The BIN weather data were generated at the 1℃ interval of OA DBT based on the standard weather data of Seoul, Korea (Korean Solar Energy Society, 2009). It is assumed that each system operates from 9:00am to 8:00pm for six days a week except for Sunday.

Furthermore, it is also assumed that the static pressure of the SA fan in UFAD systems is 25% less than that in OH systems due to reduced ductwork in UFAD applications (Bauman,2003).

SIMULATION RESULTS

Comparison of annual operating energy consumption

In Figure 8, one may see that SYSTEM 1 (i.e. the proposed system) shows 49% of annual operating energy saving compared to SYSTEM 5 (i.e. the conventional OH system) and 47% saving against the SYSTEM 3 (i.e. the conventional UFAD system).

In Figure 9, one may also see that SYSTEMs 1 and 2 which are based on IDECOAS provide the lowest central cooling and heating coil energy consumption compared with conventional OH and UFAD systems.

Fan energy and FTU energy consumptions are not much different in each system

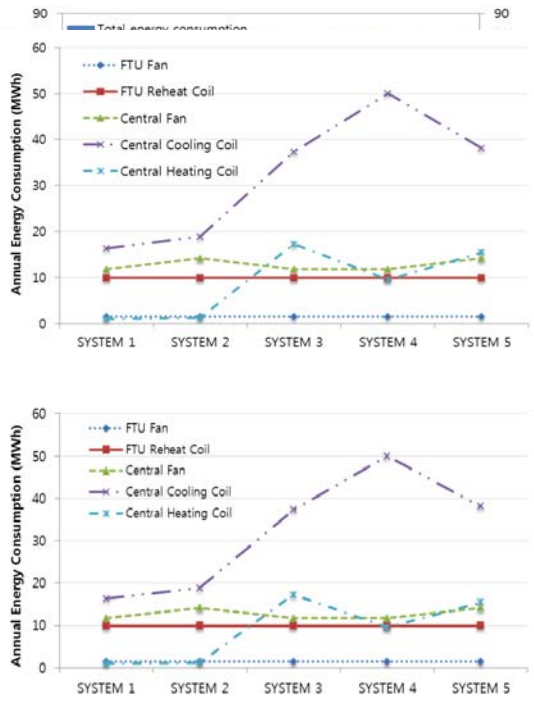


Figure 9 Annual energy consumption of each system component

As shown in Figure 10, the proposed system (i.e. SYSTEM 1) saves C/C and H/C energy significantly compared with conventional OH system (i.e. SYSTEM 5), while the fan energy consumption is almost identical. The main reason to the coil energy savings in the proposed system is the pre-conditioning of entering OA in the IEC. During the cooling season, the more enhnacement in evaporative cooling effect of the IEC and in C/C load reduction can be expected, the lower wet-bulb temperature (WBT) of the EA can be acquired.

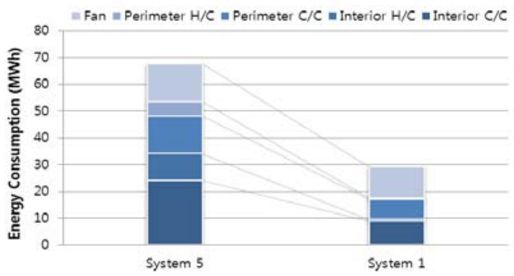


Figure 10 Component energy consumption in SYSTEMs 1 and 5

During the heating season, the IEC in SYSTEM 1 reclaims the sensible heat from the EA, and pre-heat the SA. It reduces a large amount of H/C energy consumption in the proposed system.

In the fan energy consumption, SYSTEM 1 shows 17% reduction compared with SYSTEM 5, because the SA flow of the proposed system is lower than that of the conventional OH system. In addition, the UFAD system commonly experiences 25% lower static pressure drop due to reduced terminal and branch ductworks with respect to the conventional OH system.

On the other hand, the annual energy consumption of each SYSTEM 2 component is compared with that of SYSTEM 5. In Figure 11, one may see that SYSTE 2 (i.e. the OH system integrated with IDECOAS) shows significant coil energy savings against SYSTEM 5. The reason to this coil energy saving observed in SYSTEM 2 is also mainly caused by the IEC

As for the fan energy consumption, one may see that there is no advantage in SYSTEM 2 over the conventional OH system, because the SA volume and the fan stactic pressure are almost identical in both systems.

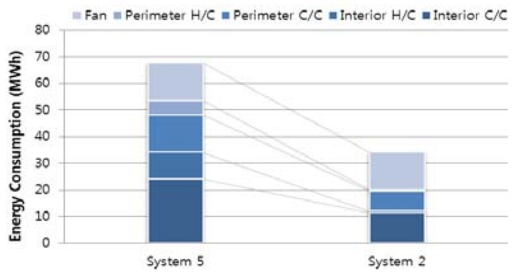


Figure 11 Components energy consumption in SYSTEMs 2 and 5

Figure 12 shows that SYSTEM 3 (i.e. the conventional UFAD system) provides 3.3% less C/C energy, but 3% more H/C energy (i.e. reheat energy) is required for maintaining higher SA temperature compared with SYSTEM 5.

However, in the fan energy consumption, SYSTEM 3 shows 17% less fan energy with respect to the conventional OH system, It is caused by lower SA flow and static pressure drop in the UFAD system.

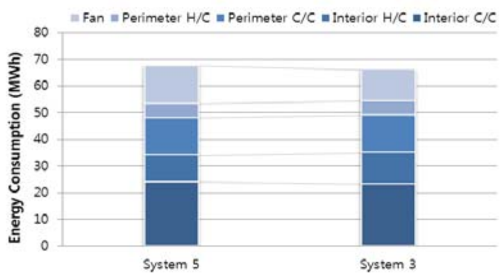


Figure 12 Components energy consumption in SYSTEMs 3 and 5

In Figure 13, SYSTEM 4 (i.e. the UFAD system with RA bypss) shows increased C/C energy consumption compared with the conventional OH system (i.e. SYSTEM 5), while the H/C energy (i.e. reheat energy) decreases. Cooling and dehumidifying the SA more than the conventional UFAD system, in order to satisfy the SA setpoint even after mixing with the coil-bypass RA increases the C/C energy consumption more than expected.

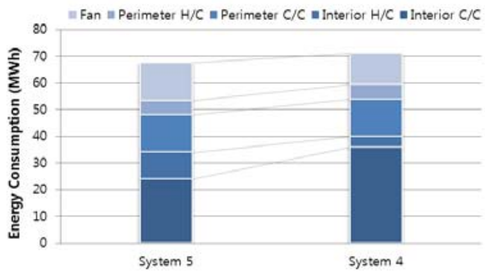


Figure 13 Components energy consumption in SYSTEMs 4 and 5

Comparison of monthly cooling coil and heating coil loads

Monthly C/C and H/C loads aquired in the energy simulation for each system are compared in Figures 14 and 15. One can see that the SYSTEMs 1 and 2 using IDECOAS show significantly low C/C and H/C loads compared with other systems through the whole year.

First of all, in Figure 14, both systems integrated with IDECOAS clearly show that the indirect evaporative cooling can be applied and provde C/C energy reduction even in the hot and humid climate zone. One should also reconize that SYSTEMs 1 and 2 which serve conditioned spaces using only 100% OA experience lower C/C and H/C loads than other RA re-circulation based systems. It means that IDECOAS integrated systems can provide significant advantage over conventional systems in both energy consumption and indoor air quality.

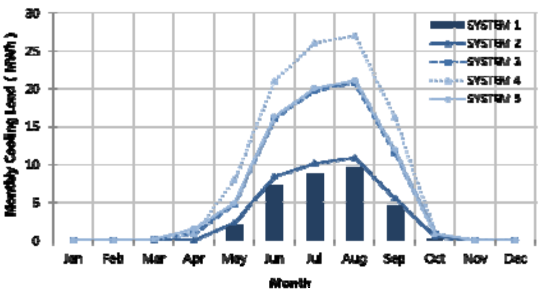


Figure 14 Monthly cooling coil load

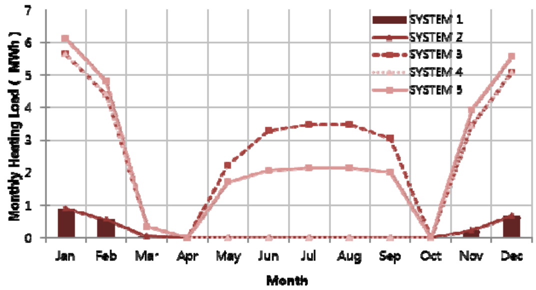


Figure 15 Monthly heating coil load

Comparison of maximum coil load

Figures 16 and 17 show the maximum C/C and H/C loads for each month, respectively. SYSTEM 1 shows the maximum C/C load of 35kW in June (Figure 16). It is the required C/C size in SYSTEM 1, and the smallest capacity required among systems considered in this research.

In Figure 17, SYSTEMs 1 and 2 show considerably lower maximum H/C load (i.e. 4kW) than other systems. It means that the H/C size can also be reduced significnatly in IDECOAS integrated systems.

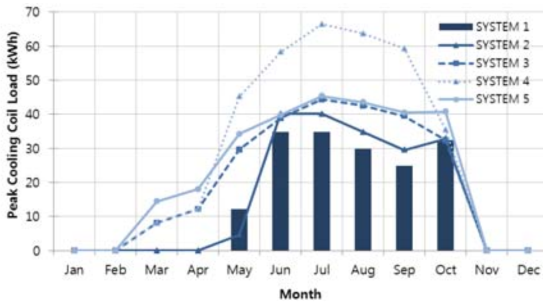


Figure 16 Maximum cooling coil load

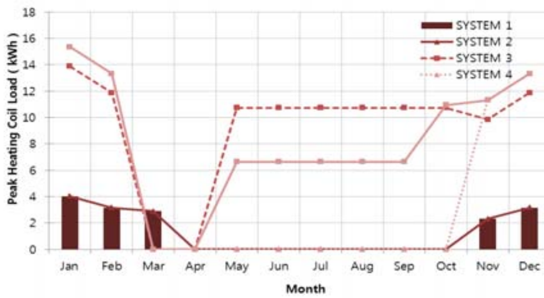


Figure 17 Maximum heating coil load

CONCLUSION

In this research, energy saving potentials of the UFAD system integrated with IDECOAS were investigated by comparing its energy performance with four different OH and UFAD systems. It was found that the proposed system is able to provide significant C/C and H/C energy reduction by pre-conditioning SA using the IEC. It was also found that the evporative cooling assisted 100% OA system can be applied even in the hot and humid climate zone if the IEC uses the room return air as the scavenger air during the cooling season. Finally, the simulation results shown in this research indicate that the proposed system can be the solution to inherent problems of the conventional UFAD system in both energy and indoor air quality aspects.

ACKNOWLEDGEMENT

This research was supported by the Ministry of Knowledge Economy in Korea under the Convergence-ITRC program (NIPA-2011-C6150-1101-0003) supervised by the National IT Industry Promotion Agency). This work was also supported by Mid-career Researcher Program through NRF grant (No.2010-0000298) funded by the Ministry of Education, Science and Technology in Korea.

REFERENCES

ASHRAE. 2003. Underfloor Air Distribution Design Guide.

Bauman F. S. 2003. Designing and Specifying Underfloor Systems: Shedding Light on Common Myths, Heating/Piping/Air Conditioning HPAC Engineering, December, pp.26-39.

Dickens K. et al. 2007. UFAD, Engineered Systems, January, Vol. 24 Issue 1, pp.74 - 84.

F-Chart Software. 2010. EES-Engineering Equation Solver

Gasparella A. et al. 2003. Indirect evaporative cooling and economy cycle in summer air conditioning, International Journal of Energy Research 27, pp. 69 - 76.

Kim H. J. et al. 2007. A Patterns of Thermal Load on the Calculation Method of Perimeter Boundary in Office Buildins (1) – Focused on the Effects of perimeter areas, Architectural Institute of Korea Autumn Conference Journal, pp. 1029 – 1032

Kim H. W. et al. 2010. Energy Saving Potentials of an 100% Outdoor Air System Integrated with Indirect & Direct evaporative coolers, Architectural Institute of Korea Journal, v. 26 n.4, pp. 313-320

Korean Solar Energy Society. 2009. Standard Weather Data

Yu K. Y. et al. 2007. A Study on Design Techniques and Effectiveness in Energy Saving of Occupied Zone in UFAD System, Journal of the Korean solar Energy Society, Vol. 27, no. 3, pp. 127 - 133.

Woods J. E. 2004. What Real-world Experience Says about the UFAD Alternative, ASHRAE Journal, February, pp. 3 - 14.