Evaluation of thermal comfort in an office building served by a liquid desiccant-assisted evaporative cooling air conditioning system

Hye-Jin Cho[1], Jang-Hoon Shin[1], Joon-Young Park[1], Won-Jun Kim[1], and Jae-Weon Jeong[*1]

1 Department of Architecture Engineering, College of Engineering, Hanyang University, 222 Wangsimni-Ro, Seungdong-Gu, Seoul, 04763, Republic of Korea
**Corresponding author: jjwarc@hanyang.ac.kr*

ABSTRACT

Recent studies examined a liquid desiccant indirect and direct evaporative cooling assisted 100% outdoor air system (LD-IDECOAS) as an energy conserving alternative to conventional air conditioning systems. An IDECOAS was introduced as an environmental-friendly air conditioning system that uses latent heat of water evaporation to cool the process air. Recently, studies suggested the integration of a liquid desiccant(LD) system with an IDECOAS to overcome a cooling reduction in evaporative cooling performance in a hot and humid climate. The supply air (SA) temperature and humidity ratio of the proposed system depends on SA flow rate and removal moisture content. However, a supplying air flow method in a conventional variable air volume(VAV) system and a relatively unstable air conditioning performance of an indirect evaporative cooler (IEC) and direct evaporative cooler(DEC) in cooling seasons could cause SA temperature to fluctuate above and below the set point temperature, and this could result in occupants feeling uncomfortable in a conditioned zone. Therefore, the purpose of the present study involves estimating thermal comfort in an office building that is served by a liquid desiccant indirect and direct evaporative cooling assisted 100% outdoor air system (LD-IDECOAS). Predicted Mean Vote (PMV) method is selected to evaluate as to whether an indoor thermal environment complies with recommended comfort zone conditions as proposed by the ASHRAE Standard 55. The seasonal mode of operation of LD-IDECOAS is suggested and used to estimate thermal properties of supply air (SA) while serving the proposed system. Energy performance and thermal environment of a building model are predicted via a series of energy simulations by using a TRNSYS 17 program integrated with an engineering equation solver program. The simulation results indicate that LD-IDECOAS did not completely cool the conditioned zone occasionally in a cooling season. However, the results also suggested that the thermal environment in a conditioned zone is generally in compliance with the ASHRAE Standard 55. Accordingly, it is concluded that using the LD-IDECOAS in an office building can produce energy savings with an acceptable level of thermal comfort.

KEYWORDS

Liquid desiccant and evaporative cooling-assisted 100% outdoor air system(LD-IDECOAS); thermal comfort; PMV; energy simulation

1 INTRODUCTION

The emergence of environmental issues, such as global climate change, has led to numerous studies that focus on a liquid desiccant system and evaporative cooling-assisted air conditioning system as an alternative to a vapor compression refrigerant system [1-3]. A recent study by Kim et al [4-7] suggested the use of a liquid desiccant and indirect and direct evaporative cooling-assisted 100% outdoor air system (LD-IDECOAS) as an environmental-friendly and energy saving air conditioning system. IDECOAS is an evaporative cooling-assisted air conditioning system that uses the latent heat of water evaporation to cool incoming air. However, the cooling performance of IDECOAS significantly decreases in a hot and humid climate due to an increase in the latent load of outdoor air [8]. Therefore, integration of a liquid desiccant system with an evaporative cooling system, such as liquid desiccant and dew point evaporative cooling assisted 100% outdoor air system (LDEOS), desiccant-enhanced evaporative (DEVap) cooling system and liquid desiccant and evaporative cooling-assisted 100% outdoor air system (LD-IDECOAS), is suggested to overcome a reduction in evaporative cooling performance in a hot and humid climate. A liquid desiccant system is a cooling system that handles a latent load of outdoor air (OA) by absorbing water vapor of OA through a liquid desiccant dehumidifier that plays a significant role in improving the evaporative cooling performance of an evaporative cooling-assisted air conditioning system in a hot and humid region. Furthermore, the system significantly impacts energy consumption. Recent studies [6,7] indicated that LD-IDECOAS provides annual operating energy savings of 68% and 23% when compared with those of a conventional VAV system and IDECOAS, respectively, thereby proving that it possesses significant energy saving potential when compared with a VAV and IDECOAS. However, simulation operations and operation results have resulted in various considerations. The temperature and humidity ratio of supply air (SA) depend on SA flow rate and dehumidification mass rate of incoming air when LD-IDECOAS is operated. A sharp increase in the latent load in a conditioned zone results in the failure of the indoor humidity control and a decrease in the cooling performance of the proposed system. Thus, if the operation performance of both liquid desiccant system and evaporative cooling system is less than the expected performance, there is a limit to stably controlling the indoor air condition, and this could cause occupants to feel uncomfortable in a conditioned zone.

Accordingly, the aim of the present study involves using energy simulations to evaluate the influence of fluctuations in supply air temperature on the thermal environment of occupants that is served by LD-IDECOAS. In this study, a thermal comfort evaluation is conducted based on the ASHRAE Standard 55. Additionally, energy performance and indoor thermal environment of the building model are predicted via a series of energy simulations by using a TRNSYS 17 program that is integrated with an engineering equation solver program.

2 SYSTEM OVERVIEW

2.1 LD-IDECOAS

LD-IDECOAS consists of a LD system, an indirect evaporative cooler (IEC), and a direct evaporative cooler (DEC) (Figure 1). A LD system dehumidifies the outdoor air to control the latent heat of the OA prior to the entry of the OA into the evaporative cooling system. After the exit of process air from the LD system, the IEC and DEC provide sensible and adiabatic cooling of the entering air to satisfy the required temperature of the SA. The heating coil (HC) and sensible heat exchanger (SHE) that are located at the EA side are operated to maintain a set point temperature of the neutral deck by using the remaining heat in the EA. The SA flow rate is modulated based on the air conditioning load in a conditioned zone in a manner similar to the conventional VAV system.

In the summer, process air is initially dehumidified by the LD unit. The dehumidified air is sensibly cooled by the IEC, and subsequently the set point of SA is achieved by entering the DEC. In intermediate seasons when outdoor air is relatively dry and cool, the LD unit is not operated and the target SA point is satisfied with the IEC and DEC. Conversely, in the winter, the LD unit and DEC are turned off, and only IEC is used as the SHE to reduce the heating load of OA by regenerating the remaining heat from EA. The HC is operated if auxiliary heating is required to satisfy the target SA point.

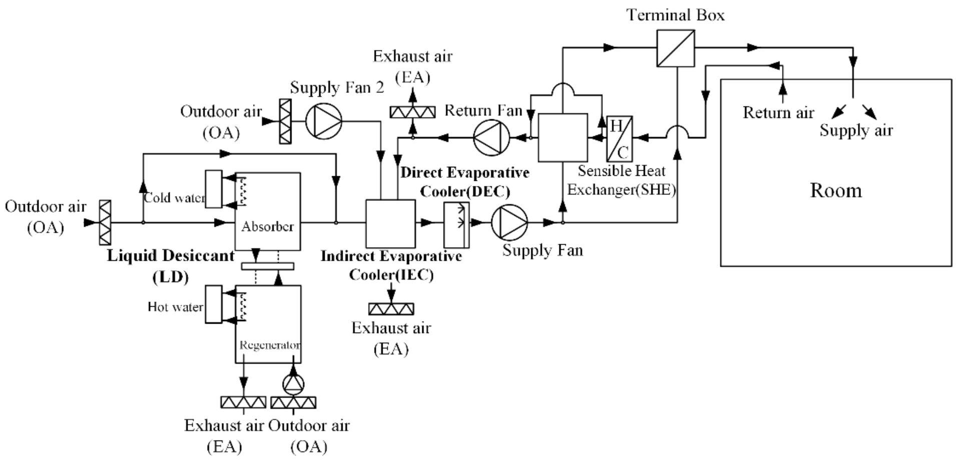


Figure 1: A schematic diagram of the LD-IDECOAS

2.2 The LD-IDECOAS operation mode

Previous study indicates that the operation mode of the LD-IDECOAS is determined by OA conditions [6]. The operation mode is classified into three modes based on OA conditions, namely, Regions A, B, C, and D (Figure 2).

Operation mode for Region A

Region A presents outdoor air conditions above line “a” and “b” that indicate the humidity ratio (HR) of SA and enthalpy or wet-bulb temperature of SA at the set point (i.e. 15℃, saturated condition), respectively (Figure 2). In Region A, hot and humid outdoor air is initially dehumidified through the LD unit until the conditions of OA satisfy the condition of line “a” by using a by-pass damper to control the air flow rate. The dehumidified air is sensibly cooled by the IEC until the wet-bulb temperature of the exiting air reaches the wet-bulb temperature on line “b,” and subsequently the isentropic cooling of the process air in the DEC satisfies the target cold deck SA temperature.

Operation mode for Region B and C

In Regions B and C, the LD system is deactivated due to dry OA. The induced OA bypasses the LD and is sensibly cooled by the IEC to reach the target SA temperature (i.e. 15℃). Additionally, the DEC is operated to satisfy the set point SA temperature.

Operation mode for Region D

Region D presents outdoor air conditions when the dry-bulb temperature of OA is lower than the set point value. In Region D, dry and cold OA bypasses the LD unit and DEC, while IEC preheats incoming air as a sensible heat exchanger to regenerate waste heat from exhaust air such that the dry-bulb temperature of OA satisfies the SA set point. An auxiliary HC located at the exhaust air is required to recover the required heat if the heat reclaimed from IEC is not sufficient to enable a cold deck to reach the SA target temperature (i.e., 15℃).

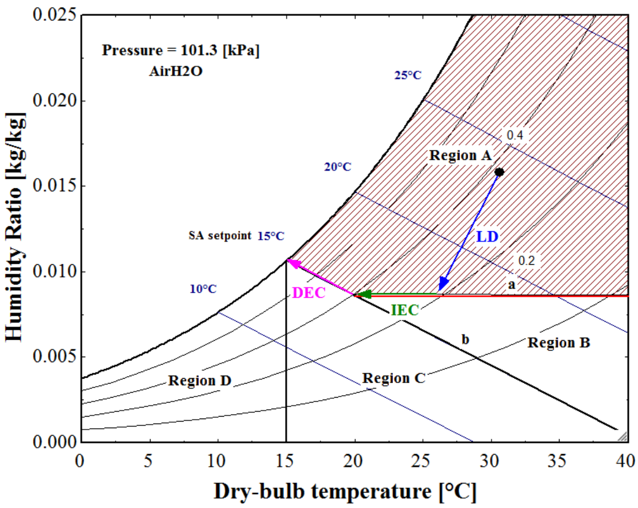


Figure 2: Psychrometric chart in Region A

3 SIMULATION OVERVIEW

In this study, the simulation procedure to predict the PMV is presented to evaluate the influence of fluctuations in the supply air temperature on thermal comfort in an office building served by LD-IDECOAS. Thermal loads and PMV values are estimated by using TRNSYS 17 [10], and an engineering equation solver (EES) [11] is applied to calculate annual thermal loads and supply air conditions based on the operation mode of LD-IDECOAS. The simulation is conducted using IWEC weather data from Seoul, South Korea.

3.1 Simulation model overview

A building located in Seoul, Republic of Korea that consists of a single-story office building with a floor area corresponding to 100 m^2 and 5 persons. All individuals possess their own computer and are engaged in light work. Based on ISO-7730 [12], each occupant generates 75 W sensible heat and 75 W latent heat. Each computer adds 230 W sensible heat to the space, and the heat generation density of the light corresponds to 13 W/m^2. Table 1 provides a summary of detailed physical information with respect to the building model.

Table 1: Simulation information related to the building model used in the study

Location	Seoul, Republic of Korea	
Building	$10 \times 10 \times 3\, m^3$	
Schedule	7:00 AM – 10:00 PM (weekdays)	
Heat gain	Occupants	5 persons/100 m^2
	Lights	13 W/m^2
U-value	Exterior wall	0.468 W/m^2K
	Roof	0.360 W/m^2K

3.2 Calculations for the thermal load and target supply air flow rate

LD-IDECOAS varies the supply air (SA) flow rates in response to changes in the thermal load in a conditioned zone. An increase in the indoor air temperature modulates the damper to satisfy the maximum SA flow rate to remove the cooling load. Conversely, the damper is controlled to deliver the proper amount of SA flow rate in response to the reduced cooling load. Accordingly, it is necessary to estimate the design SA flow rate to ensure a proper SA flow rate.

Thermal load in the building model

In this study, the peak cooling load of the model space is estimated by using a TRNSYS 17 program. The obtained peak sensible and latent cooling loads of the model space correspond to 16.14 kW and 2.40 kW, respectively.

Target supply air flow rate

All systems are simulated based on the seasonal operation schedule. The cooling set point of the model building corresponds to 24 ℃ 55% during the summer (i.e., June, July, and August), and the heating set point corresponds to 20 ℃ during the winter (i.e., November, December, January, February, and March). The design SA flow rate is calculated by using Eq. (1) if the peak sensible cooling load and the design indoor and supply air temperature are known, and the design supply air humidity ratio is obtained by using Eq. (2). The design supply air humidity ratio and air flow rate calculated by the two equations correspond to 9.70 g/kg and 1.428 m^3/s, respectively. The expressions are as follows:

$$Q_{sen} = \dot{m}_{sa} \cdot c_p \cdot (DBT_{ra} - DBT_{sa}) \quad (1)$$

$$Q_{lat} = h_{fg} \cdot \dot{m}_{sa} \cdot (w_{ra} - w_{sa}) \quad (2)$$

3.3 Simulation overview of LD-IDECOAS

It is necessary to satisfy the SA condition set point by using the LD unit, IEC and the DEC to provide a thermally comfortable environment. The inlet and outlet air conditions of each component of LD-IDECOAS are calculated by using Eq. (3) - (6). With respect to the LD unit, the incoming air temperature leaving the LD unit is determined by using Eq. (3) if the following three parameters: DBT of OA ($DBT_{LD,out}$); solution inlet temperature ($T_{sol,inlet}$), and effectiveness of LD unit ($\varepsilon_{LD,T}$) are known. After calculating the temperature of the incoming air leaving the LD unit, the outlet air temperature of IEC ($DBT_{IEC,pri,out}$) is determined by using Eq. (4) with respect to the effectiveness of IEC (ε_{IEC}). Subsequently, the temperature of the air leaving the DEC ($DBT_{DEC,out}$) is determined by Eq. (5) with respect to the known effectiveness of DEC (ε_{DEC}). Additionally, the humidity of air leaving the LD unit ($w_{LD,out}$) is determined by using Eq. (6) assuming that the value of the dehumidification effectiveness of the LD unit is the same as the value of the $\varepsilon_{LD,T}$ as shown in previous studies by Katejanekaren and Kumar (2008) and Katejankaren et al (2009) [13,14]. The dehumidification effectiveness of the LD unit is obtained by using an existing model proposed by Chung and Luo (1999) [15]. Additionally, the effectiveness of IEC and DEC are assumed as 80% and 90%, respectively, based on manufactured cut-sheets. The expressions are as follows:

$$\varepsilon_{LD,T} = \frac{(DBT_{OA} - DBT_{LD,out})}{DBT_{OA} - T_{sol,inlet}} \quad (3)$$

$$\varepsilon_{IEC} = \frac{(DBT_{LD,out} - DBT_{IEC,pri,out})}{DBT_{LD,out} - WBT_{IEC,sec,inlet}} \quad (4)$$

$$\varepsilon_{DEC} = \frac{(DBT_{IEC,pri,out} - DBT_{DEC,out})}{DBT_{IEC,pri,out} - WBT_{IEC,pri,out}} \quad (5)$$

$$\varepsilon_{LD,w} = \frac{(W_{OA} - W_{LD,out})}{W_{OA} - W_{e}} \quad (6)$$

The operation modes of the three components are determined based on the outdoor air conditions. After calculating the SA temperature and humidity ratio through Eq. (3) - (6), the indoor air properties are obtained by substituting the SA properties into the building model that is implemented by TRNSYS 17.

3.4 The simulation approach to calculate PMV

This study uses the predicted mean vote (PMV) method, which is the most extensively and widely accepted index to evaluate thermal comfort [16]. The value of the PMV index is within a seven-point thermal sensation scale as shown in Table 2 to ensure thermal comfort. The ASHRAE Standard 55-2004 recommends maintaining the PMV index at level 0 with a tolerance of ± 0.5.
The index is based on the energy balance of the human body with its environment and guarantees thermal comfort by predicting the average thermal sensation response of large groups of individuals who are exposed to different thermal conditions over long periods [17].

Indoor thermal environment condition

Thermal environment evaluation in an office building served by LD-IDECOAS is performed to examine the influence of variations in the SA temperature on building occupants in terms of thermal comfort. The thermal comfort evaluation is conducted during summer (i.e., June, July, and August) and winter (i.e., November, December, January, February, and March). The PMV index is influenced by the following six variables: metabolic rate (M), clothing insulation (I_{cl}), air temperature (T_a), mean radiant temperature (T_{mr}), air velocity (V_a), and air relative humidity (Rh) [17]. With respect to the PMV prediction model, the PMV index is set as an output parameter, and the air temperature, mean radiant temperature, and air velocity are set as input parameters. The remaining variables (i.e., metabolic rate, clothing insulation, air velocity) are considered as constant values and are summarized in Table 3. The metabolic rate and clothing insulation in an office building are determined based on ISO-7730. Additionally, the maximum velocity of static airflow is set at 0.1 m/s given that low values of wind velocity are measured inside due to the prevalence of closed windows in an office building.

Table 2: Input values of the metabolic rate, clothing insulation, and air velocity

Parameter	Contents
Metabolic rate [met]	Seated, light work, typing: 1.2 (70 W/m^2)
Clothing Insulation [clo]	Underwear, pants, short shirts, socks, shows: 0.5 (summer)
	Underwear, pants, shirts, jacket, socks, shows: 1.0 (winter)
air velocity [m/s]	Static air flow rate: maximum 0.1 m/s

Finally, the hourly PMV values are calculated by inputting the indoor air temperature, relative humidity, and mean radiant temperature values.

Calculation of PMV index

The PMV index is calculated based on Eq. (7) as follows:

$$PMV = (0.303e^{(-0.036M)} + 0.028) \cdot L \tag{7}$$

where L denotes the thermal load in the human body and is defined as the difference between the internal heat from the human body and the heat loss from the environment. The thermal load L is calculated from Eq. (8) as follows:

$$\begin{aligned} \mathrm{L} = {} & (\mathrm{M} - \mathrm{W}) - 0.0014 \cdot \mathrm{M} \cdot \left(34 - T_{a,in}\right) \\ & -3.05 \cdot 10^{-3} \cdot \left[5733 - 6.99 \cdot (M - W) - p_{a,in}\right] \\ & -0.42 \cdot (M - W - 58.15) \\ & -1.72 \cdot 10^{-5} \cdot M \cdot \left(5867 - p_{a,in}\right) \\ & -39.6 \cdot 10^{-9} \cdot F_{cl} \cdot [(T_{cl} + 273)^4 - (T_{mr} + 273)^4] \\ & \boldsymbol{-F_{cl} \cdot h_c \cdot \left(T_{cl} - T_{a,in}\right)} \end{aligned} \tag{8}$$

The other factors required in Eq. (4) are obtained from Eq. (9) – (12) as follows:

$$\begin{aligned} T_{cl} = {} & 35.7 - 0.0275 \cdot (M - W) \\ & -I_{cl} \cdot [(3.96 \cdot 10^{-8} \cdot F_{cl} \cdot [(T_{cl} + 273)^4 \\ & -(T_{mr} + 273)^4] + F_{cl} \cdot h_c \cdot \left(T_{cl} - T_{a,in}\right)] \end{aligned} \tag{9}$$

$$h_c = \begin{cases} 2.38 \cdot (T_{cl} - T_{a,in})^{0.25}, & \mathrm{A} > 12.1 \cdot \sqrt{v_{a,in}} \\ 12.1 \cdot \sqrt{v_{a,in}}, & \mathrm{A} \le 12.1 \cdot \sqrt{v_{a,in}} \end{cases} \tag{10}$$

$$A = 2.38 \cdot (\mathrm{T}_{cl} - T_{a,in})^{0.25} \tag{11}$$

$$\mathrm{F}_{cl} = \begin{cases} 1.0 + 0.2 \cdot I_{cl}, & I_{cl} \le 0.5\mathrm{clo} \\ 1.05 + 0.1 \cdot I_{cl}, & I_{cl} > 0.5\ \mathrm{clo} \end{cases} \tag{12}$$

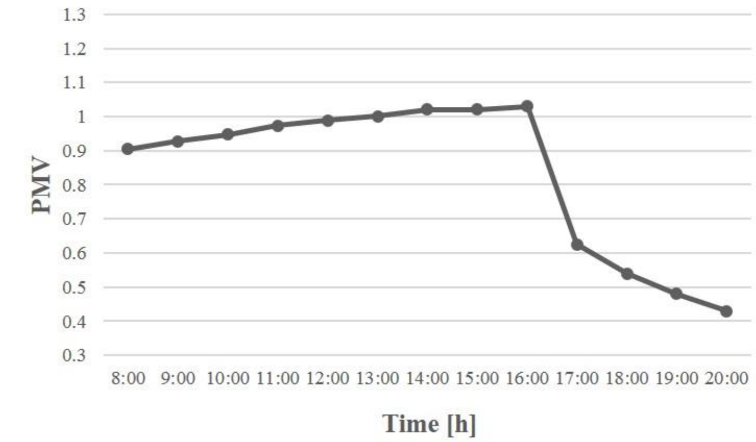
4 SIMULATION RESULTS

4.1 PMV value in the summer season

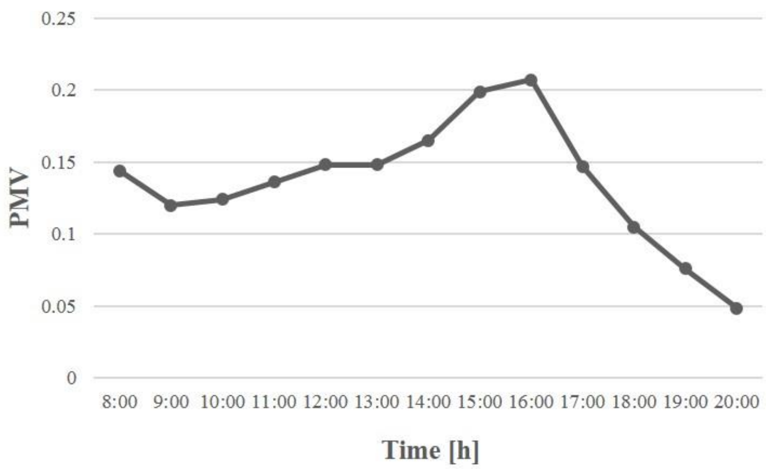
Fig. 3-a shows the PMV values for the building model served by LD-IDECOAS during summer (i.e. June, July, and August) when the cooling set point corresponds to 24℃, 55%. The results indicate that the PMV values fluctuate based on the supply air conditions. A few values exceed +1.0 indicating that individuals experience a hot feeling with respect to human thermal sensations. This is mainly because the LD-IDECOAS is not completely performed in extremely humid climates. Nevertheless, the PMV values mainly vary from -0.5 to +1.0 which is an ideal statement for human thermal environment, thereby indicating that the indoor air control mostly progresses properly by handling the latent load with the LD unit with the exception of certain extremely humid periods.

4.2 PMV value in the winter season

Fig. 3-2 shows the PMV values for the building model served by LD-IDECOAS during winter (i.e., November, December, January, February, and March) when the heating set point corresponds to 20 ℃. The PMV values in winter mostly fluctuate from -0.6 to +0.6, thereby indicating that LD-IDECOAS offers a proper heating performance for building occupants although the measurement range slightly exceeds the recommended thermal environment range as suggested by the ASHRAE Standard.



(a) Cooling season – Jul 21st



(b) Heating season – Jan 21st

Figure 3: PMV value of LD-IDECOAS: (a) cooling season – Jul 21 and (b) heating season - Jan 21st

5 CONCLUSION

In this study, a PMV predicting model was developed to use energy simulations to evaluate the influence of the supply air temperature on the thermal environment of occupants that is served by LD-IDECOAS. First, the PMV index that constitutes the most representative index to evaluate thermal comfort was used. An office building model served by a LD-IDECAOS was developed through TRNSYS 17 corresponding to the physical information of the building. Based on the operation mode of LD-IDECOAS as suggested by extant studies, PMV values during summer (i.e. June, July, and August) and winter (i.e. November, December, January, February, and March) were calculated.

During summer, the PMV values mostly vary from -0.5 to +1.0, and this indicates that the LD-IDECOAS properly cooled the conditioned zone by generally handling the latent load of incoming air with the LD unit. Similarly, the PMV values in winter are maintained within a tolerance of ± 0.6, and thus imply that LD-IDECOAS offers proper heating performance to building occupants although the measurement range slightly exceeds the recommended thermal environment range as suggested by the ASHRAE Standard. Accordingly, it is concluded that the use of the LD-IDECOAS in an office building produces energy saving with an acceptable thermal comfort level.

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