Energy Saving Potential of an Air-Conditioning System with Desiccant and Solar Assisted Ventilation

Gaurav Singh and Ranjan Das

Abstract In this paper, a simulation analysis has been performed using Energy Plus software on the conventional vapor compression-based building cooling system for warm-humid climate. In order to achieve an energy efficient approach, decoupling of latent and sensible heat loads is done using a separate desiccant-assisted dedicated outdoor air system (*DOAS*). A solar collector system is installed to provide the required amount of heating energy for regenerating the desiccant. Further, an integrated evaporative cooling (*IEC*) arrangement in *DOAS* is used to improve the system performance. The performance of the system is evaluated using three distinct modes of operation. Results show that in comparison with the conventional compression operated system, desiccant-assisted *DOAS* in conjunction with *IEC* system saves 2.62% of electrical energy on an annual basis.

Keywords Building cooling · Solar collector · EnergyPlus · *DOAS*

1 Introduction

Increased demand for air-conditioning in industries, building sectors, and other process industries are one of the prime causes for climate change and global energy consumption. Among total primary energy consumption, almost 35–40% is consumed by vapor compression (*VC*) systems [1]. This is a major concern for the researchers to improve the technological aspects in this area. Advanced techniques are developed for making the building thermally comfortable using low energy methods. From energy consumption point of view, there are various technologies which reduce the primary energy consumption in the cooling system such as radiant cooling system, absorption, and adsorption cooling system. As per the current scenario, most of the building cooling systems are based on vapor compression-based systems (*VCS*).

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Various studies have been reported on the advancement of conventional *VCS*. Sung et al. [2] developed a novel kind of mesoscale *VCS*. In this, a different kind of vane type compressor is used that reported the coefficient of performance (*COP*) up to 2.15. Harby et al. [3] performed an analysis on a small scale domestic cooling system to improve the performance of *VCS*. Using an evaporative condenser, a significant amount of energy consumption was reduced by this method. Chauhan and Rajput [4] has done an experimental analysis on the combined evaporative and compression-based system for thermal comfort and reported up to 24% of energy saving potential for their proposed system.

Decoupling the cooling and ventilation tasks can be a possible solution to reduce the primary energy consumption [5]. In this way, total thermal load of the building is decoupled through separate arrangements of cooling and ventilation [6]. In the earlier studies a quantitative analysis of dedicated outdoor air system (*DOAS*)-assisted air-conditioning system with respect to energy consumption of each installed component is not discussed for the warm-humid climatic zone. Further, the modifications required to improve *DOAS* performance is also missing. Thus, in this study three modes of air-conditioning system are compared. The first case (Case 1) is the conventional case, in which only a conventional all air *VC* system is installed in the building. In the second mode, (Case 2), a separate desiccant-assisted *DOAS* is coupled with the conventional all air *VC* system. In *DOAS*, a desiccant-assisted wheel is mounted for the dehumidification of outdoor air. Using this, system latent heat load of the supply air is catered by *DOAS* and the remaining load is fulfilled by *VCS*. In Case 2, process air is supplied directly into the building space. In the third case (Case 3), an indirect evaporative cooling (*IEC*) system is installed in the path of *DOAS* process. Flat-plate solar collectors with auxiliary heater are also coupled to supply heating energy to desiccant wheel in both cases (Case 2 and Case 3). For the performance assessment of the system, all three discussed cases are compared with reference to yearly consumption of electric energy.

2 Building Description and Methodology

In this study, a building with roof area of 400 m^2 (20 m $\times$ 20 m) with window to wall ratio (*WWR*) 40% is simulated in the EnergyPlus software. EnergyPlus is a building energy modeling platform issued by the US department of energy [7]. Construction of the building (wall, roof, floor, and window) is as per the energy conservation building code (*ECBC*) [8] and National Renewable Energy Laboratory (*NREL*) [9].

Simulations are carried out throughout the year for warm-humid climatic zone. Building geometry is shown in Fig. 1. Working durations are taken from 9:00 to 18:00 h. The cooling system for this building is designed to maintain the same thermal comfort level (dry bulb temperature of 21–26 °C and specific humidity of 0.008 kg/kg of dry air to 0.010 kg/kg of dry air) throughout the year using three different techniques (Cases 1, 2, and 3). In the building model, occupancy density

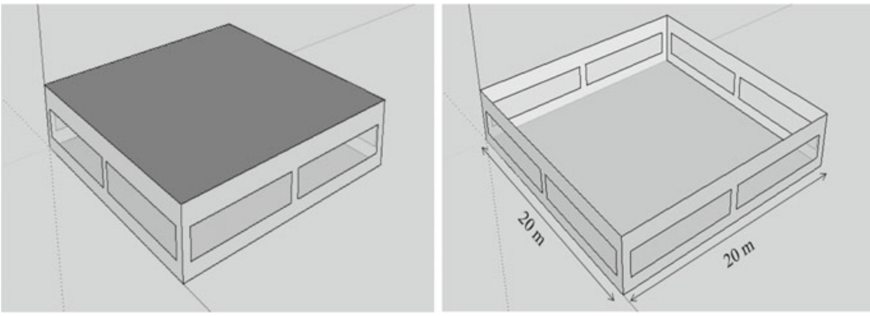

Fig. 1 3-D geometry of the building

is 10 m^2/person, light power density is 10 W/m^2, electric equipment power density is 80 W/person, and ventilation requirement is 20 *CFM*/person [8, 9]. Various losses associated with the *HVAC* system designing involve pressure losses in ducting, mechanical losses in the chiller, heat transfer losses from the building envelope, leakage losses, etc. These losses are pre-assumed in the simulation tool. Before proceeding to the results and analysis of the present system, validations of the building design and the installed *VCS* are carried out as described in the next subsection.

2.1 Validation Study

In this study, validations of the installed conventional *VCS* and the building design are done against the experimental results provided in EnergyPlus [7] and the standards prescribed by *ECBC* and *NREL* [8, 9], respectively. Various output parameters for the validation of the building in terms of heat transfer coefficient (U) value, sensible heat gain coefficient (*SHGC*), and visible light transmittance (*VLT*) are shown in Table 1.

For the system validation purpose, the current building model has been scaled up to make it comparable with the existing reference study [7] having a complete

Table 1 Validation of building parameters

Parameters	Value	*ECBC*/*NREL* Data [8, 9]	Error %
Walls (insulations, plaster, bricks)	$U = 0.422$ W/(m^2 K)	0.440	4.2
Roof (insulations, plaster, concrete)	$U = 0.430$ W/(m^2 K)	0.409	4.8
Window (single glass)	$U = 3.02$ W/(m^2 K), *SHGC* = 0.276, *VLT* = 0.749	$U = 3.30$ W/(m^2 K), *SHGC* = 0.25, *VLT* = 0.76	$U = 9.2$ *SHGC* = 9.4 *VLT* = 1.4

Table 2 *VCS* validation of present work

S. No.	Parameters	Present work (kWh)	Reference Building [7] (kWh)	Error %
1	Building latent heat load	4877	5227	6.9
2	Window heat load	8884	7853	13.1
3	Pump load	725	765	5.5
4	Coil sensible load	62,052	66,852	7.7
5	Net electricity utilized	32,607	34,848	6.8

floor area as 500 m^2. All other parameters are kept same in both the models. Table 2 shows a comparison between both studies along with the relative error of various parameters. It is observed from the present simulations that the building design and *VCS* parameters presented in Tables 1 and 2 are within the experimental and the specified benchmark data [7–9]. Error in window heat gain is somewhat higher than the reference building [7]. This is because reference building involves *WWR* of 38%, whereas the present building has *WWR* of 40% resulting in more values of this parameter.

2.2 Different Mode of Operations

In the first case (Case 1), a *VCS*-based air-conditioning system is designed. This case includes an electric chiller (having *COP* as 3.1), pump (to circulate chilled water in the cooling coil of the system), and fan (to transport the cold and dehumidified air into the building space). System is given a specified set point temperature to supply chilled water at 7 °C to the cooling coil [10]. The layout of Case 1 is shown in Fig. 2a. In Case 2, along with the conventional *VCS*, a desiccant-assisted *DOAS* is simulated for separate ventilation.

Desiccant is a material which adsorbs the moisture of air by the process of chemical dehumidification. As a result, there is an increase in air temperature with a decrease in the humidity level of the outdoor air. The temperature of the process outlet air after passing through desiccant material is nearly 43 °C with specific humidity 8×10^{-3} kg/kg of dry air. This dehumidified process air is supplied directly into the building space to meet the latent heat load. Simultaneously, the sensible heat load increased due to this effect is catered by *VCS*. Since desiccant gets saturated because of water vapor clogging; it is therefore regenerated using hot air at the temperature of nearly 50–70 °C [11]. For this purpose, a flat-plate solar collector based arrangement having 200 m^2 area is used for providing hot water to the regeneration coil. An auxiliary electrical water heating system is also installed for adverse operating conditions like unavailability of sun. Hot water from the collector is supplied to the regeneration hot water coil, from where hot air at a temperature of 60 °C [11] is supplied at the

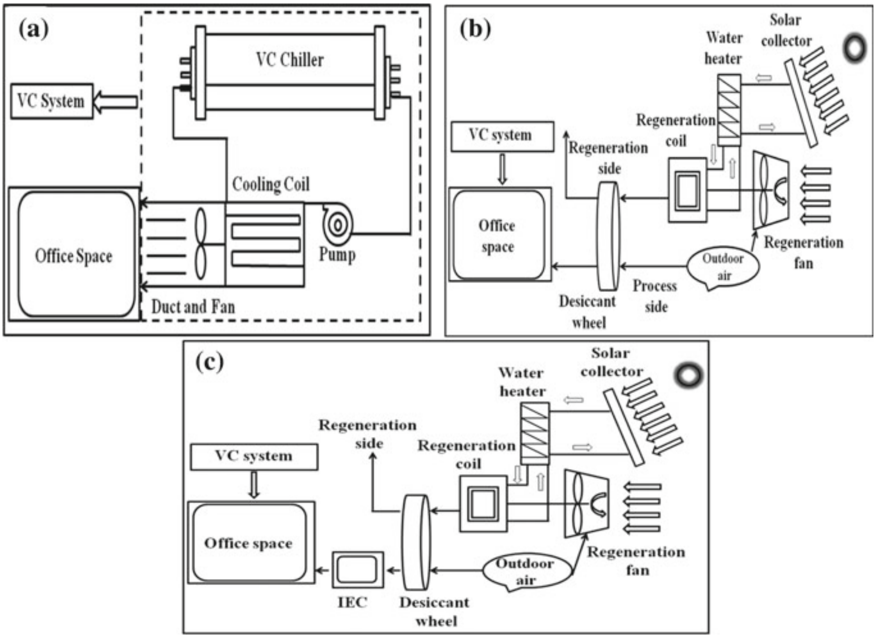

Fig. 2 Layout of the system in **a** case 1, **b** case 2, and **c** case 3

regeneration end of desiccant wheel. An outline of the system for Case 2 is depicted in Fig. 2b. Using various input data EnergyPlus solves various energy and heat balance equations to yield the outputs for the evaluation purpose. Some of the equations are discussed further. The nominal cooling capacity of the chiller is evaluated as follows [7],

$$Q_{nom} = c_{pw} \times \rho_w \times \Delta T_{des} \times \dot{V}_{des} \tag{1}$$

where c_{pw} and ρ_w denote the specific heat capacity and density of water, respectively, whereas, ΔT_{des} and $\dot{V}_{des}$, respectively, indicate temperature rise and volumetric flow of water per unit time. In an identical way, fan power consumption is calculated in the below mentioned manner [7],

$$Q_f = \frac{\left(f_{pl} \times \dot{m}_a \times \Delta P\right)}{\left(\eta_f \times \rho_a\right)} \tag{2}$$

where $\Delta P = 900\ \text{N/m}^2$, $\eta_f = 0.70$ [7] and $\rho_a = 1.2\ \text{kg/m}^3$, whereas, $\dot{m}_a$ represents mass flow of air per unit time. In Eq. (2), f_{pl} is part load coefficient indicating the ratio between required and obtained mass flow rates of air.

In Case 3, for the improvement in the ventilation cycle of *DOAS*, an *IEC* system in the path of the process side of *DOAS* is installed. The layout of Case 3 is shown in Fig. 2c. This evaporative cooling system is used to decrease the temperature of exit air from desiccant wheel at the process side. This reduces the temperature of the dehumidified air up to 28 °C that again reduces the additional sensible heat load generated by hot and dehumidified air on the air-conditioning system. This consequently enhances system performance.

3 Results and Discussion

The installed systems are simulated with the weather data of warm-humid climatic zone [12]. To assess energy saving potentials in cases 2 and 3, these are compared with the conventional *VCS*. Simulations are done throughout the year for maintaining the same preferred thermal comfort conditions. Simulation results are obtained in terms of total annual electric energy utilized by different components of the system. Figure 3 shows the hourly deviation of the maintained zone air temperature with respect to the surrounding atmosphere. Energy consumption pattern for all the cases is discussed next. Throughout the year, the attained zone air temperature varies in the range 21–26 °C.

Figure 4 shows the electric energy utilization pattern of different components installed in the system. Complete annual electricity consumption for the conventional case (Case 1) involving *VCS* is 32,607 kWh, for Case 2 this energy consumption is reduced to 32,337 kWh, which is not significant. However, improvement in the system is achieved by *IEC* system which leads the energy consumption up to 31,752 kWh (i.e., 2.62%) for Case 3. Thus, as compared to conventional *VCS*, electrical energy saving is very negligible by employing only desiccant system in the ventilation path, but, this can be by using *IEC* in *DOAS*.

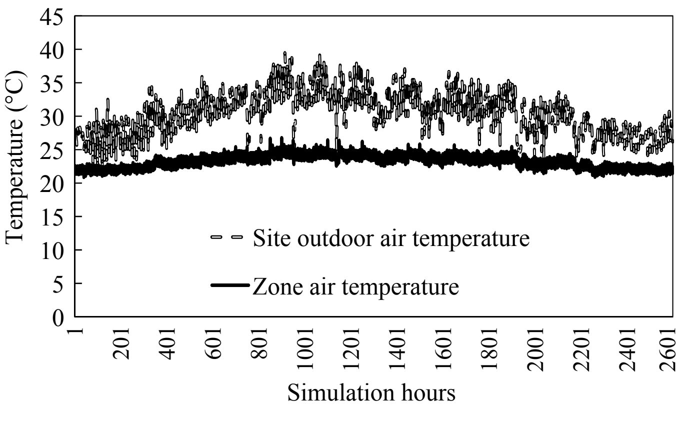

Fig. 3 Comparison of the zone and outdoor air temperatures

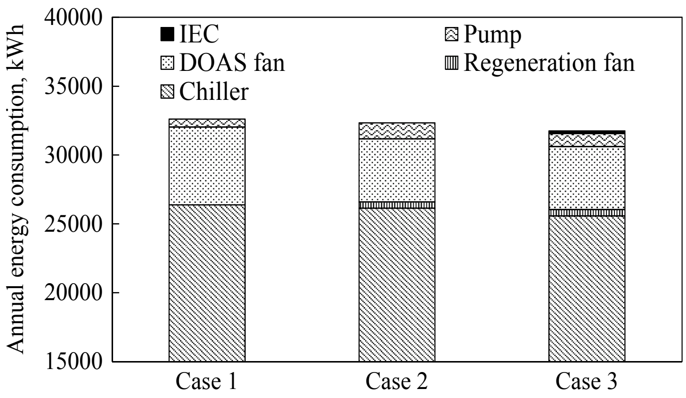

Fig. 4 Comparison of yearly consumption of electric energy

In Fig. 5, a comparison of the obtained coefficient of performance (*COP*) is studied which shows that there is an improvement in *COP* by modifying the conventional *VCS* (Case 1) with the *DOAS* (Case 2) and *DOAS-IEC* (Case 3) systems. However, in Case 3, *COP* is lesser than Case 2, because due to the integration of *IEC* the heat load removed by the system is reduced along with reduction in electricity requirement. This is advantageous in medium and large buildings and not so relevant in small ones, because, in small office buildings, the benefits provided in the form of reduced heat load is compensated against by the supplied energy to the evaporative cooler and pump arrangements.

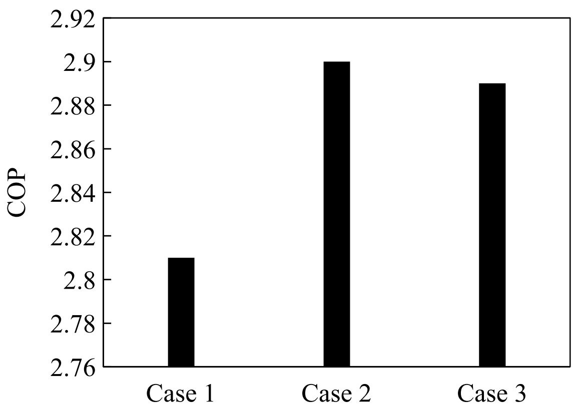

Fig. 5 Comparison of COP for different cases

4 Conclusion and Future Recommendations

This simulation study shows the impact of using desiccant-assisted *DOAS* in conjugation with conventional *VCS*. *DOAS* is responsible to handle the latent heat load of the supply air that reduces the latent load of *VCS*, but increases its sensible load. So, further improvements in *DOAS* is done by using an *IEC* that reduces the annual consumption of electric energy due to *VACS* by 2.62%. Despite somewhat low energy saving potential, the modified system involving desiccant *DOAS* and *IEC* integrated *VCS* will be beneficial for medium and large scale buildings. Further improvement of this system can be done by using sensible heat recovery wheel in conjunction with *DOAS* and *IEC*.

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References

1. Zhou, X., Yan, D., An, J., Hong, T., Shi, X., Jin, X.: Comparative study of air-conditioning energy use of four office buildings in China and USA. Energy Build. **169**, 344–352 (2018)
2. Sung, T., Lee, D., Kim, S.H., Kim, J.: Development of a novel meso-scale vapor compression refrigeration system (mVCRS). Appl. Therm. Eng. **66**, 453–463 (2014)
3. Harby, K., Gebaly, R.D., Koura, S.N., Hassan, M.: Performance improvement of vapor compression cooling systems using evaporative condenser: an overview. Renew. Sustain. Energy Rev. **58**, 347–360 (2016)
4. Chauhan, S.S., Rajput, S.P.S.: Experimental analysis of an evaporative–vapour compression based combined air conditioning system for required comfort conditions. Appl. Therm. Eng. **115**, 326–336 (2017)
5. Keun, M., Leibundgut, H., Choi, J.: Energy and exergy analyses of advanced decentralized ventilation system compared with centralized cooling and air ventilation systems in the hot and humid climate. Energy Build. **79**, 212–222 (2014)
6. Zhang, L.Z., Niu, J.L.: Indoor humidity behavior associated with decoupled cooling in hot and humid climates. Build. Environ. **38**, 99–107 (2003)
7. EnergyPlus 8.7, Open source software. https://energyplus.net/downloads. Accessed 01 Nov 2017
8. ECBC: User Guide, Energy Conservation Building Code. Bureau of Energy Efficiency, New Delhi, India (2013)
9. Deru, M., Field, K., Studer, D., Benne, K., Griffith, B., Torcellini, P., Liu, B., Halver-son, M., Winiarski, D., Rosenberg, M., Yazdanian, M., Huang, J.: US Department of Energy Commercial Reference Building Models of the National Building Stock. Technical report, National Renewable Energy Laboratory (2011)
10. User Manual: The Trane Air-Conditioning Economics (TRACE® 700). http://software.trane.com/CDS/TRACE%20700%20-%20Users%20Manual.pdf. Accessed 10 July 2018

11. Khan, Y., Singh, G., Mathur, J., Bhandari, M., Srivastava, P.: Performance assessment of radiant cooling system integrated with desiccant assisted DOAS with solar regeneration. Appl. Therm. Eng. **124**, 1075–1082 (2017)
12. Weather data by location. https://energyplus.net/weather-location/asia_wmo_region_2/IND//IND_Chennai-Madras.432790_ISHRAE. EnergyPlus weather file source. Accessed 01 Nov 2017