Performance study on a hybrid solid desiccant-vapor compression air conditioning system for hot-humid ambient conditions

R. Venkatesh[1], Madhu Ganesh[2], and R. Rudramoorthy[1]

[1]PSG College of Technology
[2]Karunya Institute of Technology and Sciences

July 16, 2024

Abstract

The paper focuses on the simulation and testing of a hybrid solid desiccant vapor compression air conditioning system under different hot-humid climates. The simulation is carried out by a BLUEJ programming framework. Air at the lowest achievable air temperatures from a solid desiccant cooling system is supplied to a standard vapor compression air conditioning system. The cooling capacities of the hybrid system under three modes indicating different supply air conditions to the cabin, are reported in the paper. From the performance study, it is inferred that the hybrid system provides significant energy savings compared to a standard air conditioner, especially in hot-humid ambient conditions. The solid desiccant cooling system thus establishes itself as an effective pre-cooler unit to a standard vapor compression air conditioning system.

Performance study on a hybrid solid desiccant-vapor compression air conditioning system for hot-humid ambient conditions

R. Venkatesh[1] Madhu Ganesh[2] R. Rudramoorthy[3]

1. Department of Mechanical Engineering, PSG College of Technology, Coimbatore, India venkiram88@gmail.com

2. Department of Aerospace Engineering, Karunya Institute of Technology and Sciences, Coimbatore, India. madhumini@gmail.com

3. Department of Production Engineering, PSG College of Technology, Coimbatore, India. drrrresearch@gmail.com

Abstract

The paper focuses on the simulation and testing of a hybrid solid desiccant vapor compression air conditioning system under different hot-humid climates. The simulation is carried out by a BLUEJ programming framework. Air at the lowest achievable air temperatures from a solid desiccant cooling system is supplied to a standard vapor compression air conditioning system. The cooling capacities of the hybrid system under three modes indicating different supply air conditions to the cabin, are reported in the paper. From the performance study, it is inferred that the hybrid system provides significant energy savings compared to a standard air conditioner, especially in hot-humid ambient conditions. The solid desiccant cooling system thus establishes itself as an effective pre-cooler unit to a standard vapor compression air conditioning system.

Introduction

The rapid increase in the emission of greenhouse gases (GHG) and ozone-depleting gases such as carbon dioxide, methane, nitrous oxide, and halogenated compounds, since the 19th century, because of increased human activity has been established beyond doubt by many research studies as reported by Fadnavis et al [1]. The rise in global temperature is predominantly caused by greenhouse gas emissions, aerosols, deforestation, etc. and the rate of rise also has increased in proportion to the acceleration of industrial activities. The study also reported that by the end of the 21st century, the average ambient temperature rise in India would touch anywhere between 4.7°C and 5.5°C and the frequency of occurrence of warm days and warm nights would increase by 55% and 70% respectively. The brisk changes in India's climate are creating more pressure on India's ecosystems, agricultural activities, and freshwater resources creating damage to biodiversity, food, water, energy security, and public health. These findings were corroborated by Biardeau et al [2] and predicted that the higher ambient temperatures, increased occurrence of extreme weather events, and soaring variations in climate would lead to a high level of risk of occurrence of heat strokes, cardiovascular and neurological diseases, and psychological disorders. Since more than 70% of the energy requirements of India are met by thermal power plants, the increase in demand for space cooling would in turn increase greenhouse gas emissions also.

Cooling has now become essential not only for comfort but also for survival and health in most parts of the world [3]. The adoption of air conditioners is aided by the increase in electrification in all the lower and middle-income countries over the last 20 years. This increase threatens the reliable operations of power grids and negates all efforts to combat climate change. Air conditioners liberate significant heat that increases the ambient temperature. The advancements and adaptation of sustainable air conditioning technologies could reduce carbon dioxide emissions by 50 billion tons [3].

Desiccant-assisted air conditioning offers an edge over other alternate technologies as it offers independent handling of sensible load and latent load, has fewer moving parts, uses natural fluids like water, uses non-corrosive working fluids, avoids crystallization in the equipment, and integrates easily with waste heat sources and solar collectors [4].

The solid desiccant air conditioning system uses materials like silica gel, zeolites, activated carbons, titanium oxide, and metal-organic frameworks for the removal of moisture from the humid air. The air becomes dry and hot after undergoing dehumidification by solid desiccant materials. The hot-dry air is further cooled by sensible and evaporative cooling heat exchangers to achieve the desired cooling temperature inside the cooling space. The solid desiccant cooling system is further classified as

- Ground-coupled solid desiccant cooling system
- Hybrid solid desiccant vapor compression air conditioning system (HSDVC)
- Standalone solid desiccant air conditioning system (SDAS)

Literature survey

Energy-efficient vapor compression air conditioners would be an inevitable choice to provide basic cooling in developed countries and standards have become stringent over the years. Further, the urgent deployment of sustainable cooling technologies in both residential and commercial spaces is much needed for protecting the planet [3]. A combination (HSDVC) of a solid desiccant-based system (SDAS) and a standard vapor compression air system (VCAS) has been investigated widely to address this. Such a system was evaluated by H Liu et al [5] and was found to provide significant energy savings by addressing 52% of the latent load and 76% of the total cooling load.

An HSDVC evaluated by A.E. Kabeel [6] et al offered benefits such as no corrosion, no crystallization, fewer moving parts, and reduced CO_2 emissions. The potential savings of carbon dioxide emissions by the hybrid solid desiccant- VCAS was 34%.

Jani et al [7] reported that an HSDVC eliminates the energy costs associated with dew-point cooling and reheating of supply air. Artificial neural networks and TRNSYS were found to be effective simulation tools for HSDVC systems. The regeneration temperature of the desiccant wheel was found to be up to 100°C for high latent loads. Humidity reduction of up to 66% could be achieved by this hybrid system with a potential energy savings of 10% to 63%. Similar results were reported by Jia et al [9] Hussain et al [10], Luo et al [15], and William M. Worek et al [16]. Ukai et al [11] reported that the HSDVC gave a maximum COP of 1.35 when the chilled water was supplied at 14°C from the chiller unit.

Lee et al [12] simulated a hybrid system coupled with direct and indirect evaporative coolers using MATLAB-Simulink. This system gave desired comfort cooling at the regeneration temperatures of 70°C and 90°C for residential air conditioning.

Sohani et al [13] simulated a building-integrated photovoltaic system along with an SDAS on TRNSYS for the city of Tehran. The results showed that the system gave savings in cooling load of 60% with a payback period of 2.87 years. Singh et al [14] simulated an HSDVC using ENERGY PLUS software for hot-humid ambient conditions. Their results showed that the system gave an annual electric savings of 5% and the system would be the best fit for large-scale buildings.

Jyun-DeLiang et al [17] investigated a ground source-based HSDVC. Their results showed that the system when used as a pre-cooler gave potential energy savings from 33% to 73%. The system developed the highest COP of 4.10 with a savings of 31.7% in energy when it is operated in the summer.

Most of the research works have addressed the savings of energy and maximum possible COPs that could be obtained from HSDVC systems. The working of those systems is primarily to supply air at a comfortable temperature of 25°C and 50% RH.

Only a few investigations reported the potential reductions in the cooling capacity of the vapor compression air conditioning system. Moreover, such reductions reported were not for a supply air temperature and relative humidity substantially closer to the comfort condition. For an air conditioner to be operated in an energy-efficient mode, the sensible heat ratio should not be less than 0.75. For hot-humid ambient conditions, a VCAS would operate below a sensible heat ratio of 0.75 resulting in high power consumption.

The objective of the research work is to find the possible reductions in the cooling capacity of a VCAS when it is made to operate with a solid desiccant cooling system in a hybrid cooling mode. This is primarily done for hot-humid ambient conditions. This research work necessitates the framework to have a sub-system to take a substantial portion of the latent load of the VCAS with a solid desiccant in hybrid mode. This is also crucial for an energy-efficient operation of a VCAS in hot-humid climates.

Solid desiccant – Vapor Compression Hybrid Air Conditioning System

The working of a VCAS is presented in the psychrometric chart given in Figure 1. The hot-humid air is given as point 1. The air is cooled sensibly till point 2 and dehumidified till point 3. Then the air is heated to point 4 to the comfort condition of 22°C and 50% relative humidity. The processes undergone by the air in standard air conditioning equipment are cooling, dehumidification, and heating. All the processes undergone by the air are highly energy-intensive.

Cooling capacity$_{\text{VCAS}} = = \dot{m_a} \times (h_{\text{amb}-1} - h_{\text{supply}-3})$(1)

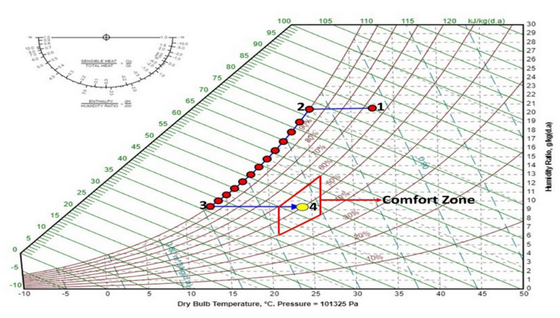

Figure 1 The cooling process of a VCAS

The working of the solid desiccant air-conditioning system is given in Figure 2. The hot-humid air specified as point 1 is sent to the desiccant wheel for dehumidification. The air after undergoing dehumidification would come out as hot-dry air given as point 2. Then the air is sensibly cooled till point 3 by a heat exchanger. Then the air is evaporatively cooled till point 4 by an evaporative cooler. Point 4 is substantially away from the comfort zone in this example. The air has to be further cooled to the comfort zone to achieve comfortable conditions for the occupants inside the cooling space. This is the condition where the further cooling of the air to comfort condition by a standard vapor compression air conditioning system is highly appreciated.

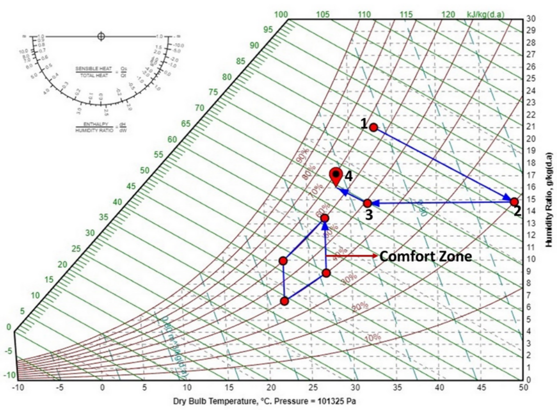

Figure 2 Working of the standalone solid desiccant cooling system

The schematic of a hybrid solid desiccant cooling system coupled with the vapor compression air conditioning system is shown in Figure 3. The air from the ambient is sent through the desiccant wheel. It is specified as point 1. The air after undergoing dehumidification by the desiccant wheel is delivered as hot and dry air. This is represented as point 2. The hot dry air is sent through the Non-Woven Fabric Type Indirect heat exchanger. The air is sensibly cooled by the indirect heat exchanger and delivered as substantially cooled air represented by point 3.

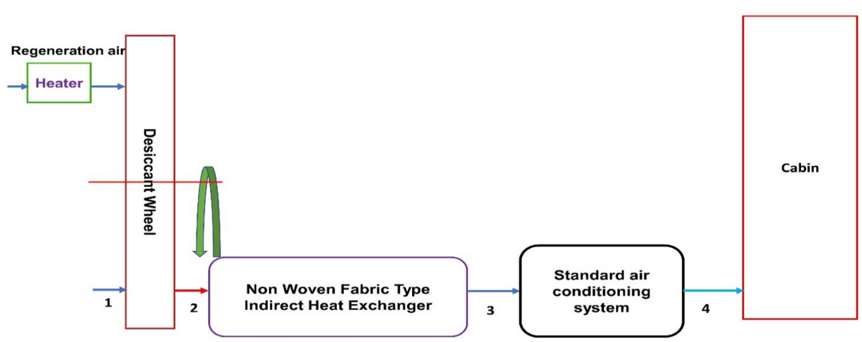

Figure 3 Solid desiccant- hybrid cooling system

The pre-cooled air by solid desiccant cooling is sent to the vapor compression air conditioning system. The air is cooled to comfort supply condition which is specified as point 4 which is sent to the cabin to address the heat load.

The working of the solid desiccant cooling system is simulated by the object-oriented programming BLUEJ simulation platform. This is a looping system and the system achieves steady-state conditions through an iterative procedure.

For equipment like the desiccant wheel, the desired humidity ratio is attained through an iterative process that involves incremental increases in the air humidity ratio. The program continues to run until it reaches a steady state ([?]T<0.001), which means that the temperature between two iterations must be less than 0.001°C at all the stages in the solid desiccant loop. Initially, the system was modeled using ideal process assumptions. Non-idealities in the process are added later to make the model more effective in making accurate predictions of outcomes in real-world situations. The operating points of all the equipment in the loop are given as desired operating conditions via a notepad.

The system is tested for numerous hot-humid conditions. The operating conditions where the system is tested are given in Figure 4. The ambient conditions for which the system is tested are in the humidity ratios of 21, 22, and 28 gkg^{-1} d.a. These conditions are taken from the experimental work reported by Venkatesh et al [18].

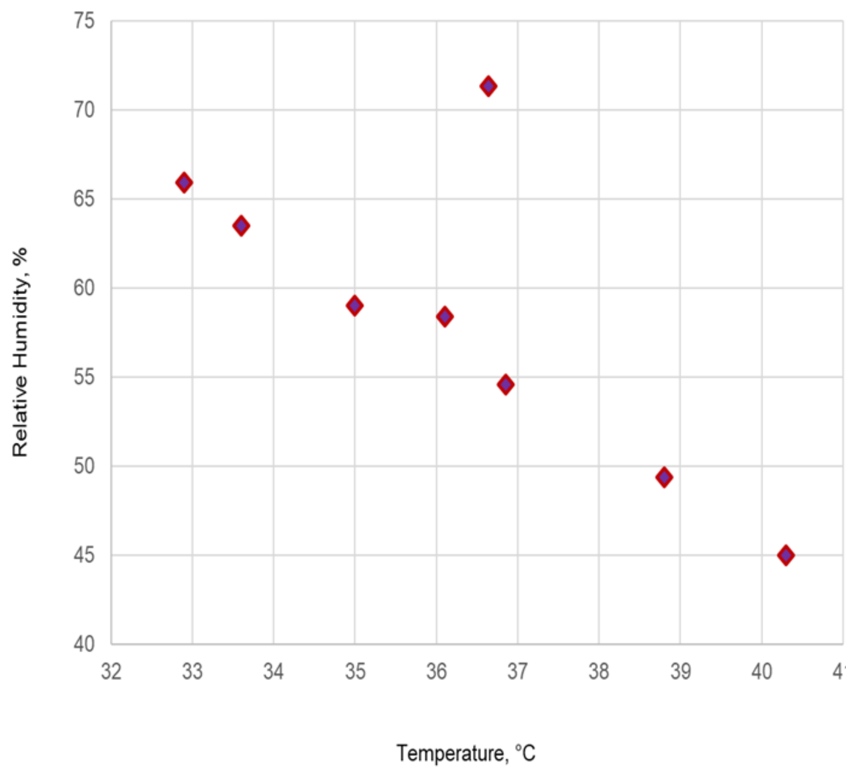

Figure 4 Testing ambient conditions of the HSDVC

The HSDVC in Figure 3 is investigated in three modes specified as follows. Mode 1 is the supply of air being given at 27.5°C and 60% Relative Humidity to the cabin. Mode 2 is the supply of air being given at 22.5°C and 75% Relative Humidity to the cabin. Mode 3 is the supply of air being given at 22°C and 50%

Relative Humidity to the cabin by using two desiccant wheels for dehumidification. The cooling capacity of the HSDVC is given by the equation 2 as follows

Cooling $\text{capacity}_{\text{HSDVCS}} = \dot{m}_a \times (h_{\text{amb}-3} - h_{\text{supply}-4})$ (2)

Performance studies of the HSDVC system

The simulation of the solid desiccant system in mode 1 and the air being cooled by the vapor compression air conditioning system is described in Figure 5. The hot humid air at point 1 is dehumidified by the desiccant wheel and it comes out as hot-dry air at point 2. Then the air is pre-cooled by the Non-woven Fabric type indirect cooling heat exchanger till point 3. The solid desiccant cooling system effectively works till point 3.

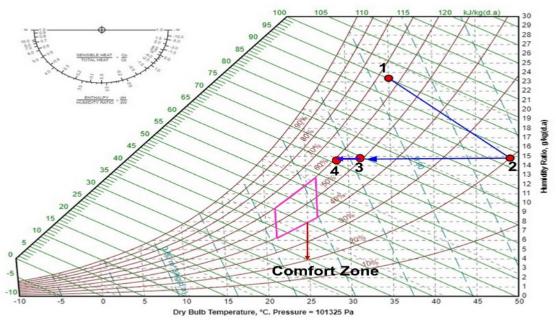

Figure 5 HSDVC system in mode 1

The air that is pre-cooled by the solid desiccant cooling system at point 3 is cooled to point 4 by the vapor compression air conditioning system. Point 4 is 27.5°C and 60% Relative Humidity. Point 4 is not in the comfort zone but still, it is a substantial comfort condition for the occupants inside the cooling space.

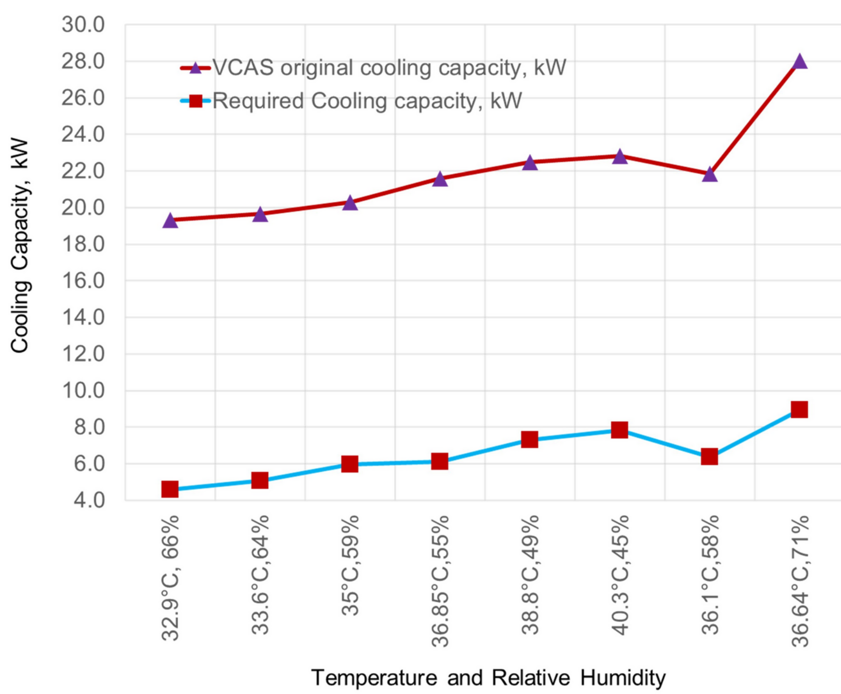

Figure 6 Cooling Capacities of HSDVC in mode1

Using Figure 6, the average cooling capacities for vapor compression air conditioning systems at ambient humidity ratios of 21,22, and 28 gkg^{-1}d.a is 20.5 kW, 22 kW, and 28 kW respectively. But when the air conditioning system is made to run in hybrid cooling mode with a solid desiccant system operated in mode 1, the average cooling capacities are 6 kW, 6.7 kW, and 9 kW respectively for the same ambient humidity ratios. So the solid desiccant cooling system gives a net reduction in cooling capacities of 13.5 kW, 15.5 kW, and 19 kW. The reductions in cooling capacities are significant by the solid desiccant-vapor compression air conditioner hybrid cooling system.

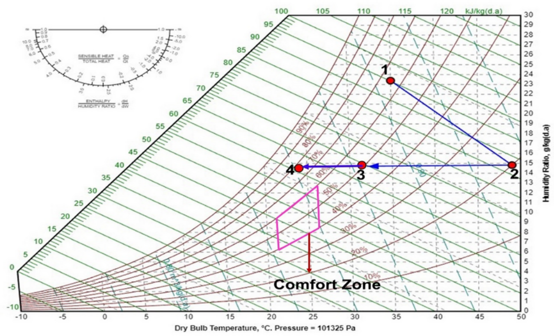

Figure 7 HSDVC system in mode 2

The simulation of the hybrid cooling system in mode 2 is described in Figure 7. The working of the system is similar to the solid desiccant-air conditioning hybrid cooling system operating in mode 1 specified in Figure 7. Mode 2 is the supply of air being given at 22.5°C and 75% Relative Humidity to the cabin. It is mentioned as point 4 in Figure 7. Point 4 given in Figure 7 is not in the comfort zone but still, it is a substantial comfort condition for the occupants inside the cooling space.

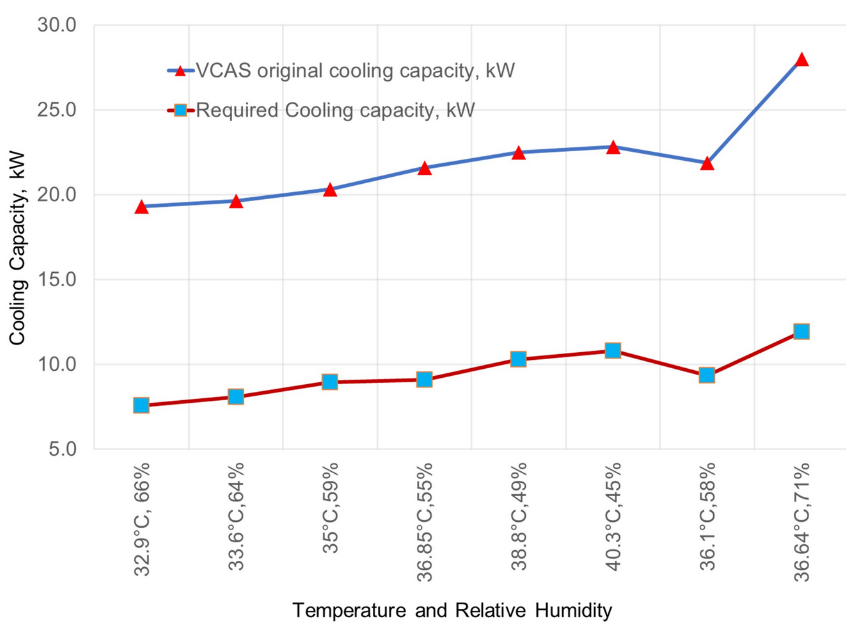

Figure 8 Cooling Capacities of HSDVC in mode 2

Figure 8 describes the original cooling capacities of the Vapor compression air conditioning system and the hybrid cooling capacities in mode 2 at ambient humidity ratios of 21,22 and 28 gkg^{-1}d.a. The average cooling capacities of the solid desiccant-vapor compression hybrid cooling system are 8.5 kW, 9.5 kW, and 12 kW respectively at the same ambient humidity ratios. The solid desiccant cooling system induces valuable reductions in the cooling capacities of 12 kW, 12.4 kW, and 16 kW when the hybrid cooling system is operated in mode 2.

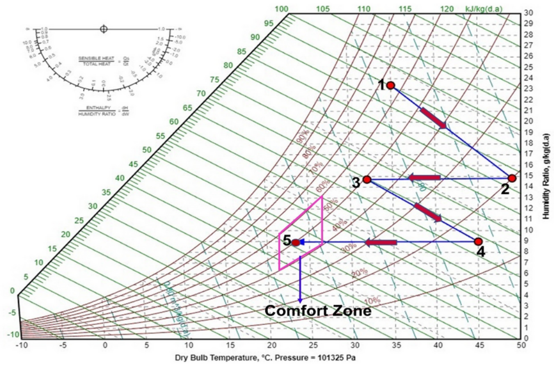

Figure 9 HSDVC in Mode 3

The simulation of the solid desiccant system in mode 3 and the air being cooled by the vapor compression air conditioning system is described in Figure 9. The hot-humid air at point 1 is dehumidified by a desiccant wheel and it becomes hot-dry air which is specified as point 2. Then hot-dry air is sensibly cooled by a non-woven fabric-type indirect heat exchanger. Then the air reaches point 3 and it is further dehumidified by a desiccant wheel. The air will become hot-dry air and it reaches point 4. From point 4, the air is cooled by a vapor compression air conditioning system to reach point 5. Point 5 is the comfort condition where the air is supplied to the cabin. Mode 3 is the supply of air being given at 22°C and 50% Relative Humidity to the cabin mentioned by point 5 in Figure 9. The operation of the hybrid cooling system in mode 3 involves the use of two desiccant wheels for dehumidification. Therefore, this can be called a Two-stage HSDVC.

The cooling capacity for the two-stage HSDVC is given by Equation 3

Cooling capacity $_{\text{two stage HSDVC}} = \dot{m}_a \times (h_{\text{amb}-4} - h_{\text{supply}-5})$ (3)

Figure 10 reveals the original cooling capacities of the VCAS and the HSDVC in mode 3 at ambient humidity ratios of 21,22 and 28 gkg^{-1}d.a. The hybrid cooling system gives average cooling capacities of 13 kW, 14.4 kW, and 16.6 kW respectively for the same ambient humidity ratios.

The hybrid cooling system gives a cooling capacity reduction of 7.3 kW, 7.6 kW, and 11.4 kW respectively for the same ambient humidity ratios in mode 3. The hybrid cooling system gives an essential reduction in the cooling capacity of the vapor compression air conditioning system for numerous hot-humid ambient conditions.

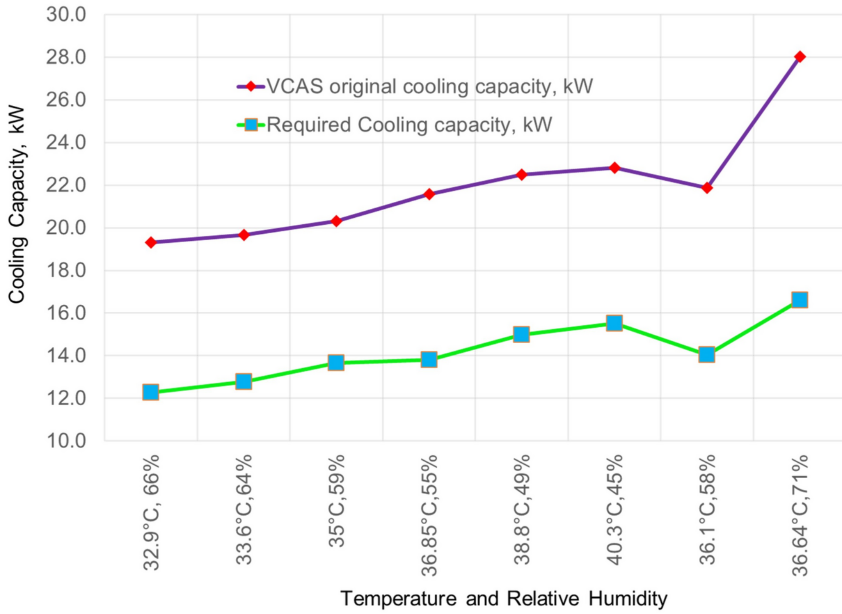

Figure 10 Cooling Capacities of HSDVC in mode 3

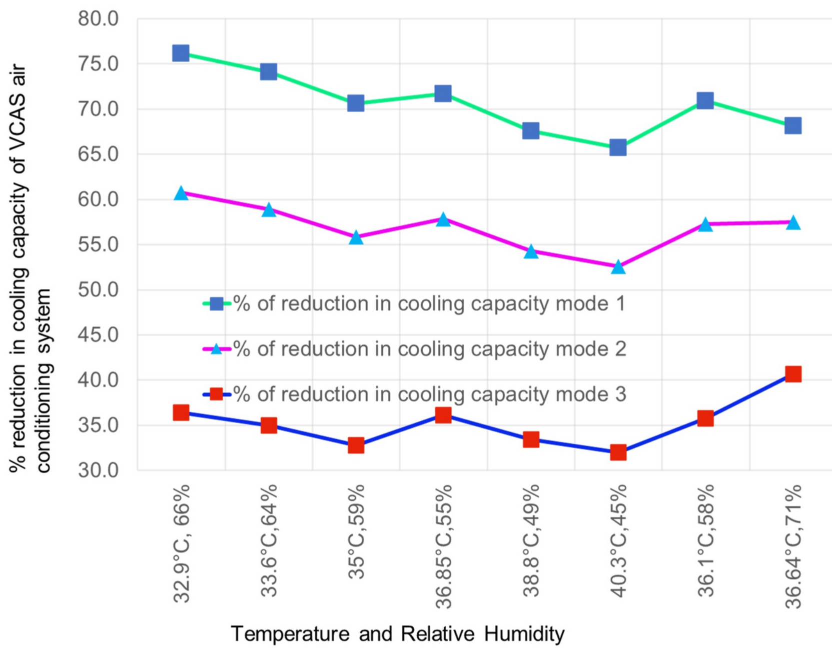

Figure 11 Required reduction of VCAS cooling capacity in all three modes

Figure 11 describes the required reduction in the cooling capacity of a vapor compression air conditioner when it is operated in mode 1, mode 2, and mode 3. In mode 1 when the supply air condition is given as 27.5°C and 60% Relative Humidity, the phenomenal reduction in the average cooling capacities of vapor compression air conditioners are 73%, 70%, and 68% respectively at the ambient humidity ratios of 21,22 and 28 gkg^{-1}d.a. At mode 2 when the supply of air conditioning is set as 22.5°C and 75% Relative Humidity, the significant reduction in the average cooling capacities of vapor compression air conditioners are 57%, 56.5%, and 57.5% respectively at the same ambient humidity ratios tested for mode 1.

Similarly in mode 3, when the supply air condition is 22°C and 50% Relative Humidity, the substantial reduction in the average cooling capacities for the vapor compression air conditioners are 34%, 35%, and 41% respectively. This is for the same ambient humidity ratios tested for mode 1 and mode 2.

Though the supply air conditioning for mode 1 and mode 2 are not exactly in the comfort zone, the cooling provided in mode 1 and mode 2 is significant and the supply air conditioning is only marginally away from the comfort zone. Therefore, the solid desiccant-vapor compression air conditioner hybrid cooling system delivers an average reduction in cooling capacities of 70.5% and 57% in mode 1 and mode 2 respectively. This demonstrates the energy-efficient working of the HSDVC in hot-humid climates. The supply of air conditioning in mode 3 is exactly in the comfort zone. In mode 3, the hybrid cooling system gives an average reduction in the cooling capacity of the vapor compression air conditioner by 37%. From the results of the study of the hybrid cooling system, it is found that the hybrid cooling system could significantly induce a reduction in the cooling capacity of the vapor compression air conditioner from 37% to 71%.

Conclusion

A single-stage solid desiccant cooling system is simulated by using a BLUEJ programming framework. The system is tested for numerous hot-humid ambient conditions. The results of the simulation of the solid desiccant cooling system are given as an input entry air condition for the vapor compression air conditioning system. The system is made to work in three modes namely 1, 2, and 3. The results of the study reveal that the system could potentially provide a reduction in the cooling capacity of the vapor compression air conditioner under the operations of mode 1, mode 2, and mode 3. The average reduction in the cooling capacity of the vapor compression air conditioner for the three modes is 71%, 57%, and 37% respectively. The solid desiccant cooling system could potentially serve as a pre-cooler to work along with the air conditioning unit in a hybrid cooling mode. Due to the substantial cooling capacity reductions demonstrated by the hybrid cooling system, the solid desiccant cooling system could be used as a pre-cooler coupled with an air conditioning system leading the path to energy efficiency

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest concerning the research, authorship, and/or publication of this article.

Acknowledgment

This project is carried out by the funding provided by DST-SERI, India, and the file no is DST/TM/SERI/2k12/81(G). The authors thank the funding agency, which helped to establish the “Centre For Alternate Cooling” at PSG College of Technology, where this work is being carried out. The authors also acknowledge the funding provided by the industry partner, Trident Pneumatics Pvt Ltd, Coimbatore, India for their support rendered in the co-sponsoring and the guidance for the project.

References

1. Fadnavis S, Mahajan AS, Choudhury AD, Roy C, Singh M, Biswas MS, Pandithurai G, Prabhakaran T, Lal S, Venkatraman C & Ganguly D 2020, ’Atmospheric aerosols and trace gases. In Assessment of Climate Change over the Indian Region’, pp. 93-116, Springer, Singapore.
2. Biardeau, LT, Davis, LW, Gertler, P, & Wolfram, C 2020, ’Heat exposure and global air conditioning’, Nature Sustainability, vol. 3, no. 1, pp. 25–28.
3. Birol, F 2018, ’The Future of Cooling: Opportunities for energy-efficient air conditioning, The Future of Cooling: Opportunities for energy-efficient air conditioning, International Energy Agency
4. Renaldi, R, Miranda, ND, Khosla, R & McCulloch, MD 2021, ’Patent landscape of not-in-kind active cooling technologies between 1998 and 2017’, Journal of Cleaner Production, vol. 296, Article No:

126507.
5. Liu, H, Dai, YJ, Köhler, M, & Wang, RZ 2013, 'Simulation and parameter analysis of a two-stage desiccant cooling/heating system driven by solar air collectors', Energy Conversion and Management, vol. 67, pp. 309–317
6. Kabeel, AE & Bassuoni, MM 2013, 'Feasibility study and life cycle assessment of two air dehumidification systems', Global Advanced Research Journal of Physical and Applied Sciences, vol. 2, no. 1, pp. 8–16.
7. Jani, DB, Mishra, M & Sahoo, PK 2016, 'Performance prediction of solid desiccant - Vapor compression hybrid air-conditioning system using artificial neural network', Energy, vol. 103, pp. 618–629.
8. Jani, DB, Mishra, M & Sahoo, PK 2018, 'Solar Assisted Solid Desiccant—Vapor Compression Hybrid Air-Conditioning System', Energy, Environment, and Sustainability, pp. 233–250.
9. Jia, CX, Dai, YJ, Wu, JY & Wang, RZ 2006, 'Analysis on a hybrid desiccant air-conditioning system', Applied Thermal Engineering, vol. 26, no. 17–18, pp. 2393–2400.
10. Hussain, S, Kalendar, A, Rafique, MZ & Oosthuizen, P 2020, 'Numerical investigations of solar-assisted hybrid desiccant evaporative cooling system for hot and humid climate', Advances in Mechanical Engineering, vol. 12, no. 6, pp. 1–16.
11. Ukai, M, Tanaka, Hiroaki, Tanaka, Hideki & Okumiya, M 2018, 'Performance analysis and evaluation of desiccant air-handling unit under various operation condition through measurement and simulation in hot and humid climate', Energy and Buildings, vol. 172, pp. 478–492.
12. Lee, Y, Park, S & Kang, S 2021, 'Performance analysis of a solid desiccant cooling system for a residential air conditioning system', Applied Thermal Engineering, vol. 182, pp. 116091
13. Sohani, A., Cornaro, C., Shahverdian, M.H., Moser, D., Pierro, M., Olabi, A.G., Karimi, N., Nižetić, S., Li, L.K. & Doranehgard, M.H., 2023. Techno-economic evaluation of a hybrid photovoltaic system with hot/cold water storage for poly-generation in a residential building. Applied Energy, 331, p.120391.
14. Singh, G. and Das, R., 2023. Performance Analysis of Evaporation and Heat Wheel-Based Building Air Conditioning Systems. Journal of Energy Resources Technology, 145(3), p.032101.
15. Luo, W.J., Faridah, D., Fasya, F.R., Chen, Y.S., Mulki, F.H. and Adilah, U.N., 2019. Performance enhancement of hybrid solid desiccant cooling systems by integrating solar water collectors in Taiwan. Energies, 12(18), p.3470.
16. Worek, W.M. and Moon, C.J., 1988. Desiccant integrated hybrid vapor-compression cooling: performance sensitivity to outdoor conditions. Heat Recovery Systems and CHP, 8(6), pp.489-501.
17. Liang, J.D., Kao, C.L., Tsai, L.K., Chiang, Y.C., Tsai, H.C. and Chen, S.L., 2022. Performance investigation of a hybrid ground-assisted desiccant cooling system. Energy Conversion and Management, 265, p.115765.
18. Venkatesh, R, Ganesh, M, Suriyaprakash, S, Deva Surya, SE, Ashok Kumar, L & Rudramoorthy, R, 2021, 'Experimental and simulation study of the performance of a desiccant loop cooling system', Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, vol.8, pp.1914-1932.