INVESTIGATION AND PERFORMANCE ANALYSIS OF HYBRID SOLID DESICCANT COOLING SYSTEM

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By

Bhabhor Kirankumar Kachraji

Enrolment No. 179999919003

Under the supervision of

Dr. Dilip.B. Jani

Associate Professor

Government Engineering College Dahod

GUJARAT TECHNOLOGICAL UNIVERSITY

AHMEDABAD

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1. Title of Thesis and Abstract

<u>Title of Thesis</u>

"Investigation and performance analysis of hybrid solid desiccant cooling system"

<u>Abstract</u>

Traditional cooling systems based on vapor compression are ineffective in humid climates due to their inability to remove moisture below the dew point of the conditioned air, which necessitates additional effort in the form of electrical power supply to run vapor compressors. Furthermore, uses of CFC based refrigerants in vapor compression based traditional HVACs are responsible for the depletion of ozone layer to contribute global warming. A solid desiccant cooling system reduces power usage while simultaneously providing fresh and clean air. It is important to examine and analyse the performance of desiccant dehumidifiers that will help to develop more efficient cooling system.

A Computational Fluid Dynamic (CFD) simulation predicts the numerical performance of the solid desiccant wheel while dehumidifying moist room air during dehumidification. The aim of this study is to conduct performance study of different desiccant wheel channel geometries like triangular, square, hexagonal, sinusoidal-1 and sinusoidal-2 using simulation carried out with the help of CFD for various operating performance input parameters like supply air temperature, velocity, pressure and humidity of air. The CFD simulation technique evaluates all channel geometry shapes and identifies the most effective geometry among them that provide the most efficient dehumidification. During simulation, the operating parameters of supply process air were considered as 25°C temperature and 50% (RH) in the case of a recirculation mode. Similarly, in the case of ventilation mode, for supply of process air, two transient climatic conditions have been selected for the city of Dahod, INDIA, as outdoor

Condition-I 29°C with 83% RH and outdoor condition II 35.8°C with 60.5% RH for the supply of process air. The simulation results estimate the moisture removal capacity for different geometries under various operating conditions. It is found that the sinusoidal types of geometry provide substantial drop in the relative humidity up to 80.01% with the average temperature raised by 38.98% of supply air and provide the most effective dehumidification of the supply process air. As a result, CFD simulation techniques aid in the saving time which spent on rigorous experimentation and avoiding the cost of critical construction for various shapes of geometry.

A solid-desiccant vapour-compression hybrid air conditioning system experimental setup was designed, fabricated and installed at Government Engineering College, Dahod. A rotary desiccant dehumidifier unit and a sensible heat recovery wheel are used, with a traditional vapour-compression air-conditioner as a backup. The system has two modes of operation: ventilation and recirculation. The investigation will be conducted in a test room measuring 2.286x2.286x2.92m with sensible and latent cooling loads of 1.38 kW and 0.27 kW, respectively. Over varying outdoor conditions, such as at various ambient temperatures and humidity ratios, steady-state measurements were taken for the hot and humid period from March to September. The impact of operating factors such as flow rate, pressure drop, regeneration temperature, and so on for system performance is covered by the experimental observation.

A computer programme was developed to operate Arduino system for measuring a psychrometric properties like dry bulb temperature and relative humidity at each state point of the system on the basis of ambient and desired inside room conditions, room cooling load, sensible heat factor and air stream flow rate. The system performance in terms of coefficient of performance and dehumidifier effectiveness has also been evaluated. The Influence of variation in ambient conditions on system performance has been discussed. The experimental trends are validated with simulation results.

The current technology has achieved a significant reduction in the process air humidity ratio at the desiccant dehumidifier's outlet while maintaining comfort levels. The results reveal that changes in ambient circumstances have a major impact on the system's performance. The proposed system has been shown to maintain indoor comfort conditions in Dahod's fairly hot and humid climate for a various application.

Keywords: Solid desiccant cooling; Desiccant wheel channel geometry; Computational fluid dynamics; Simulation, Hybrid desiccant cooling system.

2. Introduction

Today's rapid technological development has altered the human working environment, leading to an increase in the use of vapor compression-based cooling systems. A desiccant dehumidification has long been used for many industrial and agricultural purposes, such as humidity control in textile mills and post-harvest low-temperature crop-drying in stores, and is now playing an increasingly important role in the air-conditioning industry. A desiccant cooling system can be used in a wider range of climates. They can be run on an open heat-driven cycle that includes a dehumidifier, a sensible heat exchanger, and evaporative coolers. In this environmentally friendly system, a desiccant wheel is used to dehumidify the air to a low humidity level so that evaporative cooling or other cooling options can be used effectively to reduce the temperature of the air. Thus, a desiccant cooling system plays an important role as an alternative to conventional heating and cooling systems. The desiccant cooling system not only decreases energy consumption but also reduces the heat rate, which is largely affected by the global environment. A solid desiccant rotor in a desiccant cooling system removes moisture from the air to improve the indoor air quality also.

The novelty of this research work is to identify the effect of temperature and relative humidity on different desiccant channel geometries of a desiccant wheel during the adsorption process with the help of a CFD simulation technique. The CFD simulation techniques provide something similar to an experimental environment, which is also beneficial in terms of saving money and time. The performance outcomes are used to compare either the mathematical or experimental performance results of different silica gel based desiccant channel geometry, like square, triangular, hexagonal, and sinusoidal. The CFD simulation outcomes concluded that the sinusoidal geometry has an optimum performance outcome compared to the rest of the geometries. The simulation outcomes not only satisfy the past experimental trends, but are also helpful for future comparison with actual experimental as well as theoretical trends. The experimental setup of hybrid solid desiccant cooling system performed with two different mode of operation like ventilation and recirculation mode for different climatic conditions of Dahod, Gujarat regions. The available experimental results will help to identify the suitable desiccant based cooling system for specific climatic conditions.

2.1 Working principle of desiccant integrated cooling system.

Desiccant cooling systems remove moisture from the air using a range of drying materials through a natural process known as sorption, which can be adsorption or desorption. The desiccant surface attracts air humidity because of the low level of water vapor content of desiccant substances, which causes a humidity vapor pressure difference between the moist air and matrix channel. Fig.1 shows the conceptual working of the dehumidification and cooling conducted with desiccant.

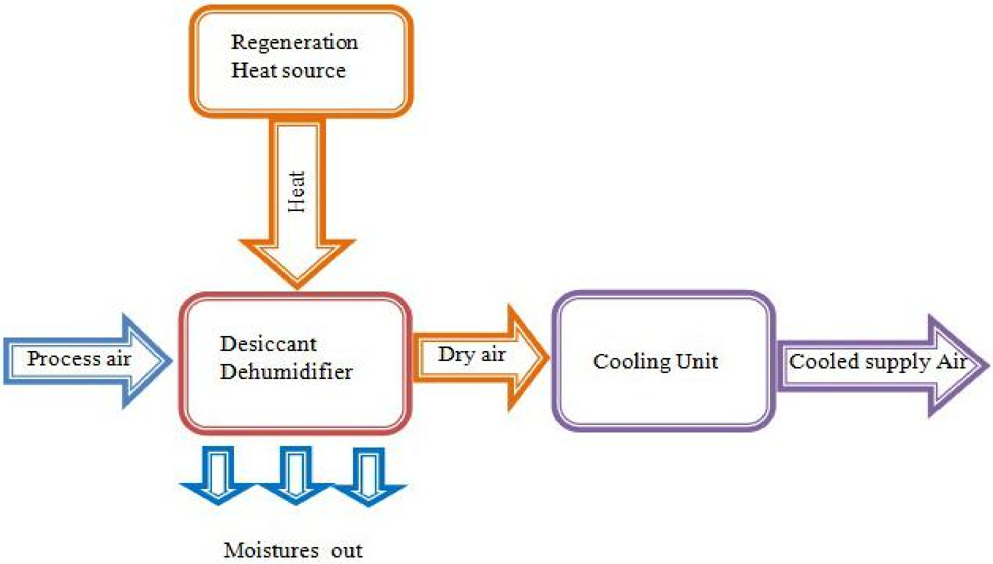


Fig.1. Conceptual working of desiccant assisted cooling [1].

The desiccant integrated dehumidification and cooling process for comfort air conditioning can be classified as either solid or liquid, depending on the type of desiccant material utilized.

3. A brief description of the state of the art of research topic.

Desiccant cooling system are developed for providing clean fresh and dehumidified air in comfort zone. During this study, the following facts are observed from the literature survey as shown in Table-1.

Sr. No.	Name of Author and Year of Publication	Work Done	Outcome
1	K. Daou, R.Z. Wang, Z.Z. Xia [2], 2006	After analyzing the available number of literatures, they presented some commented examples to illustrate how desiccant cooling can be a perfective supplement to other conventional cooling systems.	Up to 40% energy saving as compared to traditional air conditioning Regeneration by free energy (solar & waste heat) Materials are quickly regenerate at lower temperature Its potential to improve indoor air quality, cost and energy saving, as well as protect the environment from various hazardous conventional

			coolants.
2	Minaal Sahlot and Saffa B. Riffat [3], 2016	By reviewed the various literature they analyzed various LDS and gave examples of Hybrid liquid desiccant System also compared the various liquid desiccants materials and briefing the solid desiccant cooling systems.	After analyzing the various literatures Hybrid Liquid desiccant cooling system is more efficient than conventional VCR while Solid desiccant cooling system is more advanced and its inexpensive, non-corrosive, non-flammable environment friendly technology
3	Kishor S. Rambhad, Pramod V. Walke, D.J. Tidke [4] ,2015	From the various literatures they study functioning of dehumidification, cooling various solid desiccant with the focus on the use of solar energy.	By the selecting suitable desiccant materials, desiccant wheel geometry and methods of dehumidification and regeneration can improve the overall efficiency and supporting the economically as well as environment friendly.
4	D.B. Jani, Manish Mishra, P.K. Sahoo [5], 2016	Here numerous researchers conducted feasibility study by using simulation as well as various experimental methodologies.	To found various progress in solid desiccant cooling system. They found Hybrid cycles can achieve significant energy saving by use of freely available solar energy or waste heat from industrial processes for regeneration of desiccant material can make system more cost effective. It can also help to alleviate the peak electricity demand in hot sunny days.
5	Hao Hong, Feng Guohui, wang Hongwe[6], 2012	Two types of hybrid system are investigated one was compound vapor compressor and desiccant (VC+D) cooling system and other was composed of vapor compressor, desiccant and direct evaporative cooler (VC+D+EC) cooling system. The system regenerated by electricity and solar energy was conventional and solar hybrid system respectively. mathematical model of rotary desiccant wheel was established by considering thermal storage of supportive structure, and physical model and numerical model of hybrid	Under the same operating condition, compared with conventional vapor compression cooling system, coefficient of performance and energy saving of two vapor compression subsystems for hybrid systems are increased 16.09%,28.71% and 58.37%,78.71%; energy saving of whole load for conventional hybrid and solar hybrid systems are 11.76%,20.51%, and 38.22%, 53.62%. Here more energy was saved in hot, dry climates and less was saved in hot, humid climates for the conventional hybrid cycle while solar hybrid cycle always saved more energy than conventional vapor compression

		system were established too.	cycles.
6	D.B. Jani, Manish Mishra, P.K. Sahoo [7], 2015	They studied experimentally solid desiccant cooling to supplement the conventional vapor compression refrigeration air conditioner for typical hot and humid climate. A solid desiccant and vapor compression hybrid air-conditioning system for a test room of cooling capacity 1.8 kW, has been modeled in simulation studio project and simulated in TRNSYS environment for the cooling season from March to September. And the obtained result has been validated against experimental test data.	The effects of ambient humidity ratio and temperature on coefficient of performance and supply air temperature have been evaluated. The variation in coefficient of performance has been obtained at various regeneration temperatures. The simulation results show the suitability of such systems for cooling of building in hot and humid climates.
7	Avadhesh Yadav and V. K. Bajpai [8], 2012	To performs the experiment by the regeneration and adsorption of different desiccants such as silica gel, activated alumina, and activated charcoal for producing dry air is proposed. The desiccants were regenerated at temperatures in the range of 54.3–68.3°C.	The regeneration performance was greatly affected by the regeneration temperature but depended on the initial moisture content, temperature of the desiccants, and flow rate of regeneration air. Comparison of the performances showed that at high hot air flow rate the regeneration time and adsorption time were shorter for these desiccants than that at low flow rate. Silica gel was observed to perform better at high as well as low flow rates for regeneration and adsorption than activated alumina and activated charcoal.
8	Avadhesh Yadav and V.K. Bajpai [9], 2012	The regeneration and adsorption of desiccant wheel for producing the dry air was experimentally investigated. The desiccant wheel is regenerated at the temperature in the range of 43.9–72.68°C. comparing the adsorption and regeneration performance at different air flow rate and constant rph.	In the adsorption process at 138 kg/h air flow rate, the maximum adsorption rate in silica gel was 0.151 kg/h and the minimum adsorption rate was 0.093 kg/h In the regeneration process at 138 kg/h air flow rate, the maximum regeneration rate in silica gel was 0.506 kg/h and the minimum regeneration rate was 0.006 kg/h. Regeneration temperature directly affects the effectiveness of the desiccant wheel. Maximum desiccant wheel effectiveness of regeneration sector and adsorption sector is

			obtained at air flow rate of 105-394 kg/h.
9	Avadhesh Yadav and V.K. Bajpai [10], 2012	Desiccant wheel for producing dry air have been experimentally investigated. The desiccant wheel is regenerated at a temperature range of 50–55°C. The regeneration and adsorption performances are affected by the regeneration temperature, wheel rotation, air flow rate (process and regeneration) and ambient conditions. On comparison, the adsorption and regeneration rates at different rotations per hour (rph) and at a constant flow rate of 210-789 kg/h for both adsorption sector and regeneration sector.	it is found that in the range of 50–55°C average regeneration temperature, the solar-powered desiccant wheel performs well with a rotational speed of 16 rph.
10	Mohsen Ali Mandegari, Somayeh Farzad, Giovanni Angrisani, Hassan Pahlavanzadeh [11], 2017	In this study, a mathematical model was developed and validated to simulate the coupled heat and mass transfer processes in a desiccant wheel. The effect of operating parameters on the required purge angle including process and regeneration air velocities, regeneration air temperature, rotational speed and design parameters such as desiccant layer thickness, channel length (DW length) and channel hydraulic diameter, have been evaluated. Since the adoption of a purge section was recognized A comparison among three different case studies including ‘‘no purge”, ‘‘effective purge” and ‘‘optimal purge” at similar operating conditions have been carried out.	Due to calculation of purge angle based on outlet air humidity profile, resulted purge angle at saturated desiccant bed did not reflect correct physical meaning, as the tail of humidity profile rises close to inlet air humidity. The process air velocity and channel length showed the most significant influence on the outlet air humidity profile compared to other investigated parameters. Overall, the purge angles were found in the range of 4°–16° and 16°–90° for ‘‘optimal” and ‘‘effective” definitions, respectively. ‘‘optimal purge” angle (12°) provides the best moisture removal rate compared to ‘‘effective purge” angle (74°) and ‘‘no purge”. However, applying the ‘‘effective purge” resulted in minimum averaged process air humidity, whereas a significant reduction of process air flow rate (about 27%) is required.

11	X.N. Wu, T.S. Ge, Y.J. Dai, R.Z. Wang [12], Article in press	To perform experiment with substrate of a rotary desiccant wheel usually is porous ceramic fiber paper or glass fiber paper. substrate with high porosity and high thermal conductivity selected. Taking into account both dehumidification capacity and pressure drop, select sinusoidal air channel for rotary desiccant wheel.	Improve the dehumidification capacity of rotary desiccant wheel Solid desiccant dehumidification system reveals that substrate plays an important role in dehumidification processing and porous fiber paper is the best choice for substrate of rotary desiccant wheel. The substrates and desiccant materials have not been understood deeply. In the future, revealing the nature of the effect of substrate on the dehumidification performance may be the main work to fill in these blanks.
12	Neeraj Mehla, and Avadhesh Yadav [13], 2017	During the Experimentation heating and humidification of air for space have been carried out by using a phase change material (PCM)-based solar-powered desiccant wheel air conditioning (SPDWAC) in winter. The analysis of the setup has been done at different air flow rates.	At low and high air flow rates, system has mean thermal coefficient of performance of 0.121 and 0.172, respectively, and mean exergy efficiency of 0.0787 and 0.0846, respectively. The mean thermal coefficient of performance of the system at high air flow rate (127.23 kg h-1) is 1.42 times the low air flow rate (63.62 kg h-1) and average exergy efficiency of the system at high air flow rate is 1.07 times the low air flow rate. With an increase in air flow rate, efficiency of the evacuated tube solar air collector (ETSAC) increases. The average efficiency of the ETSAC at high air flow rate is 15.60%. The maximum average energy efficiency (17.80%) and exergy efficiency (17.08%) of the PCM storage system have been obtained at high air flow rate. The overall performance of the system showed that the use of PCM storage is feasible to run the system in winter during the hours of darkness.
13	Visit Akvanich and Juntakan Taweekun [14],2012	To investigate the effects of different flow-bed geometries and flow directions of air-stream through desiccant media upon pressure drop (ΔP) and	Results implied that the hollow cylindrical bed which the symmetry beds were the feasible and practical dehumidifier for dehumidification process such as the radial bed and the conical

		adsorption rate (ΔW) through CFD. The influence of flow-bed geometries and flow-directions of air-stream within the desiccant column were considerate, i.e., vertical bed, segment bed, radial bed, conical bed and the flow from inner to outer of with approximately 3 mm diameter of silica-gel as the working desiccant. For all simulation test units, amount of desiccant in the bed being close to 10 kg of silica-gel and column volume of 0.045 m^3 were used.	bed S2 or S3. For various mass flow rates between 10 and 85 kg/h, the capacity of desiccant column with the radial bed and the conical bed S2 or S3 were 1.88-58.97 Pa (0.1745-0.4634 kgw/h) and 1.10-49.37 Pa (0.1744-0.4524 kgw/h), respectively.
14	Jae Dong Chung [15]	It is reviewed that in there is some parameter in the analysis is taken such as **channel geometry, absorbent, wheel speed, regeneration temperature** etc. and comparison of different geometry.	Rectangular geometry has more hydraulic diameter and Nusselt no. so it has more heat transfer capacity compared to sinusoidal and triangular shaped geometry.
15	Avadhesh Yadav et al. [16]	In this study for channel geometry, **sine-shaped geometry** is analyzed in mathematical modeling among the different geometry like triangular, rectangular etc. Also, regeneration and process section are divided into **1:4**.	Ratio of regeneration and process section can be varied.
16	Zhiming Gao et al. [17]	It is reviewed that geometry affects the moisture removal rate.	Sinusoidal shape has more amount of moisture removal capacity compared to triangular, square and hexagonal (in sequence)
17	Weilong Wang et al. [18]	In this paper comparison between different desiccant material is given. Silica materials, and carbon materials showed a lower regeneration temperature, whereas the regeneration temperatures for zeolites and clays were higher. Also, Water content in air affects in adsorption capacity.	Different dehumidification adsorbents have different regeneration temperature ranges. The adsorption capacity also varies with the initial water content or RH in air. The higher the water content, the higher the adsorption capacity of the adsorbent.

4. Definition of the problem

- To design and manufacturing of a cost-effective hybrid solid desiccant cooling system.

- Cooling load study of an office cabin for a commercial building.
- Numerical simulation for different shapes of desiccant based channel geometry using CFD simulation techniques. Available performance simulation is further validated with past theoretical studies.
- Adopted different methods for experimentation of hybrid desiccant cooling system for different climatic conditions.
- The performance outcomes from different mode of operation for the hybrid desiccant cooling system is compared with each other.
- The experimental outcomes of the system are compared with CFD simulation.

5. Objective and scope of work

Objective of work

Design and development of hybrid desiccant cooling system for small scale office cabin for commercial buildings, to identify the performance of desiccant material based different channel geometry for humidification is difficult and time consuming to identify the best performance given by a geometry.

The following are the objectives of this work.

- To conduct cooling load analysis of office cabin available at Government Engineering College Dahod based on sensible and latent heat load.
- To analyze different types of desiccant dehumidifier channel geometry with different operating performance parameters through CFD by using Ansys-CFX and to compare the simulation results with experimental trends.
- Experimental investigation on performance of desiccant dehumidifier at different operating parameters like low humidity and high temperature ranges, high humidity and low temperature ranges of hybrid desiccant cooling system.

Scope of work

- Cooling load analysis of office cabin will help of designing desiccant wheel by how much CFM of supply air is needed to the office cabin for providing comfort condition.
- CFD simulation software ANSYS CFX is used to find out numerical performance of different desiccant channel geometry, optimum performance of the geometry will have compared with past research and will further utilize in design and fabrication of desiccant wheel for getting effective performance outcome of the desiccant cooling system.
- Develop hybrid desiccant cooling system for small office building.

- Experimental investigation on desiccant dehumidifier for humidification and dehumidification in hybrid desiccant cooling system for different climatic conditions of Dahod, Gujarat, India.

6. Original contribution by thesis

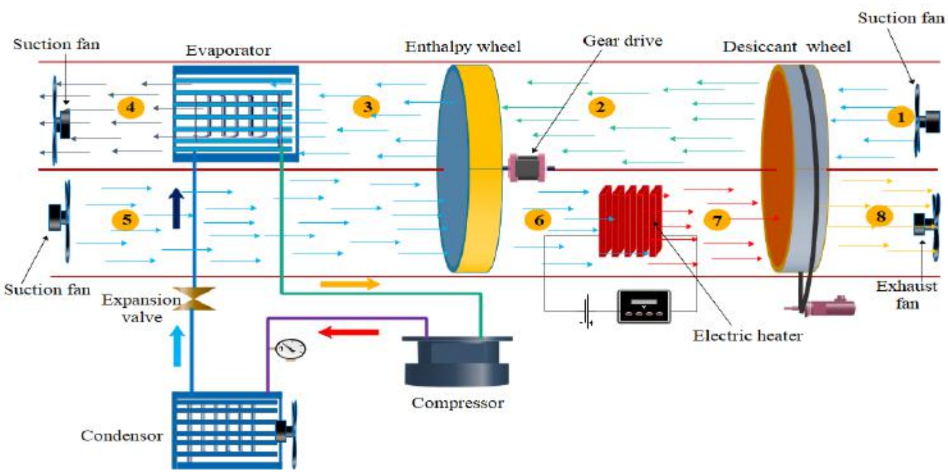
Preliminary investigation has been carried out

During the literature review, it was discovered that the performance of solid desiccant cooling systems is superior than liquid desiccant cooling systems. Solid desiccant also plays a significant role in reducing the energy consumption of any traditional cooling system.

The literature review suggested to find the suitable solid desiccant material and its performance on desiccant wheel. The optimum performance of desiccant wheel is depending upon the selection of desiccant wheel geometry. From the above review the interesting research gap is available that is to find performance of desiccant channel geometry either using experimentally or numerically. The review gap is also available for conducting experimental investigation using advanced hybrid solid desiccant cooling system particularly for small office cabin as represented in fig.2.

After a preliminary investigation, it is suggested following modification for better output of hybrid solid desiccant cooling system.

- The performance of different desiccant channel geometry for dehumidification process taking numerical simulation using CFD is helpful for selection of suitable channel geometry which will further helpful for performance improvement of the system.
- The representation of hybrid solid desiccant cooling system as given in below figure discuss the working of basic hybrid solid desiccant cooling system, which can useful for preparation of actual experimental setup of hybrid solid desiccant cooling system.



State point -1: Ambient air inlet to desiccant wheel
State point -2: Air outlet from desiccant wheel
State point -3: Air outlet from enthalpy wheel
State point -4: Air outlet from evaporating coil

State point -5: Ambient air inlet | State point -6: Air inlet to enthalpy wheel
State point -7: Air outlet from enthalpy wheel | State point -8: Air outlet from desiccant wheel

Fig.2. Representation of hybrid desiccant cooling system.

- The different operation of hybrid solid desiccant cooling system is not only helpful for finding the effect on desiccant wheel during the dehumidification in various climatic conditions for small scale commercial office cabin.

Original Contribution

- Design and identification of research problem from the literature survey are reflected in the review paper published in the International Journal of Ambient Energy (Taylor & Francis).
- Develop experimental environment in ANSYS CFX software by modeling and simulation techniques of CFD.
- Take a performance of different desiccant channel geometry like square, triangular, hexagonal, sinusoidal for dehumidification during different climatic condition of Dahod, Gujarat, India using CFD, Identified the best performance geometry will further used to design a desiccant wheel.
- Simulation for different channel geometry using CFD a research paper published in Journal of Building Engineering (SCI Indexing- Elsevier publication).
- Develop mathematical model of desiccant channels using Mathematica and outcomes presented at GTU International Conference-GTUICON-2019.
- Design and fabrication of experimental components like frame, humidifier, dehumidifier, heating coil, evaporating coil for hybrid desiccant cooling system both for recirculation and ventilation mode of operation, using locally available materials.
- All suggested devices for controlling and operating of hybrid desiccant cooling system are tested to find out best for dehumidification section and regeneration section with better output.
- Developed Arduino based data acquisition system to receive data and stored in computer including runtime simulation.

7. Methodology of research and results/discussion

7.1 The methodology adopted is as follow.

The present research work comprises: the cooling load analysis for the small office cabin, the performance evaluation for various desiccant channel geometry using CFD simulation technique and experimentation for different operating cycle performance for dehumidification of process air supplying to small office cabin.

7.2 In the present research work, the methodology adopted is as follows:

- A detail literature survey has been done for the above work for dehumidification process, and research gaps have been identified.

- At first to take cooling load analysis for the selected office cabin and identified the CFM required for the size of office and find out the diameter of the desiccant wheel.
- Numerical simulation of different channel geometry used in desiccant wheel for dehumidification process is performed by using CFD simulation technique for various operating climatic conditions with the help of ANSYS CFX software.
- Identified optimize performance outcome-based channel geometry from CFD simulation technique is further apply to make desiccant wheel is fabricated by industrial supplier.
- To fabricate experimental setup in workshop.
- During the experimental work, RTD PT-100 sensors were used with a data logging facility for recording the different parameters and experimental results. The psychometric properties of air were recorded using sensors with an Arduino microcontroller board.
- To take performance of hybrid desiccant cooling system under different operating climatic conditions with inlet supply performance parameters like velocity, pressure, temperature etc. during ventilation mode. In the ventilation mode the fresh ambient air is supply for both dehumidification section and regeneration section of the experimental setup.
- To take performance of hybrid desiccant cooling system under different operating climatic conditions with inlet supply performance parameters like velocity, pressure, temperature etc. during recirculation mode. In the recirculation mode the fresh ambient air is supply for both dehumidification section and regeneration section of the experimental setup.
- To compare the performance outcomes for both ventilation and recirculation mode under different climatic conditions.
- The theoretical results were calculated using the numerical modelling and simulation and were compared with experiments recorded results.

7.3 Cooling load analysis

Cooling load calculation for office cabin

Length of the room	=	2.286 m
Width of the room	=	2.286 m
Height of the room	=	2.29 m
Area of glass (W1)	=	Width of Glass x Height of Glass
	=	1.21x1.828 m^2
		2.211m^2
Area of the door (D3)	=	Width of Door x Height of Door
	=	1.066x2.29
		2.441m^2
Outside wall area (SE)	=	Area of Wall + Area of Window
		1.0668 x 2.29 +

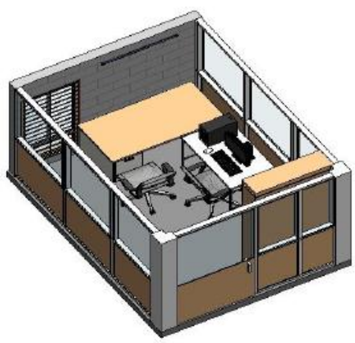


Fig.3 3D View of Office cabin

		$0.4572 \times 1.2192 m^2 = 2.998 m^2$
Partition wall areas (NE, SW, NW)	=	Area of Wall (NE)+Area of Wall (SW)+Area of wall (NW)
	=	2.286x2.29 + 2.286x2.29+ (2.286x2.29 -2.441)
		5.234+5.234+2.793
		$13.261 m^2$

Total Load (RTH) = RSH+RLH

Total Room Sensible Heat Gain: Room sensible heat gain is a combination of all type of sensible heat gain at a conditioned space i.e.

RSHG = Sensible heat gain through walls, floors and ceilings + Sensible heat gain through glasses + Sensible heat gain due to occupants + Sensible heat gain due to infiltration air + Sensible heat gain due to ventilation + Sensible heat gain due to lights and fans.

Total Heat Load	=	TSH+TLH
	=	1601.6 + 271.27
	=	1872.87W
	=	1.871KW
Total loads in Tons	=	Total load in KW/3.5
	=	1.813/3.5
	=	0.535TR (Tons of refrigerant required)
1TR	=	400CFM [19]
0.535TR	=	214CFM
	=	0.1009967543m3/s
	=	100996752.84mm3/s
Length taken as in for air supply through desiccant wheel	=	100mm
Area considered for air supply through Desiccant wheel as	=	10099mm2
Diameter for desiccant wheel is	=	$\sqrt{\frac{4}{\pi} \times 100996}$
	=	358mm

As per requirement the standard dimension taken as standard

Diameter of desiccant wheel	=	350mm
Length of Wheel is	=	100mm

7.4 Desiccant wheel classification

Desiccant dehumidifier has been classified according to aspects ration and channel size it is identified according to the different size and types of desiccant channels.

Channel geometry: Channel geometry is an important factor to design the desiccant dehumidifier because dehumidification and moisture removing capacity is different for different geometry. There are some geometries as shown in Fig. 4

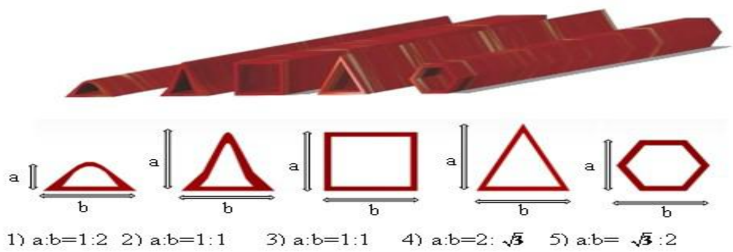


Fig.4 Different Geometry used in Desiccant Dehumidifier

7.5 CFD Modelling and simulation overview

To conduct the performance of different size of desiccant dehumidifier channels using CFD will follow the methodology for modelling and simulation as given below Fig.5

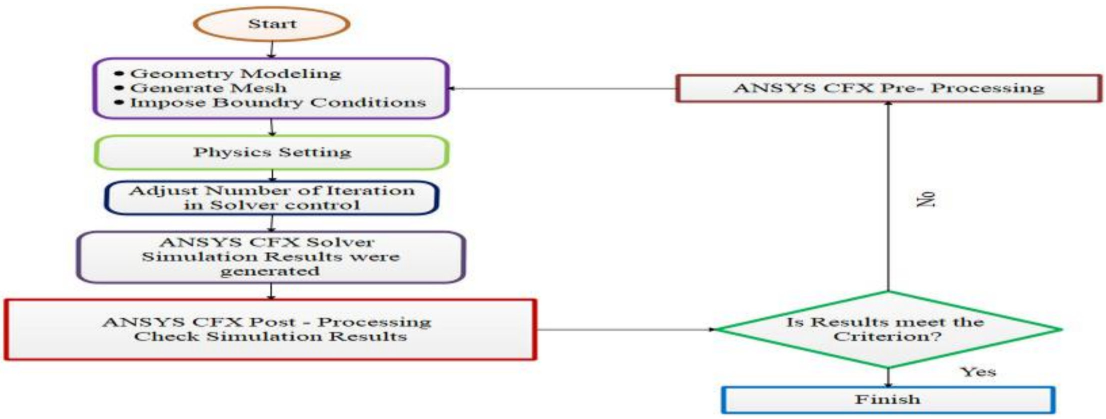
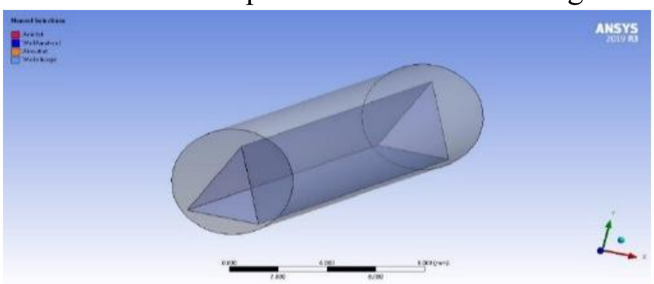
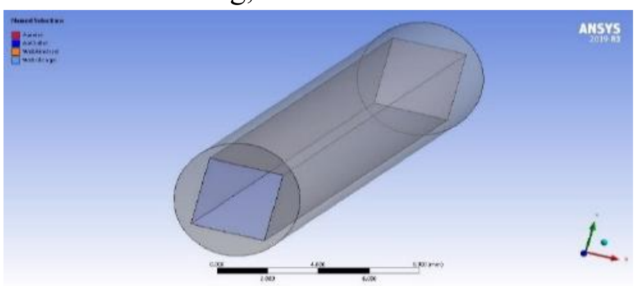


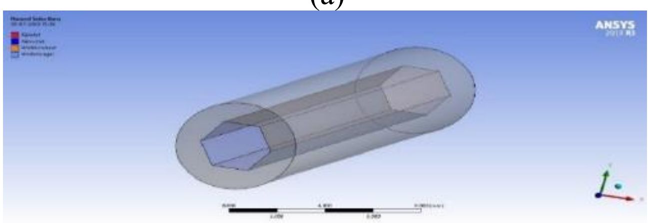
Fig.5. CFD simulation methodology using ANSYS CFX

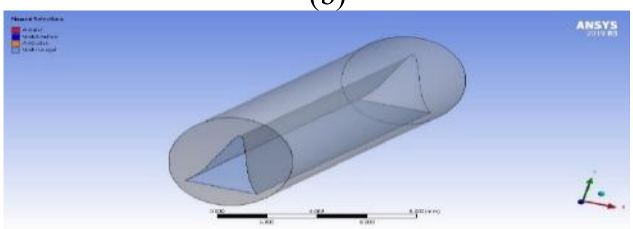
The CAD model for different desiccant channel geometry is prepared for simulation has been developed in ANSYS CFX design modeler as shown in Fig,6.



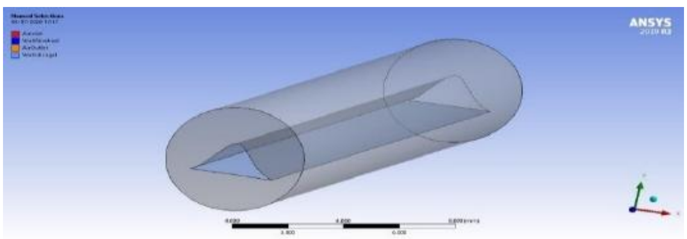


(a) (b)





(c) (d)



(e)

Fig.6 CAD models of (a)-Triangular, (b)-Square, (c)-Hexagonal, (d)-Sinusoidal-1, (e) -Sinusoidal-2 channel geometries.

Table.2 Operating parameters are taken for simulation of different channel geometry of the desiccant wheel.

Parameters		**Parametric variation**	**Base value**
1) Inlet parameters for supplying indoor air to geometries.			
	Inlet air velocity u(m/s)	0.5-8	3
	The process air inlet temperature (°C)		**25**
	RH of air for indoor conditions (%)		**50**
	Silica gel temperature T(°C)		50
2) Inlet parameters for supplying outdoor air to geometries. Monthly average ambient condition taken for simulation.			
June	Inlet air velocity(m/s)	0.5-8	3
	The inlet temperature of process air(°C)		**35.8**
	RH of air for indoor conditions (%)		**60.5**
	Silica gel temperature(°C)		50
August	Inlet air velocity(m/s)	0.5-8	3
	The inlet temperature of process air(°C)		**29**
	RH of air for indoor conditions (%)		**83**
	Silica gel temperature (°C)		50

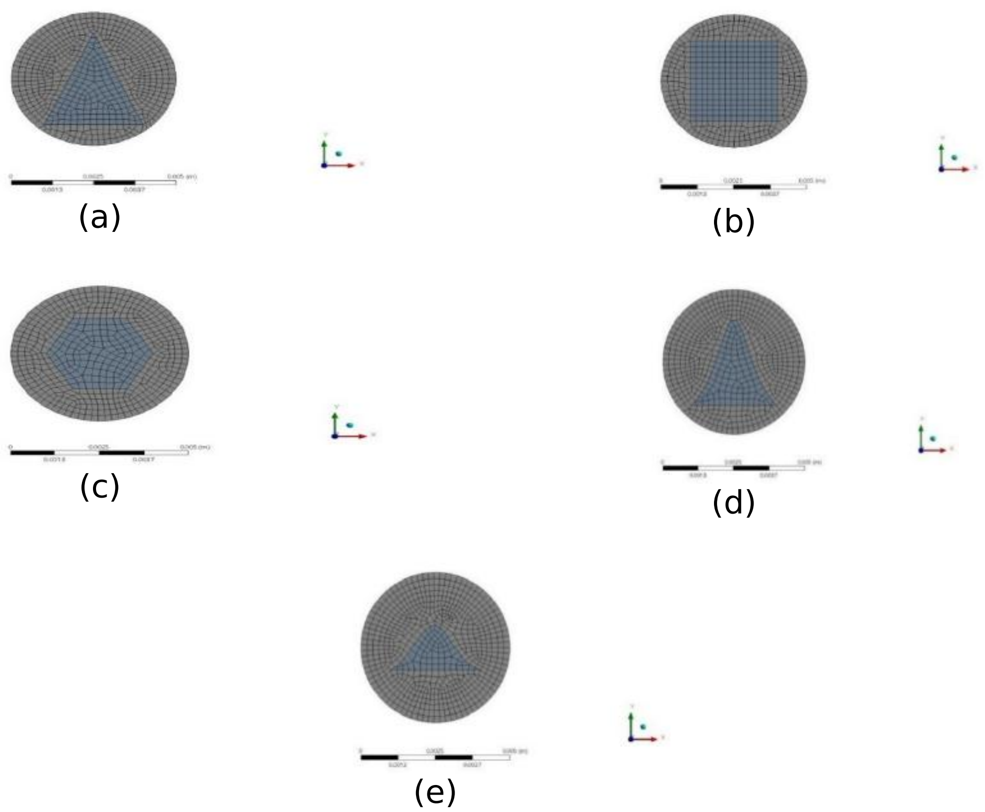
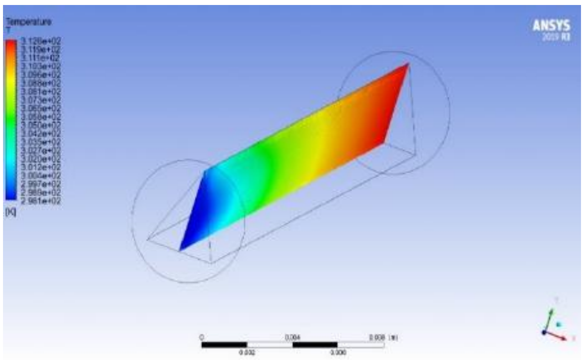


Fig.7. Meshing in computational domains for a) Triangular b) Square c) Hexagonal d) Sinusoidal-1 e) Sinusoidal-2 geometries.

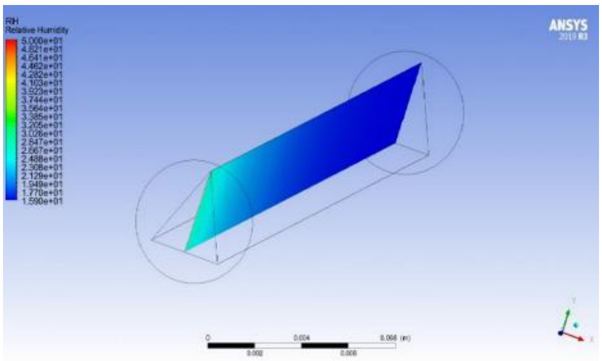
7.6 Result analysis of different channel geometries during different operating conditions.

To perform the CFD simulation on different channel geometry for various operating conditions in indoor conditions, we take the inlet operating parameters like velocity inlet of water vapor is 3m/s, the inlet temperature of water vapor is 25°C and RH is 50%. The pressure outlet is to be considered as the atmospheric and porous media temperature of various desiccant channel geometries is 50°C. Fig.8 (a) and (b) represent the simulation of triangular geometry. It shows that by supplying the water vapor in triangular geometry at 25°C temperature and 50% RH, the outlet temperature of the air has been increased by 39.6°C and the RH has decreased by 15.9%. Similarly, it is observed and analysed that for all others geometry that also behave like to adsorbed moistures during the dehumidification process.

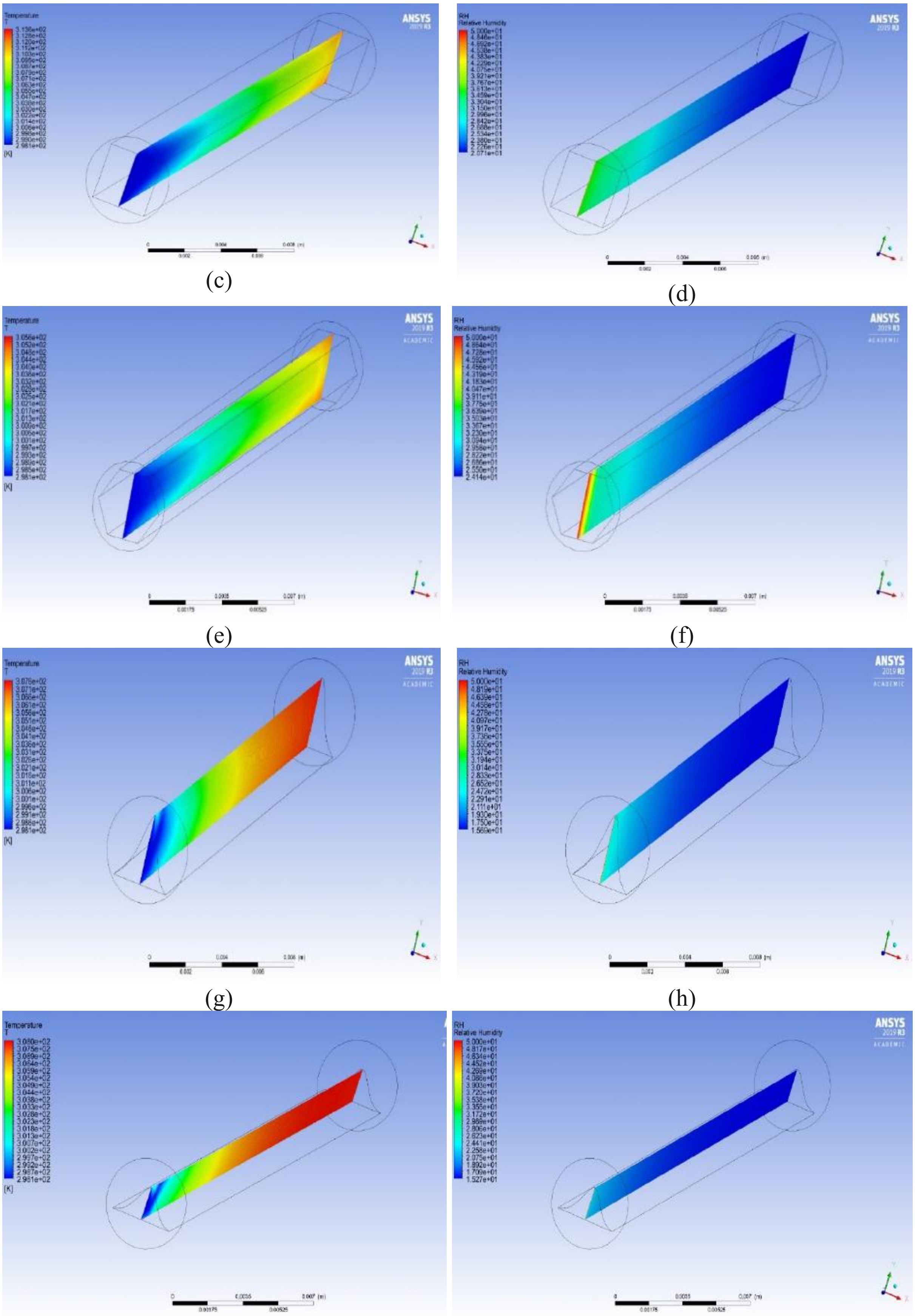
As illustrated in Fig.9, the psychometric chart depicts the simulation results for dehumidification of various channel geometries, which shows the indoor air conditions at 25°C temperature and 50% RH, as well as the outlet temperature and RH for various channel geometries. The psychometric chart gives all other parameters, like humidity ratio, specific volume, and enthalpy, etc. The humidity ratio reflected on the psychrometric chart during inlet supply conditions is 9.921g/kg, while the outcomes of humidity ratio for triangular, square, hexagonal, sinusoidal-1 and sinusoidal-2 geometries are 7.1g/kg, 9.8g/kg, 7.4g/kg, 5.4g/kg and 5.3g/kg respectively as mentioned in below Fig.8



(a)



(b)



(c) (d)

(e) (f)

(g) (h)

(i) (j)

Fig.8. Effect of temperature and relative humidity for triangular, square, hexagonal, sinusoidal-1, sinusoidal-2 geometries at 25°C temperature and 50% RH inlet operating condition.

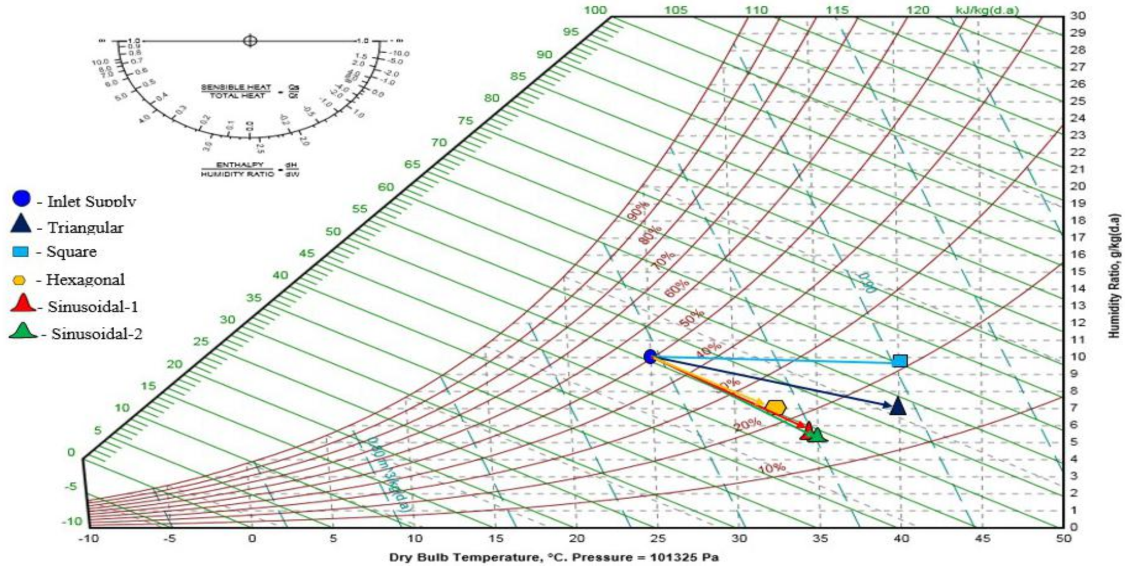


Fig.9. Psychometric representation for dehumidification process in different channel geometries for indoor supply condition.

The simulation outcomes for different out door conditions where the humidity ration has been dropped out during dehumidification process is as mentions in given below table.3& table.4

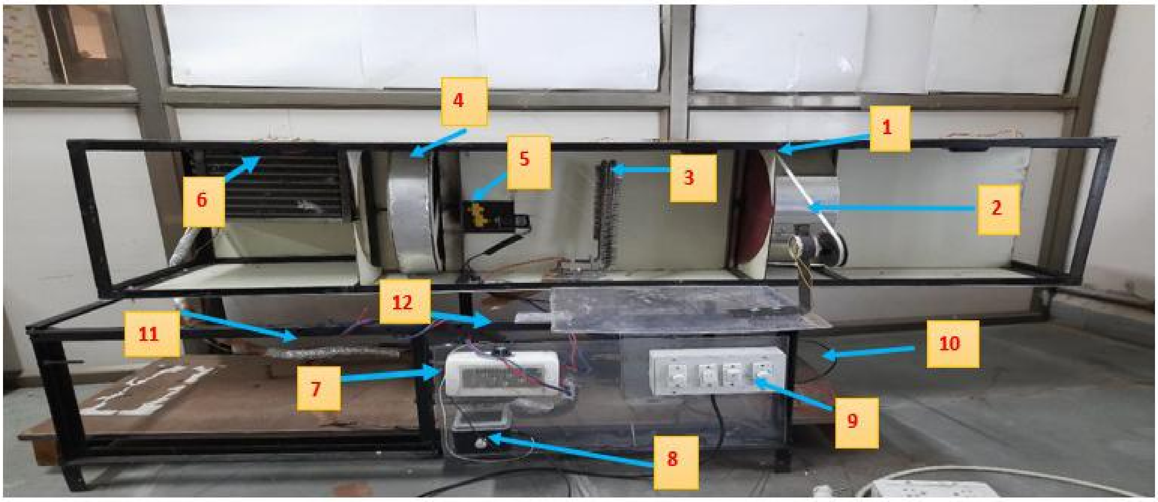
Table.3 Simulation results of channel geometries for outdoor operating condition-I.

Types of geometry	Inlet Temperature (°C)	Inlet Relative humidity (%)	Inlet Humidity ratio (g/kg)	Outlet Temperature (°C)	Outlet Relative humidity (%)	Outlet Humidity ratio (g/kg)
Triangular	35.8	60.5	22.6	48.6	16.10	11.6
Square	35.8	60.5	22.6	44.4	21.9	12.8
Hexagonal	35.8	60.5	22.6	43.1	26.48	14.5
Sinusoidal-1	35.8	60.5	22.6	49.5	10.9	8.2
Sinusoidal-2	35.8	60.5	22.6	49.9	10.29	7.9

Table.4 Simulation result of channel geometries for outdoor operating condition-II.

Types of geometry	Inlet Temperature (°C)	Inlet Relative humidity (%)	Inlet Humidity ratio (g/kg)	Outlet Temperature (°C)	Outlet Relative humidity (%)	Outlet Humidity ratio (g/kg)
Triangular	29	83	21.10	47.9	16.70	11.6
Square	29	83	21.10	42.1	25.68	13.3
Hexagonal	29	83	21.10	34.6	32.46	10.6
Sinusoidal-1	29	83	21.10	39.6	16.30	7.3
Sinusoidal-2	29	83	21.10	39.9	10.30	4.3

The actual working of hybrid desiccant cooling system represent is given below Fig.10.



1. Desiccant wheel
2. Pulley drive mechanism
3. Electric air heating coil.
4. Enthalpy wheel
5. Enthalpy wheel transmission
6. Evaporating coil
7. Dimmer heat control switch
8. Enthalpy wheel speed regulating switch
9. Desiccant wheel Suction and exhaust fan for regeneration, room air exhaust fan speed regulating switch
10. Condenser coil
11. Expansion valve
12. Compressor

Fig.10 Actual working system of hybrid desiccant cooling system

Fig.11. Actual working setup of hybrid desiccant cooling system

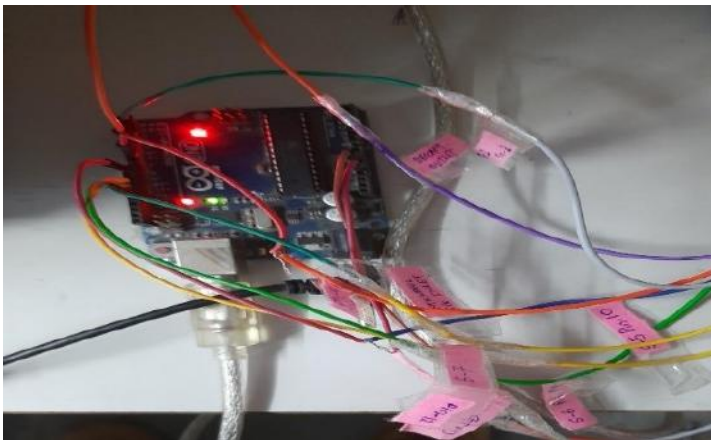


Fig.12 Arduino data receiving system

- Temperature range: -40 to 125°C (±0.5°C accuracy)
- (Relative) Humidity range: 0-100% (2-5% accuracy)
- Power: 3.3 - 6V range.

Fig.13 Digital DHT-22 sensors for humidity and temperature measurements.

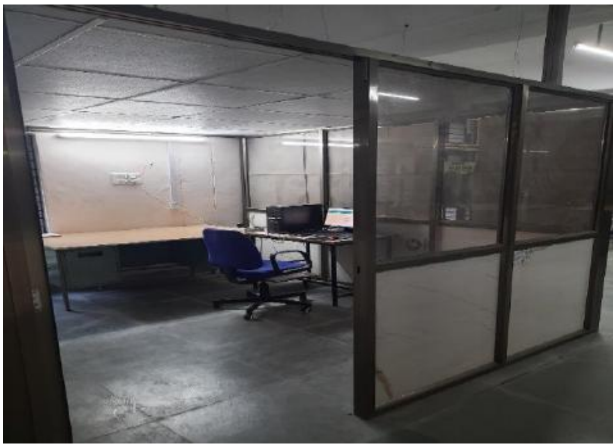


Fig.14 Test Room

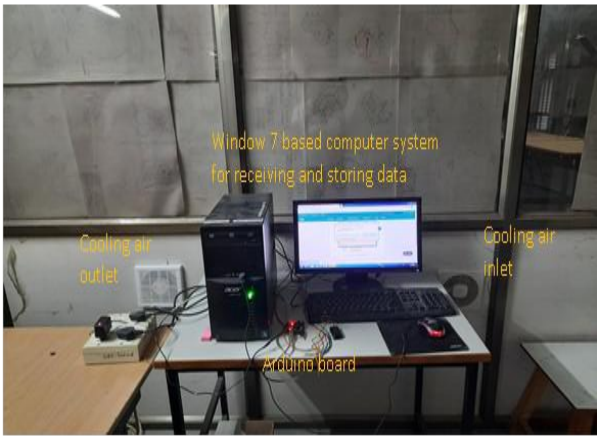
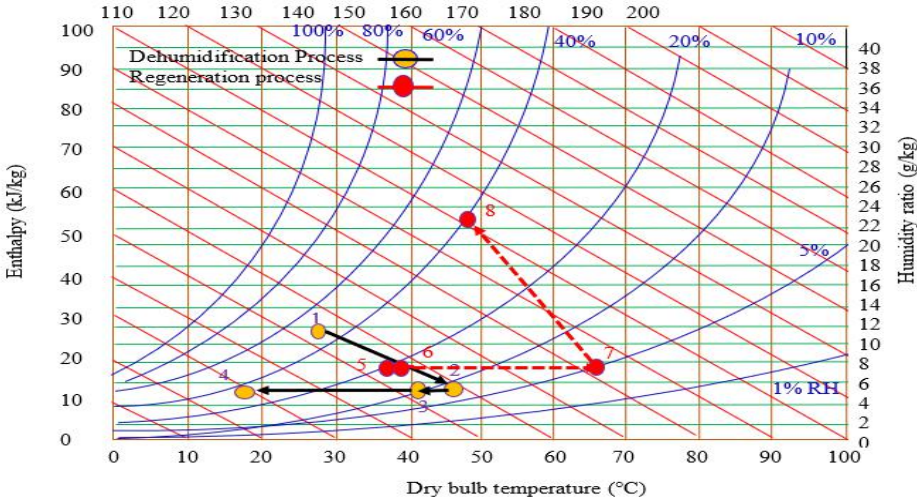


Fig.15 Experimental data collection system

PERFORMANCE OF HYBRID DESICCANT COOLING SYSTEM FOR RECIRCULATION MODE																
Operating performance parameters														Month: March		
1) Rotational speed of desiccant wheel = 90 rph														Date: 26/03/2021		
2) Rotational speed of enthalpy wheel = 20rpm														Altitude: 310m		
3) Ambient temperature = 36°C																
Desiccant Dehumidification Section																
Time in Hours	Heating Coil Regeneration Temperature (°C)	Mass flowrate(kg/hr)= 432(0.12kg/sec)														
		Enthalpy Wheel						Heating Coil			Desiccant Wheel					
		Air Inlet			Air Outlet			Air Outlet			Air Inlet			Air Outlet		
		Temp(°C)	RH (%)	Humidity ratio(g/kg)	Temp (°C)	RH (%)	Humidity ratio(g/kg)	Temp (°C)	RH (%)	Humidity ratio(g/kg)	Temp (°C)	RH (%)	Humidity ratio(g/kg)	Temp (°C)	RH (%)	Humidity ratio(g/kg)
9.00 am	50	25	50	9.88	36	21	7.8	36	21	7.8	35	22.5	7.8	21	50	7.8
10.00 am	50	27	50	11.1	43	14	7.3	43	14	7.3	37	19.5	7.3	20	50	7.3
11.00am	55	26	56	11.8	45	10.5	6.3	45	10.5	6.3	40	14	6.3	18	49	6.3
12.00am	55	26	56	11.8	45.5	8.6	5.4	45.5	8.6	5.4	41	11.3	5.4	16	48	5.4
13.00pm	65	25	54	10.7	46	8.7	5.5	46	8.7	5.5	42	10.7	5.5	16	49	5.5
14.00pm	65	26	55	11.6	47	8.5	5.6	47	8.5	5.6	42	11	5.6	15.8	49	5.6
15.00pm	70	26	53	11.1	49	7.8	5.4	49	7.8	5.4	43	10	5.4	15.2	50	5.4
16.00pm	70	26	53	11.1	50	7.4	5.5	50	7.4	5.5	44	9.5	5.5	16	49	5.5
17.00pm	75	25	56	11.8	52	7.6	5.9	52	7.6	5.9	46	9.5	5.9	17	49	5.9
18.00pm	75	26	54	11.3	55	6.5	6.2	55	6.5	6.2	47	9.3	6.2	17.5	50	6.2

PERFORMANCE OF HYBRID DESICCANT COOLING SYSTEM FOR RECIRCULATION MODE						
Operating performance parameters						Month: March
1) Rotational speed of desiccant wheel = 90 rph						Date: 26/03/2021
2) Rotational speed of enthalpy wheel = 20rpm						Altitude: 310m
3) Ambient temperature = 36°C						
Desiccant Regeneration Section						
Time in Hours	Mass flowrate(kg/hr) = 288 (0.08kg/sec)					
	Enthalpy Wheel		Heating Coil	Desiccant Wheel		
	Air Inlet	Air Outlet	Air Outlet	Air Inlet	Air Outlet	

	Temp(°C)	RH (%)	Humidity ratio(g/kg)	Temp (°C)	RH (%)	Humidity ratio(g/kg)	Temp (°C)	RH (%)	Humidity ratio(g/kg)	Temp (°C)	RH (%)	Humidity ratio(g/kg)	Temp (°C)	RH (%)	Humidity ratio(g/kg)
9.00 am	33	22	6.9	33	22.5	6.9	50	9	6.9	50	9	6.9	42	19	9.7
10.00 am	35	21	7.3	36	20	7.3	50	10	7.3	50	10	7.3	41	22	10.7
11.00am	35	20	7	35	20	7	55	7.3	7	55	7.3	7	40	28	13
12.00am	36	20	7.4	36	20	7.4	55	7.7	7.4	55	7.7	7.4	41	29	14.2
13.00pm	37	20	7.8	37.5	19.5	7.8	65	5	7.8	65	5	7.8	48	33	23.5
14.00pm	38	20	8.3	38.5	19.7	8.3	65	5.4	8.3	65	5.4	8.3	51	30	24.8
15.00pm	38	20	8.3	40	18	8.3	70	5	8.3	70	5	8.3	56	25	26.4
16.00pm	37	20	7.8	40	17	7.8	70	4	7.8	70	4	7.8	59	20	24.3
17.00pm	35	22	7.7	37	19.3	7.7	75	3.8	7.7	75	3.8	7.7	62	18	25.1
18.00pm	35	22	7.7	37	19.3	7.7	75	3.8	7.7	75	3.8	7.7	64	17	26



State point 1- 2. Adsorption process in desiccant wheel

State point-2-3. Sensible cooling process in enthalpy wheel.

State point-3-4. Evaporative cooling process in evaporative cooling coil.

State point 5-6. Sensible heating process in enthalpy wheel.

State point 6-7. Heating of regeneration air in heating coil.

State point 7-8. Desorption process in desiccant wheel

Fig.16 Adsorption and desorption process for recirculation system at 65°C regeneration temperature @ 1.00pm.

8. Achievements with respect to defined objectives

Objectives defined	Objective achieved
To conduct cooling load analysis of office cabin available at Government Engineering College Dahod based on sensible and latent heat load.	➢ Site has been selected for experimentation. ➢ Total sensible and latent load have been calculated. ➢ Found out total cooling load needs for the office cabin. ➢ Dimensions of desiccant wheel found from the estimated cooling load calculations. ➢ Published review paper in SCOPUS Indexing journal after literature review completed. ➢ Published review paper on simulation study in SCI indexing journal.
To analyze different types of desiccant dehumidifier channel geometry with different operating performance parameters through	➢ Study and learned simulation software and identified the suitable software with outcome accuracy in desiccant cooling. ➢ Prepared models of various channel geometries

CFD using Ansys-CFX and to compare the simulation results with experimental trends.	utilized in desiccant wheel in ANSYS CFX. ➢ Completed grid independency study and optimized effective and suitable grids used for different desiccant geometries. ➢ Performance have been completed for different channel geometry using ANSYS CFX on different operating climatic conditions for Dahod, Gujarat. ➢ Published SCI paper on performance analysis on different channel geometry using CFD.
Experimental investigation on performance of desiccant dehumidifier at different operating parameters like low humidity and high temperature ranges, high humidity and low temperature ranges of hybrid desiccant cooling system.	➢ Prepared hybrid desiccant cooling system experimental setup. ➢ Different regulating and operating controlled devised has been identified and connected for experimentations. ➢ ARDUINO UNO based computer-controlled data acquisition system has been established for receiving all data from dehumidification section, regeneration sections and from office. ➢ After successful testing of the system then started performance for hybrid desiccant cooling system. ➢ The performance conducted with different regeneration temperature at different mode of operation like recirculation mode and ventilation mode. ➢ The performance conducted during all seasons from month of March to September in different climatic conditions for city Dahod, Gujarat. ➢ Results obtained during different operating parameters for different climatic conditions have been analyzed. ➢ Performance outcomes from experimentation for different mode of operation are compared with CFD simulation results. ➢ Identified suitable mode of operation.

9. Conclusion

The CFD simulation of the adsorption cooling system using desiccant dehumidifier packed with silica gel has been successfully simulated. CFD comparison study was carried out on a different desiccant channel geometry of desiccant dehumidifier. The sinusoidal type of desiccant channel geometry was considered to have better adsorption capacity as compared to square, triangular and hexagonal types of geometry during the performance.

- ➢ The use of CFD simulation approach to simulate adsorption cooling system differs from most simulation work reported in the literature on adsorption cooling systems.
- ➢ The performance of desiccant wheel for channel geometries to came out dehumidification process was investigated using the CFD simulation technique for three different INDIAN climatic conditions: indoor air supplying conditions, outdoor

air supplying condition-I, and outdoor air supplying condition-II. The dehumidification performances obtained by CFD simulation for various geometries were found to vary in terms of temperature and relative humidity for different climatic conditions. The simulation results of various channel geometries during indoor air supply air at 25°C temperature and 50 % RH (9.921 g/kg) show that the triangular channel section gives 39.6°C temperature with a 7.1 g/kg humidity ratio, square channel had 40.6°C temperature and 9.8 g/kg humidity ratio, hexagonal 32.6°C and 7.4 g/kg humidity ratio, and sinusoidal-1 resulted in a 34.6°C temperature.

- Similarly, during outdoor condition-I, supply air at 35.8°C temperature and 60.5 % RH (22.6 g/kg) shows that the triangular channel section gives 48.6°C with 11.6 g/kg humidity ratio, a square channel gives 44.4°C temperature and 12.8 g/kg humidity ratio, a hexagonal channel gives 43.1°C temperature and 14.56 g/kg humidity ratio, and sinusoidal-1 gives 49.5°C and 8.2 g/kg humidity ratio.
- The dehumidifier performance obtained by the CFD simulation of different channels for outdoor condition-II with inlet supply of water vapor at 29°C temperature and 83 % RH (21.10 g/kg) resulted in the triangular geometry reflecting 47.9°C temperature with an 11.6 g/kg humidity ratio. A square channel has a temperature of 42.1°C and a humidity ratio of 13.3 g/kg, a hexagonal channel has a temperature of 34.6°C and a humidity ratio of 10.6 g/kg, sinusoidal-1 has a temperature of 39.6°C and a humidity ratio of 7.3 g/kg, and sinusoidal geometry-2 has a temperature of 39.9°C and a humidity ratio of 4.3 g/kg at the outlet. By comparing the CFD simulation results of different channel geometries during different operating conditions, it is observed that the sinusoidal geometries were found to be the most effective in dehumidification as compared to all the other types of geometries under various climatic conditions.
- The simulation has been tested for capability of simulating adsorption system heat transfer and moisture removal capacity. A comparison of simulated results and experimental data proves that the CFD simulation model is a reliable tool. Due to the improvement in porous media CFD simulation, the water vapor uptake or off-take of the adsorbent beds can now be accurately simulated in terms of heat transfer and porous adsorbent bed design.
- Using CFD simulation the time and cost of designing an adsorption cooling system could be reduced as it provides valuable prediction for component performances with minor modification.
- The hybrid desiccant cooling system ensured an improved performance in cool and humid climatic conditions with a significant reduction in humidity ratio of the process air from 12 (g_{water} / $kg_{dry\ air}$) to 5.4 (g_{water} / $kg_{dry\ air}$) during recirculation mode

and from 13.4(g $_{water}$ / kg $_{dry\ air}$) to 5.6 (g $_{water}$ / kg $_{dry\ air}$) during ventilation mode when it passes through the rotary desiccant dehumidifier.

- For a fixed outdoor condition by increasing the regeneration air temperature from 50°C to 75°C, the dehumidifier effectiveness increases from 0.33 to 0.52 during recirculation mode while 0.13 to 0.48 during ventilation mode. Therefore, recirculation mode of operation is suitable for all climatic conditions.

10. **Details of papers presented in conferences and published in journals arising from Thesis**

Sr. No	Title	Publishers	Impact Factor
1	Progressive development in solid desiccant cooling: a review	International Journal of Ambient Energy, Received 08 Jun 2019, Accepted 08 Oct 2019, accepted author version posted online: 17 Oct 2019, Published online: 31 Oct 2019 DOI: 10.1080/01430750.2019.1681293 Taylor & Francis (SCOPUS Journal)	3.5
2	Performance analysis of desiccant dehumidifier with different channel geometry using CFD.	Journal of Building Engineering Volume 44, December 2021, 103021 https://doi.org/10.1016/j.jobe.2021.10 3021 Elsevier Publication (SCI Journal)	5.318
3	A review on use of TRNSYS as simulation tool in performance prediction of desiccant cooling cycle.	Journal of Thermal Analysis and Calorimetry 140, 2011–2031 (2020). https://doi.org/10.1007/s10973-019-08968-1J Springer publication (SCI Journal)	4.626
4	A paper entitled "A comparative study of different geometry of Rotary Desiccant Dehumidifier"	has been published at Multi-disciplinary International Conference on GTUCON19 in engineering theme: scientific revolution through Engineering and Technical Research Organized by GTU- School of Engineering and Technology.	International Conference
5	A review on Mathematical modeling for Rotary Desiccant Dehumidifier	International Journal of Innovative knowledge concept, Published: 2018-09-27ISSN: 2454-2415 Vol. 6, Special Issue 2, 2018 DOI 11.25835/IJIK-270 www.doie.org	UGC Approved
6	Comparative Study of Heat &Energy Wheels	IJSRD -International Journal for Scientific Research & Development| Vol. 6, Issue 08, 2018| ISSN (online): 2321-0613	UGC Approved

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