Integration of Dedicated Outdoor Air Systems – Recommended Options for Various Climatic Conditions of India

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Abstract

Dedicated Outdoor Air Systems, DOAS, are increasingly being considered in air-conditioning for providing better Indoor Air Quality, IAQ, and reducing energy consumption. DOAS can be designed to handle all or part of the space latent loads along with some part of sensible load. DOAS usually operate along with some other sensible cooling equipment, mainly Variable Refrigerant Flow, VRF system, Radiant Panels, RP, Chilled Beams, CB, or conventional Fan Coil Units, FCU. Non-compressor based DOAS options are investigated to optimally integrate them with various existing conventional air-conditioning systems. VRF systems have emerged as one of the energy efficient HVAC options in recent years, therefore judiciously combining DOAS with VRF system is investigated. The paper lists various configurations of DOAS and recommends best option for energy efficient and cost effective integration with balance air conditioning system. A novel versatile DOAS hardware configuration, with fewer components is introduced and investigated for suitability for various Indian climatic conditions. Best configurations for year round operation in different climatic conditions of India are suggested. Energy savings offered by the new patented DOAS configuration is 20 to 30% higher than conventional cross-flow based DOAS.

Keywords

Non-compressor DOAS, Indirect Evaporative Cooling, Liquid Desiccant Dehumidification, DOAS Configurations, Total Heat Exchangers

1. Introduction

After the introduction of ASHRAE Standard 62.1 ventilation requirements have increased, in order to maintain proper indoor air quality. One of the options of meeting the increased loads without commensurate increase in energy consumption is to treat the outdoor air separately using a Dedicated Outdoor Air System, DOAS.

Sensible and latent loads of outdoor air are usually higher than that of the recirculating air loads per unit air flow. Using DOAS to pre-treat this air before mixing with the return air or introduction in the conditioned space helps reduce compressor power in a compressor based DOAS. This is due to the fact that significant latent load and part of the sensible load is handled by DOAS using an evaporator operating at higher evaporator temperature, as compared to that used for dehumidifying the return air using a conventional VAV, VRF units, etc. with direct fresh air inlet.

A non-compressor based DOAS can be deployed to further reduce the total load to avoid a significant portion of the load due to outdoor air by recovering the cooling/dehumidification or heating /humidification potential of the air being exhausted from the conditioned space.

One of the options is to deep dehumidify the outdoor air to such an extent that the treated supply air can handle the entire latent load from the conditioned space. This opens up the possibility of optimally coupling Radiant Panels, RP, Chilled Beams CB, Variable Refrigerant Volume Systems, VRF, to minimize the overall energy consumed while catering the total cooling load. In this option, the evaporator of the DX RP, CB, VRF system can operate at higher temperature, 16 to 18°C, or use higher temperature chilled water, 16 to 21°C. These temperatures are higher than the usual DX evaporator operating temperature of 7.2°C or the chilled water supply and return temperature of 7°C and 12°C.

Direct expansion, DX systems such as packaged units or VRF collectively handle sensible and latent load. Normally, Sensible Heat Ratio (SHR) for these systems is 0.6 to 0.8 while design SHR for coils handling 100% outdoor air is 0.4 or even lesser in hot and humid climate. This makes DX systems overdesigned for sensible cooling and under designed for latent cooling. Also, during part load efficiencies compressors in DX system operate at fast cycles resulting in increase in humidity of the conditioned space. It has to be noted that sensible and latent loads might not peak at same time. Due to recent advances in good roof insulation, reduced windows heat transfer coefficients, increased solar shading and energy efficient lighting, sensible load has seen a drastic reduction. Latent loads which are mainly due to ventilation/infiltration and occupant has not seen such major reduction. So, equipment with high SHR have not been able to effectively control humidity in the space. This problem asserts need for decoupling of sensible and latent loads for exactly meeting air conditioning requirement or deploying sub-systems which are capable of handling significant variations in the SHR. One such sub-system is a heat pump dehumidifier with variable hot water recovery deployed after the cooling dehumidification coil in AHUs.

There can be various choices for this air conditioning system, variable refrigerant flow, VRF systems, RPs, CBs, FCUs and packaged unitary equipment. Most of the literature focuses on integration of DOAS with radiant panels. Compared to VAV systems, ceiling mounted RPs come in compact size, but are costly at this time. RPs require less maintenance due to absence of any moving parts, but humidity control in the space has to be closely controlled in tune with the supply chilled water temperature.

Mumma, (2002) addresses the concerns of condensation, cooling capacity and cost and concludes that, when properly designed, these concerns cannot be an excuse for rejecting radiant panels. Several literatures about radiant panels maintain that even though initial cost of radiant panels are higher, operating costs go down resulting in least life cycle cost compared to VAV system.

Rane et al. (2014) disclose a simple significantly cheaper yet versatile RP configuration which allows condensation. It is deployed on the walls and beams in place of the ceiling. Condensed water drains out through a narrow collection channel. These panel heat and mass exchangers offer very high heat and mass transfer surface area per unit projected area, ~12 m^2/m^2 projected area. This along with higher heat transfer coefficient due to condensation of moisture enable these panels to transfer 1 TR cooling/dehumidification load using 1.8 m^2 panel frontal area. This is significantly smaller than 20 to 40 m^2 panel area required to dispense 1 TR of sensible cooling duty using most of the commercially available RPs. Another advantage of these novel RPs is that they can be operated in DX mode both for cooling/dehumidification and heating. Cost of these RPs is only about INR 10,000/TR.

VRF systems have emerged as energy efficient HVAC systems in recent years, due to the application of inverter driven variable speed compressors in it is outdoor units, which offer good part load efficiency. Combining DOAS with VRF can be a potential option for future HVAC system. Appropriate combination of DOAS and VRF system can be superior in terms of thermal comfort and life cycle cost. For any choice of sensible cooling equipment, knowledge of proper integration strategies of DOAS with these systems is essential for energy efficient operation.

2.1 Ventilation for VRF

Since VRF systems work on principle of direct expansion, these system raise question of ventilation. As in conventional air handling units, fresh air cannot be mixed with recirculated air (except in some indoor units where limited provision of fresh air supply is feasible) and supplied to conditioned space. Therefore, a separate fresh air supply is needed along with VRF system. In many non-critical applications infiltration air is considered enough for fresh air requirement. However, with strict ventilation codes (ASHRAE Standard 62.1) being introduced in recent years and new building design techniques making buildings air tight, a separate fresh air supply is a must to maintain proper indoor air quality. Design of energy efficient ventilation system, which reduces ventilation load without compromising indoor air quality, is need of today's HVAC industry.

Different VRF manufacturers have come up with energy efficient methods of ventilation that can be integrated with VRF system. Most manufacturers use a typical ERV method that consists of a cross-flow type core with specially processed paper or membrane based total heat exchanger. This paper is capable of performing heat as well as moisture transfer. Depending on airflow capacity and mode of operation, temperature exchange efficiency of these heat exchangers varies from 72 to 88% and enthalpy exchange varies from 58 to 83%. Some systems incorporate ERV with DX cooling coil that can appropriately condition the outdoor air to desired conditions. Again, depending on different conditions of airflow and operation mode, temperature exchange efficiency varies from 72 to 87% and enthalpy exchanger efficiency varies from 60 to 69%. Heating and humidification is achieved by using a DX expansion coil (operating in heating mode) and a humidifier element.

Besides this, various other techniques are applied for energy efficiency. By pass mode is a commonly used technique where, in favourable conditions, outdoor air is directly brought into the conditioned space for energy efficiency. CO_2 sensor is used to regulate airflow into the conditioned space. Ventilation air is either adjusted or completely switched off when CO_2 concentration is within the desired limit. This is especially useful in applications with large fluctuations in occupant density.

2.2 Series and Parallel Arrangement of Terminal Equipment

It is evident that DOAS require additional balance load handling cooling equipment for handling partial or total latent and sensible load. Mainly, there are two ways of connecting DOAS with terminal equipment: series and parallel. In series connection, treated fresh air from DOAS is supplied to balance load handling units where recirculated air from these units and treated fresh air from DOAS is collectively supplied to conditioned space. In parallel connection treated fresh air from DOAS is supplied directly to conditioned space. Radiant panels and chilled beams/ceilings can be connected only in parallel to DOAS.

Some advantages of using parallel combination are:

a. There is decrease in initial and operating cost due to downsizing of fan. Since balance load handling equipment has to handle only recirculation air, its fan size is reduced compared to series connection which results in lesser pressure drop across the fan.
b. Cooling coil in terminal units is not de-rated as it handles only warm recirculation air.

c. Balance load handling equipment may be shut-off during low sensible load conditions.

3 Components of DOAS

Components of a typical commercially available DOAS system using desiccant wheels is represented in *Figure 1*.

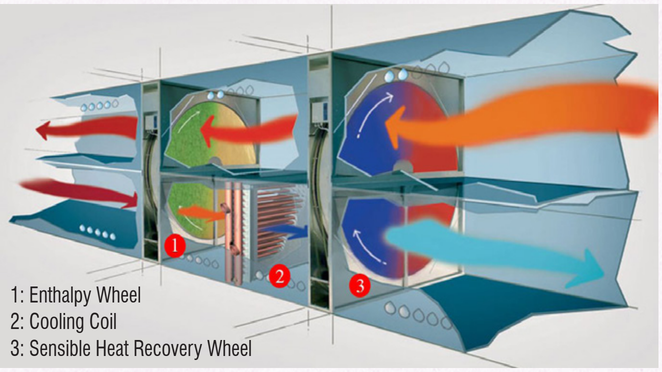


Figure 1: Typical Two Stage Solid Desiccant based DOAS (http://in.ostberg.com)

3.1 Total Heat Exchanger

Total heat exchanger is capable of handling sensible as well as latent loads. It can be an enthalpy wheel or a membrane based total heat exchanger that is typically processed paper based. Enthalpy wheel consists of sensible heat exchange device coated with desiccants to allow heat and moisture transfer. Total heat exchanger is a good energy saving option in hot and humid climate. It reduces the cooling capacity requirement of subsequently used cooling coil. It has to be noted that total heat exchangers cannot be used if entering outdoor air has less enthalpy than exhaust air, as in this case it will further increase load on the cooling coils. Total energy recovery units normally have effectiveness value ranging from 0.6 to 0.8, Mumma, (2007). ASHRAE Standard 90.1-2007 Section 6.5.6.1 requires use of total heat recovery of effectiveness of at least 50% for fan flow rate of 2400 l/s or higher when supplying air at 70% or greater of design air quantity.

3.2 Sensible Heat Exchanger

Sensible heat exchanger is capable of exchanging sensible heat only. In all DOAS configurations, sensible heat exchange device is placed after the cooling coil. After dehumidification in cooling coil there is sensible heat exchange between supply air and return air, preheating supply air before entering the conditioned space. Sensible heat exchange devices can be avoided when air can be supplied at low temperature (below 13°C) and saturated directly into the conditioned space. Normally, air can be supplied cold except in cases of conditioned space being at high occupant density, where cold ventilation air results in overcooling.

3.3 Cooling Coil

Cooling coils are used to cool and dehumidify air to handle the entire latent load and some portion of sensible load. Sensible cooling of outdoor air reduces cooling requirement of balance load handling equipment. Cooling coils can be operating in DX system or chilled water circulation. In DOAS primary function of cooling coil is to dehumidify the air and not to cool it. In hot and humid climates sensible heat ratio (SHR) for outdoor air is 0.4 to 0.2 or even lesser. Therefore, cooling coil should operate in very low SHR. If air flow in these systems can be drastically reduced or coil bypass technique applied such that coil surface temperature goes down significantly, low SHR can be achieved.

3.4 Desiccant Dehumidification

Compressor based dehumidification is energy intensive because process air has to be cooled below its DPT and sometimes reheated to ensure comfortable supply of indoor air. Dehumidification through desiccants can be a potential alternative to these dehumidification systems. As a rule, desiccant systems are generally better choice if DPT is below 4°C, Mumma (2001). Desiccant systems are energy efficient because they allow direct expansion systems to work at higher evaporator temperature.

a. *Solid Desiccant Dehumidification*: Activated alumina, silica gel, zeolites are some example of solid desiccants. Solid desiccant dehumidification and regeneration is an adiabatic process.

b. *Liquid Desiccant Dehumidification:* Lithium chloride, lithium bromide, calcium chloride, potassium formate solutions are examples of liquid desiccants. Liquid desiccant system can be adiabatic or diabetic. Internally cooled diabetic liquid desiccant system is better than adiabatic system. Liquid desiccant can be regenerated by low grade heat sources.

The desirable properties of liquid desiccants are:

a. Ideal liquid desiccant should have low vapour pressure for dehumidification.
b. Higher working range of the desiccant concentration is desirable.
c. Desiccant should be non-toxic, non-corrosive, odourless and non-flammable.
d. Liquid desiccant solutions should have low crystallization temperature at working concentration.

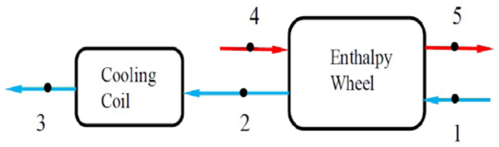
Potassium formate, KCOOH, solution promises to be a good liquid desiccant. It has wide range of operation 20 to 75% concentration, it has low crystallization temperature 1°C at 70% concentration and is compatible with MS, Al, SS, Cu and brass (Mehta 2009).

4. DOAS Configurations for Integration with HVAC System

Research on integrating DOAS with sensible cooling equipment has focussed on strategies for dehumidifying outdoor air to such extent that it is capable of handling the entire latent load. This allows DX parallel equipment like VRF system to work at higher evaporator temperature resulting in high COP.

Different configurations suggested by various researchers are summarized here. Description, advantages and limitations of each configuration are discussed along with its schematic and psychrometric representation.

4.1 Enthalpy Wheel Along with Cooling Coil (EW+CC)



State Points

1 Outdoor air
2 Outdoor air after enthalpy exchange with indoor air
3 Supply air
4 Indoor air
5 Exhaust air

Processes

1-2 Cooling and dehumidification of fresh air by EW
2-3 Cooling and dehumidification of fresh air by CC
3-4 Fresh air supply in conditioned space
4-5 Heating and humidification of exhaust air by EW

a. Advantages

i Total heat exchange reduces energy requirement of cooling coil.

ii Cold supply air reduces sensible cooling requirement on sensible cooling system.

iii When handling only sensible load VRF system operates at higher evaporator temperature which increases COP of the system

b. Limitations

i In direct expansion dehumidification, air has to be cooled much below its DPT for deep dehumidification. This is energy intensive process.

ii Not applicable where air cannot be supplied at low temperature (below 13°C) directly into conditioned space.

c. Applications

i Suitable for hot and humid climate

ii Indoor applications with moderate latent load like residential and commercial buildings.

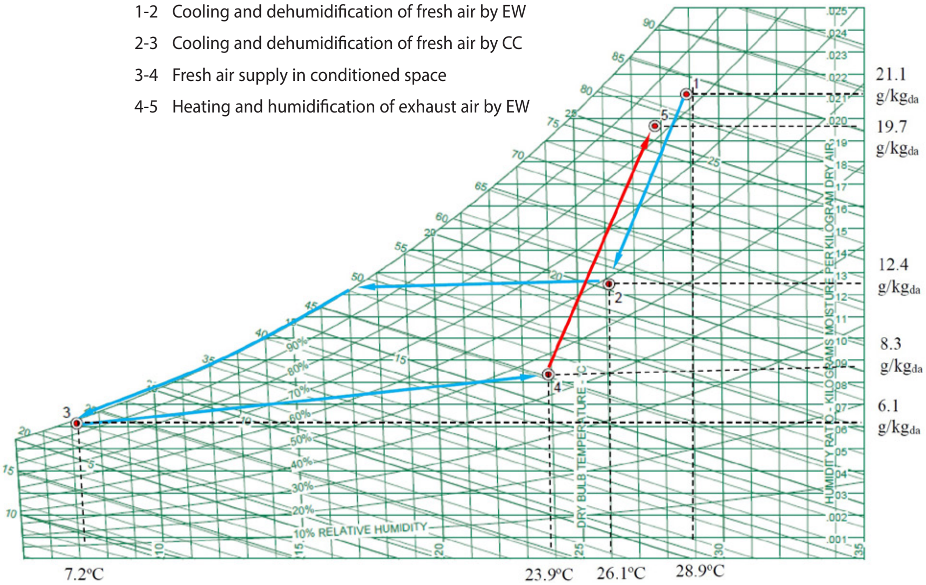
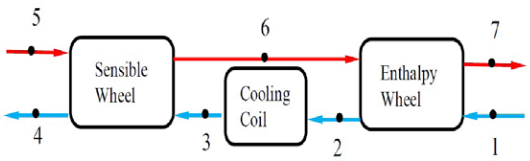


Figure 2: Psychrometric Representation of EW+CC (Mumma, 2001)

4.2 Enthalpy Wheel Along with Cooling Coil and Sensible Wheel (EW+CC+SW)



Processes

1-2 Cooling and dehumidification of fresh air by Enthalpy Wheel
2-3 Cooling and dehumidification of fresh air by Cooling Coil
3-4 Sensible heating of fresh air by Sensible Wheel
4-5 Fresh air supply in conditioned space
5-6 Sensible cooling of exhaust air by Sensible Wheel
6-7 Heating and humidification of exhaust air by Enthalpy Wheel

a. Advantages

i Reheating required in certain applications is available for free.

b. Limitations

i Compared to (EW+CC) combination there is an additional initial and operating cost of sensible heat exchanger.

c. Applications

i Suitable for hot and humid outdoor conditions.

ii Facilities with high occupant density (relatively high latent load) where cold air supply results in overcooling like conference halls and movie theatres.

State Points

1 Outdoor air
2 Outdoor air after enthalpy exchange
3 Cooled outdoor air
4 Supply air to indoor
5 Indoor air
6 Sensible heated indoor air
7 Exhaust air to outdoor

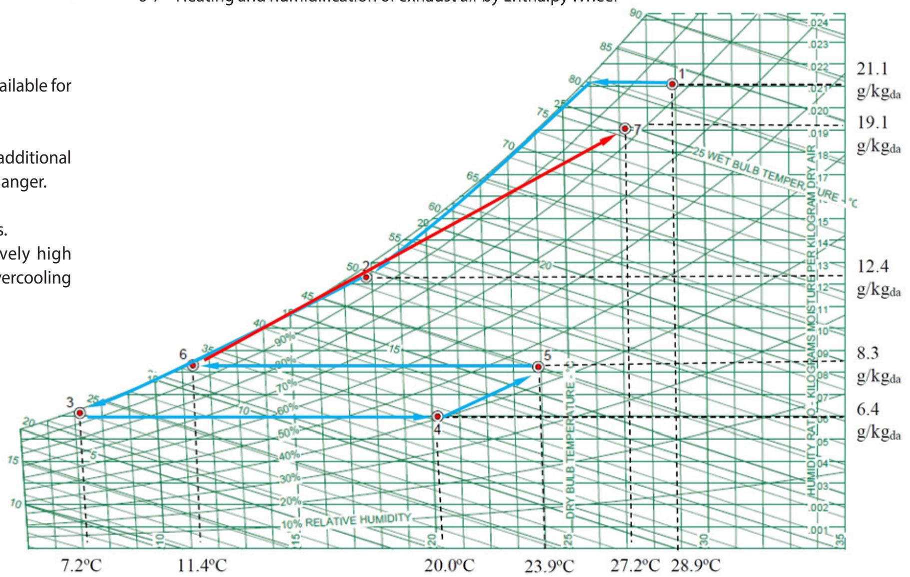
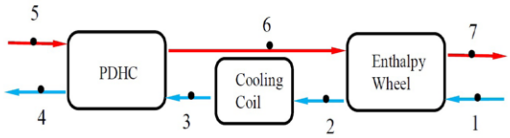


Figure 3: Psychrometric Representation of EW+CC+SW (Mumma, 2001)

4.3 Enthalpy Wheel Combined with Cooling Coil and Passive Dehumidification Component (EW+CC+PDHC)



Processes

1-2 Cooling and dehumidification of fresh air by Enthalpy Wheel
2-3 Cooling and dehumidification of fresh air by Cooling Coil
3-4 Heating and dehumidification of fresh air by PDHC
4-5 Fresh air supply in conditioned space
5-6 Cooling and humidification of fresh air by PDHC
6-7 Heating and humidification of exhaust air by Enthalpy Wheel

a. Advantages

i Since PDHC is used for dehumidification at low temperature, cooling coil can operate at higher temperature which increases its COP.

ii Since supply air dry bulb temperature is higher, no reheating is required.

b. Limitations

i Compared to (EW+CC) combination there is an additional initial and operating cost of PDHC.

c. Applications

i Suitable for hot and humid outdoor conditions.

ii Facilities with high occupant density (relatively high latent load) where cold air supply results in overcooling like conference halls and movie theatres.

State Points

1 Outdoor air
2 Outdoor air after enthalpy exchange
3 Cooled outdoor air
4 Supply air to indoor
5 Indoor air
6 Cooled and humidified indoor air
7 Exhaust air to outdoor

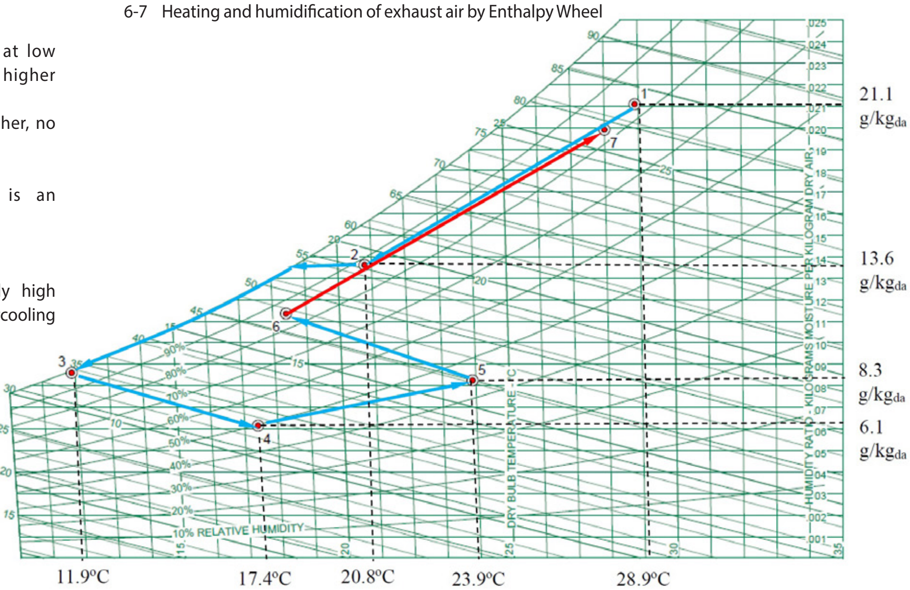
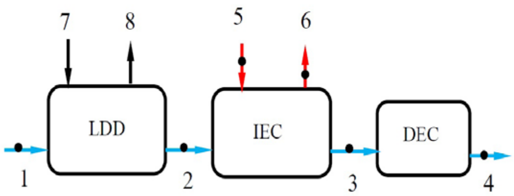


Figure 4: Psychrometric Representation of EW+CC+PDHC (Mumma, 2007)

4.4 Liquid Desiccant Combined with Indirect and Direct Evaporative Cooling (LDD+IEC++DEC)



Processes

1-2 Desiccant dehumidification of outdoor air
2-3 Cooling of fresh air by indirect evaporative cooling
3-4 Cooling of fresh air by direct evaporative cooling

State Points

1 Outdoor air
2 Outdoor air after dehumidification
3 Indirectly evaporatively cooled outdoor air
4 Supply air
5 Indoor air before IEC
6 Indoor air after IEC
7 Cold water inlet
8 Warm water outlet

Advantages

a. The system is non-compressor based.

b. Reheating is not required as in DOAS with DX cooling coil.

Limitations

a. The system lacks compactness, due to subsystems like cooling tower and regenerator.

b. Direct evaporative cooling cools fresh air increases its specific humidity hence the system is applicable for indoor conditions with no or minimum latent load.

Applications

a. Suitable for hot and humid outdoor conditions. Excluding the desiccant dehumidification system, this technique becomes suitable for hot and dry climate.

b. Due to the direct evaporative portion this DOAS is suitable to indoor applications with very low latent load. However if direct evaporative cooling portion is removed system becomes suitable to facilities with moderate latent load.

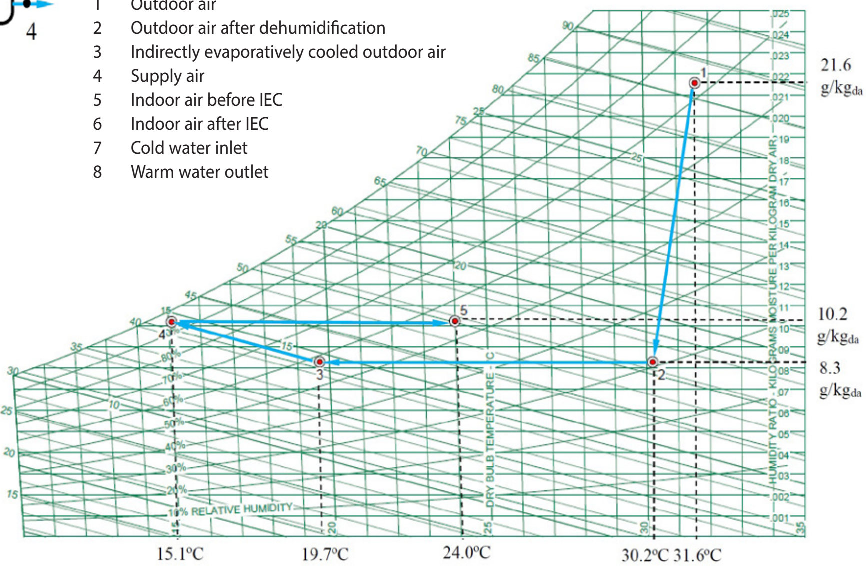
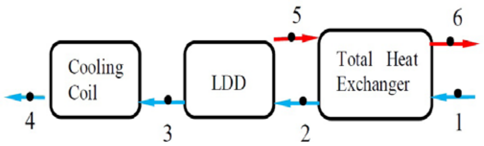


Figure 5: Psychrometric Representation of LDD+IEC+ DEC (Jeong et al., 2013)

4.5 Total Heat Exchanger Along with Liquid Desiccant Dehumidification and Cooling Coil (THX+LDD+CC)



Processes

1-2 Cooling and dehumidification of outdoor fresh air
2-3 Desiccant dehumidification of fresh air
3-4 Sensible cooling of fresh air by Cooling Coil
4-5 Fresh air supply to indoor
5-6 Heating and humidification of exhaust air

Advantages

a. Deep dehumidification through cooling coil is avoided. Cooling coil is used for sensible cooling of air from high temperature. Cooling coil operates dry such that its evaporator operates at higher temperature increasing COP.

Limitations

a. Adiabatic dehumidification heats air to higher temperatures. If diabetic dehumidification technique is applied capacity of cooling coil can come down.

Applications

a. Suitable for hot and humid outdoor conditions.
b. Indoor applications with very low latent load.
c. Most suitable for application where waste heat is available for desiccant regeneration.

State Points

1 Outdoor air
2 Outdoor air after total heat exchange
3 Outdoor air after desiccant dehumidification
4 Supply air
5 Indoor air
6 Exhaust air

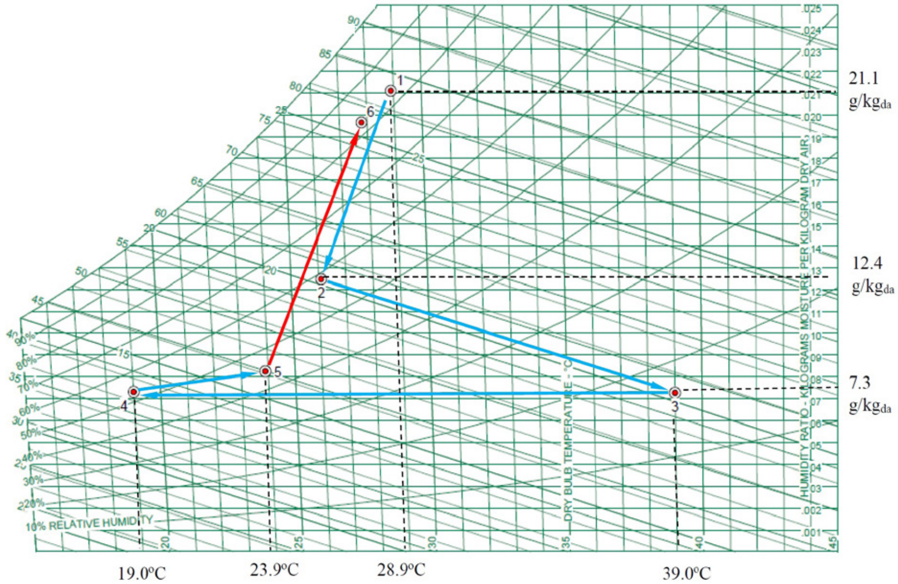


Figure 6: Psychrometric Representation of THX+LDD+CC (Ge et al., 2011)

5. Recommended Configuration

After analysis of different configurations of non-compressor based DOAS, cooling and liquid desiccant dehumidification of outdoor fresh air by indirect evaporative cooling of exhaust air is identified as a preferred option for integration with conventional air-conditioning systems. In this configuration, shown in *Figure 7*, exhaust air is evaporatively precooled before heat and mass exchange process. Fresh air is dehumidified by contacting with falling film of liquid desiccant. Heat of absorption of water vapour by the liquid desiccant is absorbed by direct dehumidification and heating of exhaust air. These processes are elaborated with sample calculations for Mumbai and Delhi in later sections and are represented on psychrometric charts in *Figure 9* and *10*.

Cooling and dehumidification of fresh air as well as direct dehumidification of exhaust air are carried out in a single compact heat and mass transfer unit. The cross section of the heat and mass exchanger element is depicted in *Figure 8*, (Rane and Chavan, 2013). Multiplicity of these elements are arranged in parallel, with Exhaust Air flowing through its passages and Fresh Air flowing through channels formed by gaps between the extrusions.

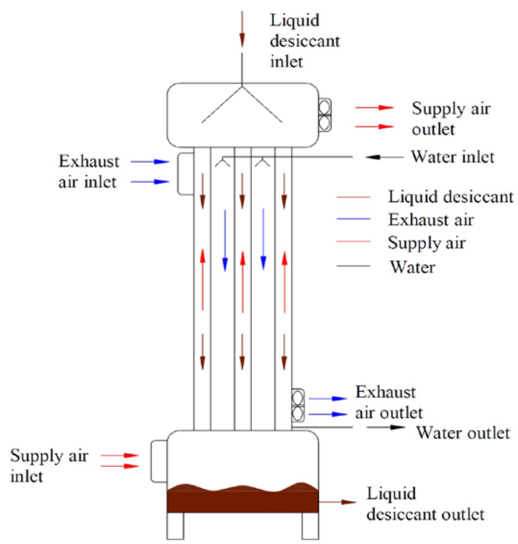


Figure 7: System Schematic for Liquid Desiccant Dehumidification of Outdoor Air by Simultaneous Indirect Evaporative Cooling with Exhaust Air

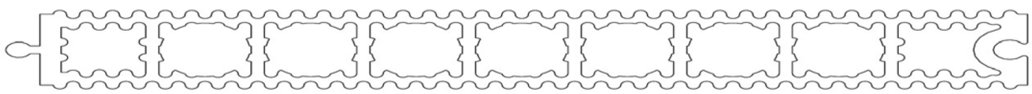


Figure 8: Patented 9 Channel Al Extrusion with Corrugated Passages Proposed for Use in Heat and Mass Exchanger for DOAS (Rane and Chavan, 2013)

Small modular DOAS can now be deployed with unitary systems including split air conditioners catering to individual rooms.

5.1 Sample Calculation

Theoretical calculations for monsoon weather conditions at 1% reliability for Mumbai are listed hereafter. While performing the analysis, following assumptions were made:

a. Direct evaporative cooling of exhaust air has humidification effectiveness of 80%.
b. Mass flow rate of fresh air inlet and exhaust air outlet is equal which is taken as 150 cfm.
c. Approach between exhaust and supply air is taken as 3°C.

Potassium formate (KCOOH) is chosen as the desiccant for the analysis. Desiccant properties are taken at specific gravity of 1.56 which is KCOOH concentration of 74% (Cabot 2014).

Outdoor Design Conditions		Indoor Design conditions	
WBT	27.4°C	DBT	27°C
MCDBT	31.0°C	rh	50%
Rh	76.03%	WBT	19.5°C
W	21.81 g/kg_{da}	w	11.19 g/kg_{da}
DPT	26.3°C	DPT	15.7°C
H	86.9 kJ/kg_{da}	h	55.61 kJ/kg_{da}

Values known from design conditions and assumptions

$t_1 = 31°C$, $t_3 = 27°C$, $t_{wb.3} = 19°C$, $h_1 = 86.88 kJ/kg_{da}$, $h_4 = 81.53\ kJ/kg_{da}$, $\boldsymbol{\varepsilon}_h = 80\%$

Temperature of indoor air after humidification

$$t_A = t_3 - \varepsilon_h (t_3 - t_{wb.3}) \quad \ldots(6.1)$$

$$= 27°C - 0.8\ (27°C - 19.5°C) = 21°C$$

Enthalpy of outdoor supply air after being cooled by humidification and heating of indoor air

$$h_2 = h_1 - (h_4 - h_A) \quad \ldots(6.2)$$

$$= 86.88\ kJ/kg_{da} - (81.53\ kJ/kg_{da} - 55.61\ kJ/kg_{da})$$

$$= 60.96\ kJ/kg_{da}$$

Corresponding DBT = 25.2°C and w = 14.02 g/kg_{da}

Total cooling provided by humidification and heating

$$Q_{12} = m_{oa}\ (h_1 - h_2) \quad \ldots(6.3)$$

$$= 0.082 kg/s\ (86.88\ kJ/kg_{da} - 60.96\ kJ/kg_{da}) = 2.12\ kW$$

Dehumidification effectiveness

$$\varepsilon_{dh} = \frac{w_1 - w_2}{w_1 - w_e} \quad \ldots(6.4)$$

$$= \frac{21.81\ g/kg_{da} - 14.02\ g/kg_{da}}{21.81\ g/kg_{da} - 8.7\ g/kg_{da}} = 59.42\%$$

<u>Quantity of water consumed</u>

Indirect evaporative cooling

$$m_{we.iec} = m_{ia}\ (w_A - w_3)$$

$$= 0.0824\ kg/s\ (13.62\ g/kg_{da} - 11.19\ g/kg_{da}) \quad \ldots(6.5)$$

$$= 0.2\ g/s = 0.72\ kg/h$$

Humidification and heating

$$m_{we.ddh} = m_{ia}\ (w_4 - w_A) \quad \ldots(6.6)$$

$$= 0.0824\ kg/s\ (20.94\ g/kg_{da} - 13.62\ g/kg_{da})$$

$$= 0.6\ g/s = 2.17\ kg/h$$

Psychrometric analysis of the DOAS for different cases in India, i.e. warm and humid (Mumbai), composite (New Delhi) conditions to demonstrate its effectiveness and energy savings are presented in *Figure 9* and *10* respectively.

6. Feasible Options for Different Indian Climate Zones

Regions having similar characteristics features in their climate are grouped under climate zones. India can be divided into six climatic zones, namely, hot and dry, warm and humid, moderate, cold and cloudy, cold and sunny and composite (http://mnre.gov.in/solar-energy/ch2.pd). Particularly mean, minimum and maximum monthly temperatures and relative humidity are considered here. A place is assigned to one of the first five climatic zones only when the defined conditions prevail there for more than six months. In cases where none of the defined categories can be identified for six months or longer, the climatic zone is called composite. According to recent code of Bureau of Indian Standards, the country may be divided into five major climatic zones. Both the cold and cloudy regions as well as cold and sunny region is viewed together as cold climate; the moderate climate is renamed as temperate climate. The applicability of this DOAS at various climate conditions is a major issue to be addressed.

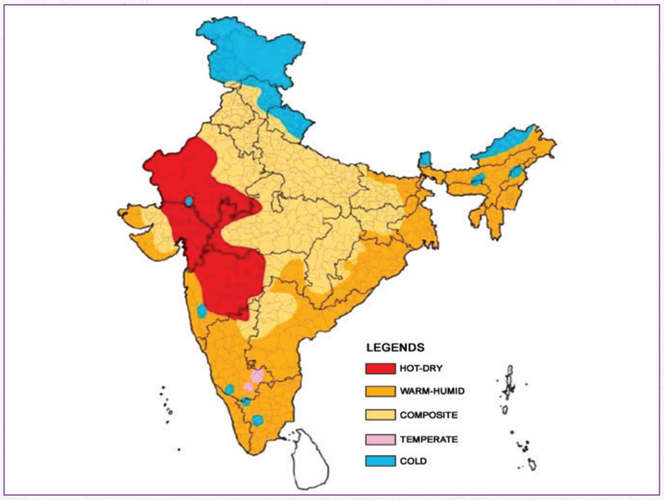
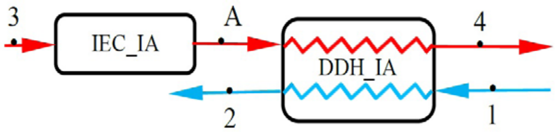


Figure 9: Climate Zones of India (http://mnre.gov.in/solar-energy/ch2.pd)

Assumptions: $\varepsilon_{humidifier}$, ε_{he} 80%, temperatures 1% reliability: $t_{1.db}$ 31°C, $t_{3.db}$ 27.4°C, volf 0.071 m³/s



Heat Interactions

$Q_{12} = mf_{oa} (h_1 - h_2) =$ **2.12 kW** $=$ 0.082 kg/s x (86.9 kJ/kg$_{da}$ – 60.9 kJ/kg$_{da}$)

$Q_{A4} = mf_{oa} (h_4 - h_3) =$ **2.12kW** $=$ 0.082 kg/s x (81.5 kJ/kg$_{da}$ – 55.6 kJ/kg$_{da}$)

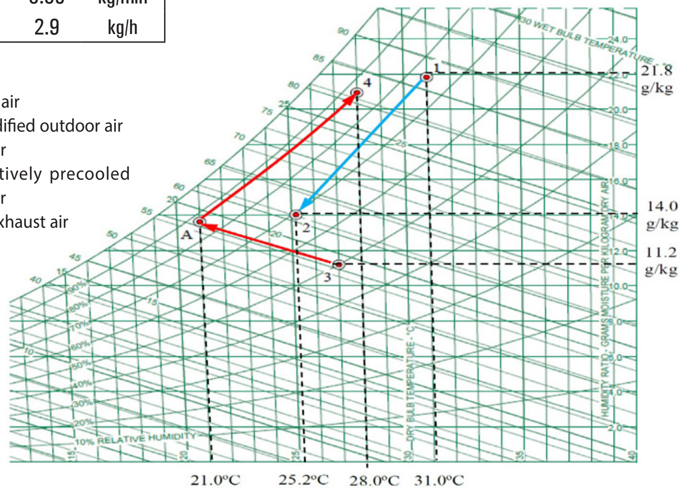
Processes

1-2 Cooling and dehumidification of outdoor fresh air
3-A Evaporative precooling of indoor air
A-4 Heating and humidification of indoor exhaust air

Specific Parameters	Units	oa 1	2	3	ia A	4	Water Consumed IEC	DHH	Total	Units
t_{db}	°C	**31.0**	**25.2**	**27.0**	21.0	28	0.20	0.6	0.8	g/s
t_{wb}	°C	**27.4**	21.0	**19.5**	19.5	26.2	0.01	0.04	0.05	kg/min
t_{dp}	°C	26.3	19.2	15.7	18.7	25.6	0.71	2.2	2.9	kg/h
ϕ, rh	%	**76.0**	69.3	**50.0**	86.9	86.9				
W	g/kg$_{da}$	21.8	14	11.2	13.6	20.9				
h	kJ/kg	**86.9**	**61.0**	**55.6**	55.6	81.5				
mf	g/s	82			82					
	kg/min	4.9			4.9					
	kg/h	295			295					
volf	m³/s	0.07			0.07					
	cfm	150			150					

State Points

1 Outdoor air
2 Dehumidified outdoor air
3 Indoor air
A Evaporatively precooled indoor air
4 Indoor exhaust air



Water Consumption

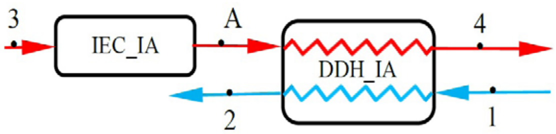
$mf_{wc} = mf_{ia} (W_4 - W_3) =$ **0.8 g/s**
= 0.082 kg/s (20.9 - 11.2) g/kg$_{da}$ = 0.048 kg/min = 2.86 kg/h

$mf_{we.dhh} = mf_{ia} (W_4 - W_A) =$ **0.6 g/s**
= 0.082 kg/s (20.9 - 13.6) g/kg$_{da}$ = 0.036 kg/min = 2.16 kg/h

$mf_{we.iec} = mf_{ia} (W_A - W_3) =$ **0.2 g/s**
= 0.082 kg/s (13.6 - 11.2) g/kg$_{da}$ = 0.012 kg/min = 0.71 kg/h

Figure 10: LD based Fresh Air Dehumidification and Cooling Using Indirect Evaporative Cooling with Exhaust Air for Mumbai

Assumptions: $\varepsilon_{humidifier}$, ε_{he} 80%, temperatures 1% reliability: $t_{1.db}$ 32.3°C, $t_{3.db}$ 29.1°C, volf 0.071 m³/s



Heat Interactions

Q_{12} = MF$_{OA}$ (H$_1$ – H$_2$) = **2.60 KW** = 0.082 KG/S X (95.1 KJ/KG$_{DA}$ – 63.5 KJ/KG$_{DA}$

Q_{A4} = MF$_{OA}$ (H$_4$ – H$_A$) = **2.60 KW** = 0.082 KG/S X (87.2 KJ/KG$_{DA}$ – 55.6 KJ/KG$_{DA}$)

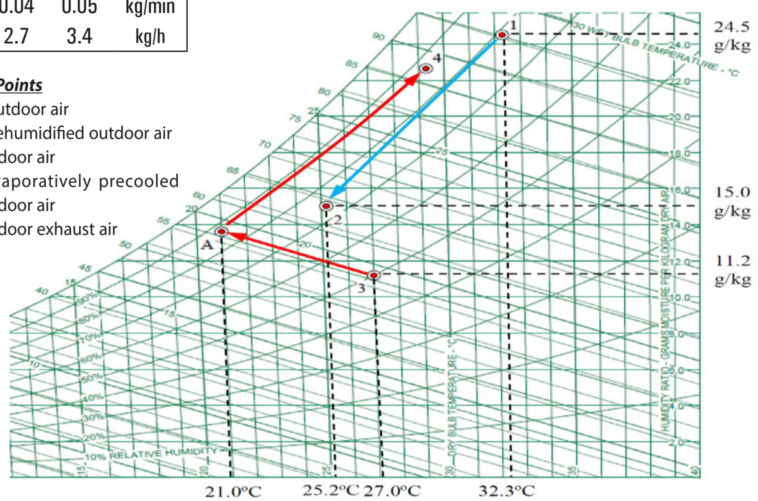
Processes

1-2 Cooling and dehumidification of outdoor fresh air
3-A Evaporative precooling of indoor air
A-4 Heating and humidification of indoor exhaust air

Specific Parameters	Units	oa 1	2	3	ia A	4	Water Consumed IEC	DHH	Total	Units
t_{db}	°C	**32.3**	**25.2**	**27.0**	21.0	29.2	0.20	0.7	0.9	g/s
t_{wb}	°C	**29.1**	21.7	**19.5**	19.5	27.4	0.01	0.04	0.05	kg/min
t_{dp}	°C	28.2	20.3	15.7	18.7	25.6	0.71	2.7	3.4	kg/h
ϕ, rh	%	**79.0**	74.2	**50.0**	86.9	86.9				
W	g/kg$_{da}$	24.5	15	11.2	13.6	22.6				
h	kJ/kg	95.1	63.5	**55.6**	55.6	87.2				
mf	g/s	82			82					
	kg/min	4.9			4.9					
	kg/h	295			295					
volf	m³/s	0.07			0.07					
	cfm	150			150					

State Points

1 Outdoor air
2 Dehumidified outdoor air
3 Indoor air
A Evaporatively precooled indoor air
4 Indoor exhaust air



Water Consumption

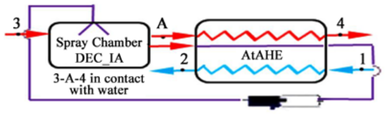
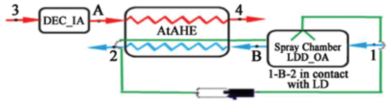
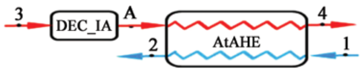
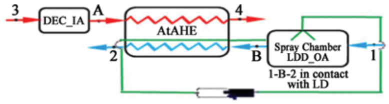
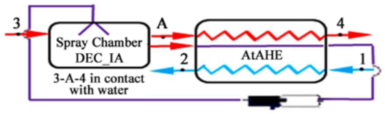
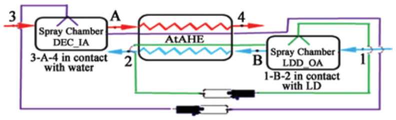
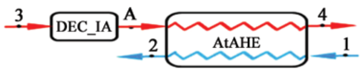
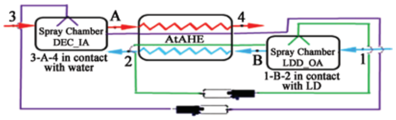
$mf_{wc} = mf_{ia} (W_4 - W_3) =$ **0.9 g/s**
= 0.082 kg/s (22.6 - 11.2) g/kg$_{da}$ = 0.056 kg/min = 3.36 kg/h

$mf_{we.dhh} = mf_{ia} (W_4 - W_A) =$ **0.7 g/s**
= 0.082 kg/s (22.6 - 13.6) g/kg$_{da}$ = 0.044 kg/min = 2.66 kg/h

$mf_{we.iec} = mf_{ia} (W_A - W_3) =$ **0.2 g/s**
= 0.082 kg/s (13.6 - 11.2) g/kg$_{da}$ = 0.012 kg/min = 0.71 kg/h

Figure 11: LD based Fresh Air Dehumidification and Cooling Using Indirect Evaporative Cooling with Exhaust Air for New Delhi

Table 1: Recommended DOAS Configurations for Different Climate Zones to Optimize Energy Saving

Sr No.	Climate Zone	Summer	Monsoon
		Schematic and State Point Processes	Schematic and State Point Processes
1.	Temperate Climate t = 25 to 30°C rh < 75%	 3 to A: IA undergoes evaporative cooling A to 4: IA gets diabatically heated and humidified 1 to 2: OA gets sensibly cooled	 3 to A: IA undergoes evaporative cooling A to 4: IA gets sensibly heated 1 to B: OA gets undergoes liquid desiccant dehumidification B to 2: OA gets sensibly cooled
2	Hot and Dry Climate t > 30°C rh < 55%	 3 to A: IA undergoes evaporative cooling A to 4: IA gets sensibly heated 1 to 2: OA gets sensibly cooled	 3 to A: IA undergoes evaporative cooling A to 4: IA gets sensibly heated 1 to B: OA gets undergoes liquid desiccant dehumidification B to 2: OA gets sensibly cooled
3	Warm and Humid Climate t > 25°C rh > 55%	 3 to A: IA undergoes evaporative cooling A to 4: IA gets diabatically heated and humidified 1 to 2: OA gets sensibly cooled	 3 to A: IA undergoes evaporative cooling A to 4: IA gets diabatically heated and humidified 1 to B: OA gets undergoes liquid desiccant dehumidification B to 2: OA gets sensibly cooled
4	Composite Climate when six months or more do not all fall within any of the other categories	 3 to A: IA undergoes evaporative cooling A to 4: IA gets sensibly heated 1 to 2: OA gets sensibly cooled	 3 to A: IA undergoes evaporative cooling A to 4: IA gets diabatically heated and humidified 1 to B: OA gets undergoes liquid desiccant dehumidification B to 2: OA gets sensibly cooled

6.1 Warm and Humid Climate Zone

The entire coastal region of India's peninsula falls in this zone (includes prominent cities Mumbai, Chennai and Kolkata). May is the hottest month in these regions with temperatures being greater than 30°C and relative humidity higher than 55%.

West Coastal Region: Summer is from April to May and monsoon season lasts from June to September due to South West Monsoon winds. Although temperatures are not very high in summer, conditions are uncomfortable due to high humidity. March is warm and October is hot during daytime. Winter is cool and pleasant and lasts from November to February.

East Coastal Region: Temperatures and humidity is always high greater than 30°C and 55%rh. Summer is typically from March to June. Monsoon lasts from July to November with precipitation peaking in October and November. Winter season does not typically exist in such regions. *Table 2* shows the different conditions during different months in this region along with best suitable DOAS.

Table 2: DOAS Options for Warm and Humid Climate Zone during Various Periods in a Year

Months	Condition		DOAS option	
	Day	Night	Day	Night
Jan-Feb	Comfortable	Cool	Ventilation	
Mar	Warm	Warm	Fan induced Ventilation	
Apr-May	Hot and Humid		OA_SC+IA_(EPC+SH)	Fan induced Ventilation
Jun-Sep	Warm and very Humid		OA_SLC+IA_(EC+DHH) As shown in Fig 2.2	
Oct	Hot and Humid		OA_SC+IA_(EPC+SH)	
Nov-Dec	Comfortable	Cool	Ventilation	

6.2 Hot and Dry Climate Zone

The Thar Desert area in Rajasthan, eastern Gujarat, and central Maharashtra falls in this zone (includes Jodhpur, Jaipur, Ahmedabad, Nagpur, Sholapur). Summer is from March to May, the months of April to June being very hot. Day temperature is 40 to 45°C and night temperature is 20 to 30°C. Winter is cool and pleasant and lasts from November to February with day temperatures of 5 to 25°C and night temperature of 0 to 10°C. Diurnal variation is more than 10°C (Press Information Bureau English Releases, 2015). Relative humidity is fairly low throughout the year except in monsoon. Monsoon is short from June to August but has high humidity coupled with high temperatures. September is relatively cooler and October is hot during daytime. *Table 3* shows the different conditions during different months in this region along with best suitable DOAS.

Table 3: DOAS Options for Hot and Dry Climate Zone during Various Periods in a Year

Months	Condition		DOAS option	
	Day	Night	Day	Night
Jan-Feb	Comfortable	Cool	Ventilation	
Mar-May	Hot and Dry	Hot and Dry	Evaporative Cooling or **OA_SC+IA_(EPC+SH)**	
June-Aug	Hot and Humid	Hot and Humid	**OA_SLC+IA_(EC+DHH)**	
Sep	Warm	Cool	Fan induced Ventilation	Ventilation
Oct	Hot and Dry	Comfortable	Evaporative Cooling or **OA_SC+IA_(EPC+SH)**	
Nov-Dec	Comfortable	Cool	Ventilation	

6.3 Composite Climate Zone

The Composite Zone is defined as the zone when six months or more do not all fall within any of the other categories. Thus, this zone has distinct hot and dry, hot and humid and cold seasons. Northern and Central India, Telangana region of Andhra Pradesh and Eastern Rajasthan fall in this zone. Summer starts from April, May and June being particularly harsh. Monsoon is short from June to August but has high humidity coupled with high temperatures. September is warm and humid and October is hot during daytime. Winter is cool and pleasant and lasts from November to March. This type of climate exists in Indian cities like New Delhi, Kanpur and Allahabad. During summer day temperature is 32 to 43°C and night temperature is 27 to 32°C. During winter day temperature is 10 to 25°C and night temperature is 4 to 10°C. During dry period relative humidity is low 20 to 25% and during wet period relative humidity is on higher side 55 to 95% (Press Information Bureau English Releases, 2015). *Table 4* shows the different conditions during different months in this region along with best suitable DOAS

Table 4: DOAS Options for Composite Climate Zone during Various Periods in a Year

Month	Condition		DOAS option	
	Day	Night	Day	Night
Jan-Feb	Cool	Cold	Ventilation	Heating may be required
Mar		Cool		Ventilation
Apr-May	Hot and Dry	Hot and Dry	Evaporative cooling or **OA_SC+IA_(EPC+SH)**	
Jun-Aug	Hot and Humid	Hot and Humid	**OA_SLC+IA_(EC+DHH)**	
Sep	Warm and Humid	Cool	Fan induced Ventilation	Ventilation
Oct	Hot and Dry	Comfortable	Evaporative cooling or **OA_SC+IA_(EPC+SH)**	
Nov-Dec	Cool	Cool	Ventilation	
		Cold	Ventilation	Heating may be required

6.4 Temperate Climate Zone

The Temperate Zone is where temperature and humidity values lie in the human comfort zone for most of the year. Prominent cities in this region include Pune and Bangalore as they are surrounded by hills. The day temperatures are relatively high during March, April and May; the corresponding night temperatures are within comfort level. Monsoon is from June to October and Winter is from November to February. Both seasons are cool and pleasant. During summer day temperature is 30 to 34°C and night temperature is 17 to 24°C. During winter day temperature is 27 to 33°C and night temperature is 16 to 18°C (Press Information Bureau English Releases, 2015). Relative humidity is fairly moderate throughout the year. *Table 5* shows the different conditions during different months in this region along with best suitable DOAS.

Table 5: DOAS Options for Temperate Climate Zone during Various Periods in a Year

Month	Condition		DOAS option	
	Day	Night	Day	Night
Jan-Feb	Comfortable	Cool	Ventilation	
Mar-May	Hot and Dry	Cool	Evaporative cooling or **OA_SC+IA_(EPC+SH)**	Ventilation
Jun-Oct	Comfortable		Fan induced Ventilation	
Nov-Dec	Comfortable	Cool	Ventilation	

6.5 Cold and Cloudy (Humid) Climate Zone

The Cold and Cloudy Zone is characterized by predominantly cool conditions. The months from October to May are uncomfortably cold. The conditions during December, January and February are extremely cold with night temperatures falling below freezing line. Prominent locations are hill stations and the Himalayan region. *Table 6* shows the different conditions during different months in this region along with best suitable DOAS.

Table 6: DOAS Options for Cold and Cloudy Climate Zone during Various Periods in a Year

Month	Condition		DOAS option	
	Day	Night	Day	Night
Jan-Feb	Cold	Very Cold	SH_AtAHR	
Mar		Cold		
Apr-May			Heating through direct solar radiation	SH_AtAHR, Daytime heat trapped by providing thermal mass
June	Comfortable	Cool	Ventilation	SH_AtAHR
Jul-Aug	Warm		Ventilation	
Sep	Comfortable		Ventilation	SH_AtAHR
Oct	Cold	Cold	Heating through direct solar radiation	SH_AtAHR, Daytime heat trapped by providing thermal mass
Nov	Cold		SH_AtAHR	
Dec		Very Cold		

6.6 Cold and Sunny (Dry) Climate Zone

The Cold and Sunny Zone is characterized by predominantly cold conditions. This region includes climate in extreme high Himalayan altitudes and the Leh Ladakh cold desert region. Outside conditions are rarely within the comfort zone except during daytime in the months of July and August. In fact, the months of December, January and February experience sub-zero temperatures almost throughout the day and night. Nights are severely cold with temperatures ranging from –14°C in January to –11°C in December. January is the coldest month (minimum and maximum temperatures being –14°C and –3°C respectively). March, April, October and November are less severe. However, the temperatures at night are below freezing point. Table7 shows the different conditions during different months in this region along with best suitable DOAS

Table 7: DOAS Options for Cold and Sunny Climate Zone during Various Periods in a Year

Month	Condition		DOAS option	
	Day	Night	Day	Night
Jan-Apr	Very Cold	Severe Cold	SH_AtAHR	
May	Cold	Very Cold	Heating through direct solar radiation	LD with AtAHRU, SH_AtAHR
June		Cold		SH_AtAHR,Daytime heat trapped by providing thermal mass
Jul-Aug	Comfortable		Ventilation	
Sep	Cold		Heating through direct solar radiation	
Oct		Very Cold		LD with AtAHRU, SH_AtAHR
Nov-Dec	Very Cold	Severe Cold	SH_AtAHR	

6.7 Recommended DOAS for Specific Indoor Air Conditions

Different DOAS configurations for specific indoor air conditions were also studied in these climate zones. *Table 8* details the type of indoor condition along with application and different air fractions and the feasible DOAS that can be applied.

Table 8: DOAS Options for Different Indoor Conditions and Fresh Air Fraction

Climatic Zone	Type of Indoor Condition		Fresh Air Fraction	Non Compressor based DOAS option
Warm and Humid (Mumbai, Chennai, Kolkata)	Comfort Conditions*	(Part Sensible PartLatent)	High	OA_ SLC u IA_(EPC + DHH)
	Industrial Applications**	High Latent to Sensible Load ratio	Low	Hybrid AC
			High	OA_SC u IA_(EPC + SH),
		High Sensible to Latent Load ratio	Low	Hybrid AC, Diabatic desiccant dehumidification of outdoor air by cold water circulation
			High	OA_(SLC + HA) u IA_(EPC + DHH), Diabatic desiccant dehumidification by evaporatively cooled exhaust air
Hot and Dry (Jaipur, Jaisalmer, Sholapur, Jalgaon)	Comfort Conditions*	(Part Sensible Part Latent)	High	OA_SC u IA_(EPC + SH)
	Industrial Applications**	High Latent to Sensible Load ratio	Low	OA_SC u OA_(EPC + SH), OA_SC u OA_(IEC + DHH)
			High	OA_SC u IA_(EPC + SH), OA_SC u IA_(IEC + DHH)
		High Sensible to Latent Load ratio	Low	OA_(SC + DEC) u OA_ SH
			High	OA_(SC + DEC) u IA_SH
Composite (Delhi, Hyderabad, Kanpur, Allahabad)	Comfort Conditions*	(Part Sensible Part Latent)	High	OA_SC u IA_(EPC + SH), OA_SC u IA_(IEC + DHH)
	Industrial Applications**	High Latent to Sensible Load ratio	Low	Hybrid AC, OA_SC u OA_(EPC + SH), OA_SC u OA_(IEC + DHH)
			High	OA_SC u IA_(EPC + SH), OA_SC u IA_(IEC + DHH)
		High Sensible to Latent Load ratio	Low	OA_(DEC+SC) u OA_SH, Hybrid AC, Diabatic desiccant dehumidification of outdoor air by cold water circulation
			High	OA_(SC+DEC) u IA_SH, OA_(SLC + HA) u IA_(EPC + DHH), Diabatic desiccant dehumidification by evaporatively cooled exhaust air

Table 9: DOAS Options for Different Indoor Conditions and Fresh Air Fraction

Climatic Zone	Type of Indoor Condition (Sensible to Latent Load Ratio)		Fresh Air Fraction	Non Compressor based DOAS option
Temperate (Bangalore, Pune)	Comfort Conditions*	(Part Sensible Part Latent)	High	OA_SC u IA_(EPC + SH)
	Industrial Applications**	High Latent to Sensible Load ratio	Low	OA_SC u OA_(EPC + SH)
			High	OA_SC u IA_(EPC + SH)
		High Sensible to Latent Load ratio	Low	OA_SC u OA_(IEC + DHH)
			High	OA_SLC u IA_(EPC + DHH)
Cold and cloudy (Ootacamund, Shimla, Mahabaleshwar, Shillong, Srinagar)	Comfort Conditions*	(Part Sensible Part Latent)	High	OA_SC u IA_SH
	Industrial Applications**	High Latent to Sensible Load ratio	Low	OA_SC u OA_SH
			High	OA_SC u IA_SH
		High Sensible to Latent Load ratio	Low	SH_LD u AtAHRU
			High	SH_LD u AtAHRU with IA
Cold and Sunny (Leh, Ladakh)	Comfort Conditions*	(Part Sensible Part Latent)	High	SH_LD u AtAHRU
	Industrial Applications**	High Latent to Sensible Load ratio	Low	SH_LD u AtAHRU
			High	SH_LD u AtAHRU with IA
		High Sensible to Latent Load ratio	Low	OA_SC u OA_SH
			High	OA_SC u IA_SH

** includes Residences, Retail Facilities, Commercial and Public Buildings, Tall Buildings, Places of Assembly, Hotels, Motels, and Dormitories, Educational Facilities, Health-Care Facilities, Justice Facilities, Automobiles, Mass Transit, Aircraft, Ships*

*** includes Industrial Air Conditioning, Enclosed Vehicular Facilities, Laboratories, Engine Test Facilities, Clean Spaces, Data Processing and Telecommunication Facilities, Printing Plants, Textile Processing Plants, Photographic Material Facilities, Museums, Galleries, Archives, and Libraries, Nuclear Facilities, Mine Air Conditioning and Ventilation, Industrial Drying, Ventilation of the Industrial Environment, Industrial Local Exhaust, Kitchen Ventilation*

7. Conclusions

Appreciating the importance of Indoor Air Quality ASHRAE Standard 62.1 has enhanced the ventilation rates compared to earlier recommendations. Meeting this standard using conventional variable air volume systems results in increased energy consumption in HVAC systems. Dedicated outdoor air systems, DOAS, have evolved as a potential option for meeting this standard to achieve good indoor air environment while addressing the energy consumption issue.

VRF systems have emerged as one of the preferred HVAC system in recent years. Inverter driven variable speed compressors in their outdoor units offer good part load efficiency. To meet indoor air quality requirement, VRF should be integrated with DOAS based ventilation system. Small modular DOAS can now be deployed with unitary systems including split air conditioners catering to individual rooms.

Literature review on various DOAS configurations is briefly reported, which identify different options available along with their features, advantages and limitations.

Total heat exchanger with a low temperature cooling coil, that handle entire space latent load and some portion of sensible load is one of the DOAS options that can be integrated with conventional air-conditioning systems. In applications where air cannot be supplied at low temperature, a suitable sensible heat exchange system can be added to the DOAS configuration.

DOAS consisting of internally cooled liquid desiccant based sub-system to handle entire latent load along with sensible cooling of outdoor air by indirect evaporative cooling of exhaust air is discussed briefly. This modular design can be integrated with conventional air-conditioning systems. This type of system finds application in cases where waste heat is available for regeneration of desiccant. Regeneration of liquid desiccant through condenser heat recovery can be considered. Using solution heat exchangers for cooling strong liquid desiccant solution by exchanging heat with incoming weak desiccant solution is one of the energy efficient method of cooling desiccant after regeneration.

The feasibility of DOAS for regions of different climatic conditions in India was investigated and appropriate configurations suggested for each case. DOAS configuration is suitable for warm and humid climate which have fairly high relative humidity values throughout the year. In places with low or moderate relative humidity values like in moderate or hot and dry climates, DOAS is most suitable for use in monsoon conditions even though it can be used in summer as well for direct or indirect evaporative cooling.

Acknowledgement

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Nomenclature

h	enthalpy, kJ/kg
m	mass, kg
Q	cooling load, kW
t	temperature, °C
w	specific humidity, g/kg
W	work done, kJ
Abbreviations	
CB	chilled beam
DBT	dry bulb temperature
DCV	demand controlled ventilation
DOAS	dedicated outdoor air system
DPT	dew point temperature
DX	direct expansion
EPC	evaporative pre-cooling
FCU	fan coil unit
HVAC	heating ventilating and air conditioning
IA	indoor air
LD	liquid desiccant
OA	outdoor air
SC	sensible cooling
SHR	sensible heat ratio
SLC	sensible and latent cooling
VAV	variable air volume
VRF	variable refrigerant flow
Greek Letters	
ε	Effectiveness
μ	coefficient of viscosity
ρ	Density
Suffixes	
c	Cooling
comp	Compressor
da	dry air
dec	direct evaporative cooler
dh	Dehumidification
i	Inlet
ia	Indoor air
o	Outlet
oa	Outdoor air
r	Refrigerant
s	supply air
wb	wet bulb

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