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Final Project Report

Assessing the Application of Vacuum-Based Membrane Dehumidification for Tropical Climates.

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ABSTRACT: The tropics are often characterized by high temperatures and elevated humidity ratios that contribute to heat stress. Implementing certain passive design strategies for cooling, such as natural ventilation, can help reduce thermal discomfort, but during summer conditions relying on passive strategies alone for cooling is not enough and has its limitations. Incorporating membranes in mechanical systems reduce latent loads for cooling and eliminate the need to reheat the supply air. As a building element, vacuum-based membranes could be applied as a low-energy cooling strategy to condition and increase the potential of natural ventilation in hot and humid climates. This study analyses the implementation of vacuum-based membranes for dehumidification. The purpose of this research is to evaluate the Vacuum-based membrane dehumidification system against a Dedicated Outside Air System (DOAS) in terms of energy consumption and performance in improving thermal comfort inside an office space for hot and humid climates.
KEYWORDS: vacuum-based membrane, dehumidification, hot and humid climates, tropics, low energy dehumidification, absolute humidity.

1. INTRODUCTION

The tropics are often characterized by year-round high temperatures (Tmin ≥ +18 ◦C), high amounts of solar radiation and abundant annual precipitation, and most importantly, humidity ratios generally higher than 12 grams of moisture per kilogram of dry air year-round.

The combination of high temperatures and elevated humidity ratios contribute to the heat stress that characterizes this climate. Implementing certain passive design strategies for cooling, such as natural ventilation, can help reduce thermal discomfort, but during summer conditions relying on passive strategies alone for cooling is not enough and has its limitations.

In response to this, commercial and office space buildings in tropical locations rely exclusively on mechanical systems for cooling, leading to high electricity consumption. This mainly to the dehumidification process of cooling down the air to its dewpoint temperature (to condensate the moisture out of the air) and reheating the air up to the desired supply temperature.

This study analyses the implementation of vacuum-based membranes for dehumidification. The purpose of this research is to evaluate the Vacuum-based membrane dehumidification system against a Dedicated Outside Air System (DOAS) in terms of energy consumption inside an office space for hot and humid climates.

2. MEMBRANE MODULE BACKGROUND

A membrane is a barrier; its essential purpose is to selectively separate two species. Selectivity and permeability are important for the membrane's performance. Figure 1 shows a general membrane process, where the membrane separates the "Feed Side" and the "Permeate Side". In the case of vacuum-based membrane dehumidification, the flux of water vapor occurs across the membrane from the high concentration state (feed side/outdoor-humid air) to the low concentration state (permeate side). According to (Woods, 2014), a higher permeability means less membrane area for a given transfer rate, and a higher selectivity means a purer product stream, which can be either the permeate or the retentate.

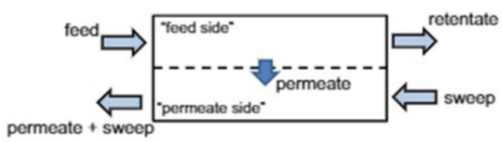

Figure 1 Feed and Permeate States in the membrane process. (Woods, 2014)

The membrane module used in this study was developed by Pamela Cabrera in the National University of Singapore Lab. The membrane is a flat sheet membrane that follows the geometric design of the Miura fold. The Miura fold allows for

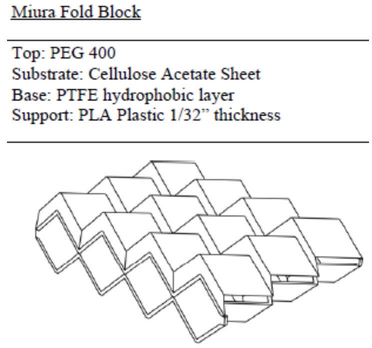

Figure 2 Membrane Structure and Materials. (Cabrera, 2019)

more passages in the membrane, increasing surface area, as well as inner turbulence improving the module effectiveness.

The top layer is made of a hydrophilic material that absorbs the water content of the humid air (PEG400); the substrate layer is a cellulose acetate sheet with a base hydrophobic layer of PTFE (Cabrera, 2019). This layer releases the moisture into the permeate side. Higher selectivity requires less pressure gradient to permeate water across the membrane (Cabrera, 2019).

The membrane module has an effectivity of 0.15g/m2s. For the study, the membrane effectivity remains constant, meaning that it is assumed that the flow of water vapor in the membrane is uniform during operation. Further studies should account for performance losses.

Energy-wise, since the membrane selects the water molecules by diffusion, the only energy input in the system is the energy required for the vacuum pump (Cabrera, 2019). The pressure difference created by the vacuum pump across the membrane and the membrane module is also a relevant element to drive the mass transfer (humidity flux). When humid air passes above the membrane, the output is drier air, but its temperature remains constant. Only the water content in the air decreases, making it an isothermal process.

Incorporating membranes in mechanical systems reduce latent loads for cooling and eliminate the need to reheat the supply air. As a building element, vacuum-based membranes could be applied as a low-energy cooling strategy to condition and to increase the potential of natural ventilation in hot and humid climates.

3. METHODOLOGY

The hot and humid locations selected were La Lima, Honduras and Miami, USA. Only summer conditions were analysed, thus only the month of June was simulated. A one-zone (shoe box) model was set up to represent an office space for the simulation. The zone has an area of 25m^2 with a height of 3 meters, and a window to wall ratio of 32% on north and east walls. South and west walls have no windows.

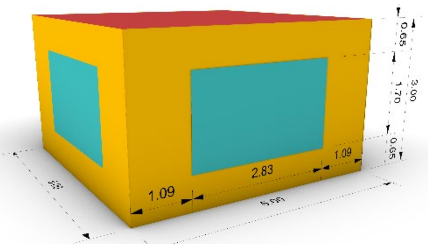

Figure 3 Zone Dimensions

The simulations were done using the software TRNLizard; where the model construction types, infiltration rates, internal loads were set up. Initially, hand calculations and a excel sheet were developed out to determine the amounts of g/kg for the membrane to reduce, membrane area and the vacuum pump power required. Finally, the set of equations and constants were set as inputs in the TRNLizard model to generate the results.

3.1 MEMBRANE AND VACUUM POWER CALCULATIONS

The study methodology is developed to answer the following questions:

1. How much humidity should we reduce? What is the target?
2. How much membrane area is required to achieve the goal of humidity reduction?
3. How much vacuum pump power is needed to reach the desired humidity reduction?

To answer question#1, we use ASHRAE Standard 62-2001 as a guide. The ASHRAE Standard 62-2001 recommends the relative humidity of 30–60% for indoor environments. (Yang, Yuan, Gao, & Guo, 2015). Hence, the maximum supply humidity target in the set to 50% relative humidity. This means the membrane module must reduce the outdoor air relative humidity levels to 50% relative humidity before supplying it to the indoor space. Using TRNLizard, the Deck Template was modified to create a new Psychrometric Type ("Type33e-3" (Type 33)), and to input the equation:

$$rh50 = 50 \quad !\,constant\ relative\ humidity$$

Where a different psychrometric module will compute the absolute humidity (kg/kg) for constant 50% relative humidity conditions. This new unit is used in the User Equations to retrieve the absolute humidity in g_{water}/kg_{dryair} with this equation:

$$X_{amb_{50rh}} = [34{,}1] * 1000$$

Where [34] is the reference to the new Psychrometric type and [1] is indicated to retrieve the absolute humidity output. Knowing the absolute humidity value at constant 50% relative humidity, the following formula subtracts the outdoor air absolute humidity (g_{water}/kg_{dryair}) to the absolute humidity at 50 relative humidity (g_{water}/kg_{dryair}), which will equal to the humidity reduction produced by the membrane module.

$$MemRed = (x_{amb}) - (x_{amb_{rh50}})$$

To calculate the membrane area required to achive the $MemRed$, the following formula was generatedand added as an input in the TRNLizard User Equations list:

$$mA = \frac{(VentReq * MoistAirDensity * MemRed)}{MembraneEffectivity}$$

Here VentReq (Ventilation Requirements) is the total volume flow rate required for the space (m3/s). This is calculated based on the space population and the liters per second (l/s) required for minimum fresh (outdoor) air ventilation rates for office spaces. Engineering experience and field studies indicate that an outdoor air supply of about 10 l/s per person is very likely to provide acceptable perceived indoor air quality in office spaces, whereas lower rates may lead to increased sick building syndrome symptoms. (Clark, 2013) Therefore, a rate of 10 l/s ·person was used. For hand calculations this formula can be used to calculate the total ventilation requirements:

$$ventreq = \frac{(Population * FreshAirPerPerson)}{1000}$$

In TRNlizard, we calculate the ventilation requirements based on the input of 36m^3/h set in the Mechanical Ventilation component in the "OrPersonRelatedVolumeFlow" section. The following formula was also added to the User equations:

$$ventreq = (Vol\_A1\ *\ ACR\_ahu\_mv\_A1)/3600$$

Here Vol_A1 is the volume of the space (m^3), and $ACR\_ahu\_mv\_A1$ is the number of air changes in the mechanical ventilation unit (1/h).

To calculate the density of moist air with hand calculations, we first need to know the density of dry air density. Dry air density depends on pressure and temperature. In this study the following formula was utilized:

$$Dry\ air\ density = AP/((Rspecific) * (Tamb + 273.15))$$

Where AP, is the atmospheric pressure (101,325 Pascals). Rspecific is the specific gas constant, R = 287 J/kg·K. Tamb is ambient temperature.

Knowing the density of dry air, the following formula applies to calculate the moist air density:

$$MoistAirDensity = \frac{(DAdensity) * (1 + x)}{(1 + x * Rw/Ra)}$$

Where DAdensity (kg/m3), is the density of dry air. X is the humidity ratio of outdoor air (kg/kg). Rw is the gas constant of water vapor, Rw= 461.5 J/kg K, and Ra is the gas constant of air, Ra= 286.9 J/kg K. In TRNLizard, the moist air density is retrieved from the Psychrometric (Type 33) by adding the following equation into the User Equations list:

$$MoistAirDensity = [33,4]$$

Where [33] is the reference to the Psychrometric type and [4] is indicated to recall the moist air density output.

Finally, for hand calculations, the equation to calculate the total membrane area can also be displayed in this way:

$$Membrane\ Area(m^2) = \frac{[(\frac{m3}{s}) * (\frac{kg}{m^3}) * g/kg)]}{g/m^2 \cdot s}$$

With this equation, we answer question #2 of the methodology process.

As mentioned before, the dehumidification process of the membrane module depends on the different pressure states between the feed and the permeate side. To create the transmembrane pressure gradient, a vacuum pump must be installed at the permeate side, where the pressure should be always lower than the water vapor partial pressure of the outdoor air. (Chen, 2019)

The formula to calculate the vacuum power derives from the power equation:

$$Power = \frac{\dot{m} * Work}{Mass * \epsilon} = \frac{\dot{m} * \Delta P * V}{Mass * \epsilon} = \frac{\Delta P * \dot{V}}{\epsilon}$$

Where vacuum pump power is the product of the pressure difference [Pa] multiply by the Volumetric flow [m3/s] (inside the membrane) and divided by the pump efficiency assumed to have an efficiency of 0.80, based on (Chen, 2019) analysis.

First, we analyzed the configuration shown in Figure 4. Here, the water vapor is expelled to the ambient, therefore the output pressure is set to 101,325Pa (101,325 N/m²). The desired permeate pressure is 2,500Pa (2,500 N/m²).

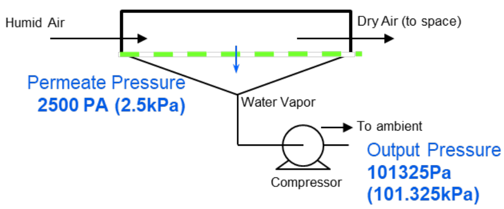

Figure 4 Schematic of 1-Stage Vacuum Based Membrane Dehumidification Process.

Another configuration, Figure 5, is to pump the water vapor to a lower output pressure instead of ambient absolute pressure. In this concept, the compressor discharges the water vapor into a second membrane module, which puts the low-pressure vapor in contact, through a membrane, with ambient air. (Woods, 2014). Then the vacuum pump will only pump (water vapor) to the ambient vapor pressure. In this case, the output pressure is assumed to be 4,000Pa (4kPa). Permeate pressure is 2,500Pa (2.5KPa).

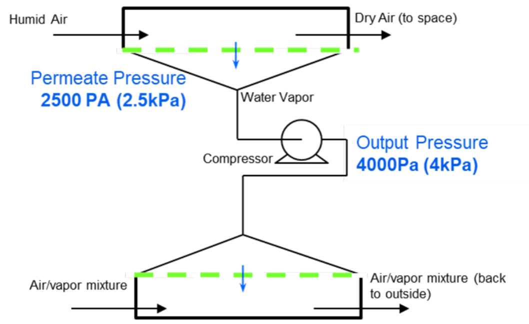

Figure 5 Schematic of 2-Stage Vacuum Based Membrane Dehumidification Process.

Additionally, we calculate the volumetric flow using the following formula:

$$\dot{V} = \frac{nRT}{mP}\dot{m}$$

Where n is equivalent to 1 mole, R is the molar gas constant [8.314 m^3·PA/K·mol]. T is outdoor air temperature in Kelvin, m is the molecular mass of water [0.018kg/mol]. P is the pressure in the permeate side [Pa] and $\dot{m}$ is the mass flow inside the membrane module [kg/s]. In hand calculations and the TRNLizard file, the module mass flow was calculated using this equation:

$$modelmassflow = (MemArea * MembraneEffectivity)/1000)$$

The volumetric flow equation is added to the User Equations list by adding the previously stated constants and the following formula:

$$VF = ((mole * R * (Tamb + 273.15))/((mole * mw) * pPA)) * modelmassflow$$

Finally, the power calculations for both systems configurations produce the following results (Figure 6):

1) A 1-Stage Vacuum Based Membrane Dehumidification system requires 1906.4 Watts or a total of 13.24(W/m^3/h). With the m^3/h of 144 m^3/h (based on 10 liters per person and a population of 4 people in the study zone.)
2) A 2-Stage Vacuum Based Membrane Dehumidification system requires 28.9 Watts or a total of 0.20(W/m^3/h). With the m^3/h of 144 m^3/h (based on 10 liters per person and a population of 4 people in the study zone.)

A second membrane in the system reduces the vacuum power by 98.4% in comparison 1-stage membrane system.

Efficiency	Volumetric flow	Feed Pressure	Permeate Pressure	Vaccum Power	
-	m^3/s	N/m^2	N/m^2	Nm/s	W
0.800	0.0154	101325	2500	1906.38	1906.4
0.800	0.0154	4000	2500	28.94	28.9

Figure 6 1-Stage and 2-Stage Vacuum Power Results

The equation and the results prove that higher pressure differences (ΔP) in the system yield higher vacuum power demand for dehumidification. Therefore, the system chosen for this study is the 2-Stage Vacuum Based Membrane Dehumidification system.

Additionally, we can include the vacuum equations in the User Equation panel to calculate total the vacuum pump power in W/m^2 using TRNLizard:

$$vpPower = ((fPA - pPA) * VF)/vpefficiency$$
$$vpPower2 = vpPower/Area\_A1$$
$$totalelectri = vpPower2 + q\_vent\_el\_A1$$

Where, the total electricity is the sumation of the air handling unit fan electricity usage (W/m^2) and the vacuum power in W/m^2.

3.2 CASE 1: DOAS SYSTEM

Case 1 was set up to represent and simulate the regular operation of a Dedicated Outside Air System with additional cooling included to condition the space. The DOAS system uses the Outside (Humid) Air and handles the sensible and latent loads by circulating the humid air through the cooling and reheat coil before supplying it to the zone/space. A parallel system, the additional cooling, handles, in most cases, the sensible loads produce indoors (internal loads from people gain, equipment, building envelope, solar radiation.)

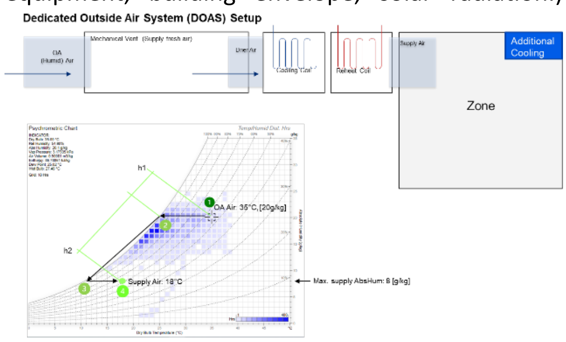

Figure 7 CASE 1: Dedicated Outside Air Setup and Process Representation in Psychrometric Chart.

Case 1 TRNLizard input setups are the following:

CASE 1	DOAS SYSTEM + Additional Cooling: ON	
	Mechanical Ventilation:	AHU
	OrPersonRelatedVolumeFlow:	36 [m³/h]
	SupplyTempWinterOcc	20°C
	SupplyTempWinterUnOcc	20°C
	SupplyTempSummerOcc	17°C
	SupplyTempSummerUnOcc	17°C
	MaxSupplyAirHumidity	X_amb_50RH_kg
	SpecFanPower	0.50 [W/(m³/h)]
	SensibleHeatRecovery	0%
	LatentHeatRecovery	0%
	Cooling_SetTemperature	26 DEG
	Cooling_SetHUMS	100%
	MaxSpecCoolPower	100 [W/m²]

Figure 8 Case 1-TRNLizard input details.

3.3 CASE 2: DOAS AND MEMBRANE SYSTEM

Case 2 is set as an optimization of the Case 1 DOAS System. In this case, the system supplies only ambient air temperature dehumidified by the membrane system. The membrane and vacuum pump equations are included to have the membrane system dehumidify the air to the previously stated $X_{amb_{50rh}}$ conditions (and not the heating and cooling coils) before supplying it to the space.

Also, we considered the 2-Stage Vacuum Based Membrane Dehumidification system setup. Again, a parallel cooling system is included to handle the sensible loads of the zone.

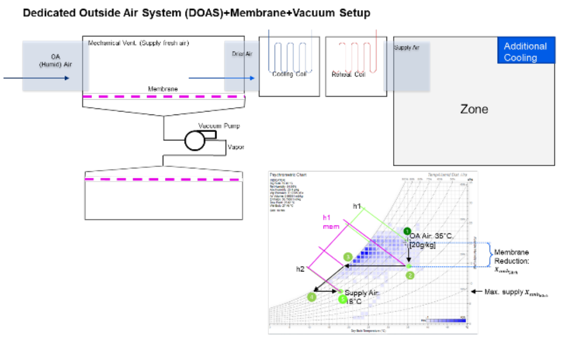

Figure 9 CASE 2: DOAS System and 2-Stage Vacuum Based Membrane Dehumidification system setup.

Case 2 TRNLizard input setups are the following:

CASE 2	NATVENT+ Membrane + Additional Cooling:ON	
	Mechanical Ventilation:	AHU
	OrPersonRelatedVolumeFlow:	36 [m³/h]
	SupplyTempWinterOcc	Tamb
	SupplyTempWinterUnOcc	Tamb
	SupplyTempSummerOcc	Tamb
	SupplyTempSummerUnOcc	Tamb
	MaxSupplyAirHumidity	X_amb_50RH_kg
	SpecFanPower	0.50 [W/(m³/h)]
	UserEquation for Mem+Vacuum	ON
	SensibleHeatRecovery	0%
	LatentHeatRecovery	0%
	Cooling_SetTemperature	26 DEG
	MaxSpecCoolPower	100 [W/m²]

Figure 10 Case 2-TRNLizard input details.

The expected results for CASE 2; are: first, higher fan energy demand since the vacuum pump is required for the dehumidification process of the membrane. Second, the results should indicate a reduction in the latent loads of the system, meaning since the membrane is already providing the dehumidified air to the space most of the cooling power should be for the sensible loads. Since the supply air in Case 2 is Ambient Temperature, the sensible cooling power required should be higher for in this case systems.

3.4 CASE 3: NATURAL VENTILATION

Case 3 was set up to represent and simulate the usage of natural ventilation to condition the space. This case is created to analyse the Predicted Mean Vote (PMV) in the zone when using natural ventilation.

Case 3 TRNLizard input setups are the following:

CASE 3	Natural Ventilation	
	Mechanical Ventilation:	AHU
	ACH	3
	Min ACH	1
	SupplyTempWinterOcc	Tamb
	SupplyTempWinterUnOcc	Tamb
	SupplyTempSummerOcc	Tamb
	SupplyTempSummerUnOcc	Tamb
	MaxSupplyAirHumidity	Amb_X
	SpecFanPower	0.50 [W/(m³/h)]
	UserEquation for VacuumPower	OFF
	SensibleHeatRecovery	0%
	LatentHeatRecovery	0%
	Cooling_SetTemperature	OFF
	MaxSpecCoolPower	OFF

Figure 11 Case 3-TRNLizard input details.

3.5 CASE 4: NATURAL VENTILATION AND MEMBRANE SYSTEM

Case 4 was set up to represent and simulate the usage of natural ventilation and the membrane system to dehumidify the outdoor air. This case is created to analyse the Predicted Mean Vote (PMV) in the zone against, Case3, using natural ventilation alone.

Case 4 TRNLizard input set ups are the following:

CASE 4	Natural Ventilation+ Membrane	
	Mechanical Ventilation:	AHU
	ACH	3
	Min ACH	1
	SupplyTempWinterOcc	Tamb
	SupplyTempWinterUnOcc	Tamb
	SupplyTempSummerOcc	Tamb
	SupplyTempSummerUnOcc	Tamb
	MaxSupplyAirHumidity	Amb_X50RH
	SpecFanPower	0.50 [W/(m³/h)]
	UserEquation for VacuumPower	ON
	SensibleHeatRecovery	0%
	LatentHeatRecovery	0%
	Cooling_SetTemperature	OFF
	MaxSpecCoolPower	OFF

Figure 12 Case 4-TRNLizard input details.

4. RESULTS AND CONCLUSIONS

4.1 ENERGY DEMAND

In this study, we analysed and compare the energy demand of Cases 1 and 2. More specifically, by comparing the results of the following TRNLizard outputs:

1. Q_ahu_sen_dh_ht_A1: sensible heating power (after dehumidification to achieve set point temperature).
2. Q_ahu_lat_hu_A1: latent heating power for AHU to control humidity of supply air.
3. Q_tot_ht_A1: Total heating power of air node.
4. Q_cool_A1: Total sensible cooling power of air node (from ideal cooling component).
5. Q_ahu_sen_cl_A1sensible cooling power to achieve set point temperature of supply air.
6. Q_ahu_dh_cl_A1: cooling power to control humidity of supply air.
7. Q_tot_cl_A1 total cooling power of air node (sensible-latent cooling ideal cooling, sensible-latent cooling of AHU, sensible cooling after dehumidification for AHU, active layer.)
8. Q_ahu_el_A1: electricity usage of fans AHU.

For the Honduran climate, Figure 13, in Case 2 the supply air is Ambient Temperature, the sensible heating power (Q_ahu_sen_dh_ht_A1) results indicate a sensible heating power of 0.00kWh/m^2 for the DOAS System. This is a decrease of 100% in comparison with the 0.22 kWh/m2 required by the DOAS_Membrane System.

The total sensible cooling power in the air node/zone (Q_cool_A1) is 32 % higher for Case 2. Meaning that the ideal cooling component has a higher sensible load since in Case 2, since the Air Handling unit is not preconditioning the supply air.

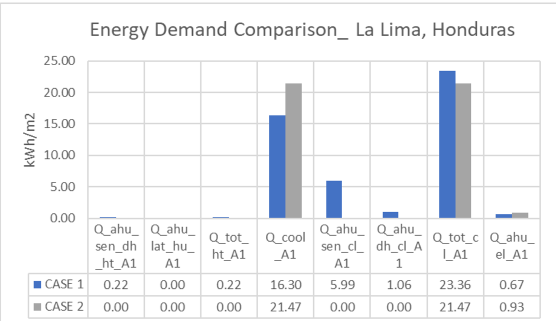

Figure 13 Energy Demand CASE 1 and CASE 2 Comparison for La Lima.

The sensible cooling power to achieve the set point temperature of the supply air (Q_ahu_sen_cl_A1) in Case 1 is higher(5.99kWh/m^2), since the set point is 17°C.

The additional cooling power of the zone to cool from set point temperature to dew point temperature (Q_ahu_dh_cl_A1), indicates a 100% decrease in the Case 2 system. Meaning that additional dehumidification power is not necessary in Case 2.

Regarding the fan energy demand, as expected the Case 2 system configuration requires higher fan energy demand. The results show a 39% increase in fan electricity usage in the zone.

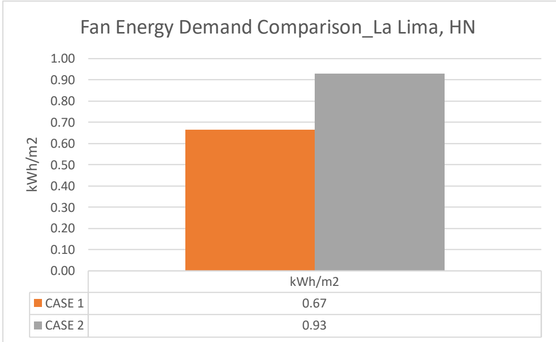

Figure 14 Fan Energy CASE 1 and CASE 2 Comparison for La Lima, Honduras.

Finally, the total sensible cooling power in the airnode is 8.09% lower in the DOAS_Membrane system.

For Miami's climate, Figure 15, in Case 2, the the sensible heating power results indicate a sensible heating power of 0.00kWh/m^2 for the DOAS System. This is a decrease of 100% in comparison with the 0.11 kWh/m2 required by the DOAS_Membrane System.

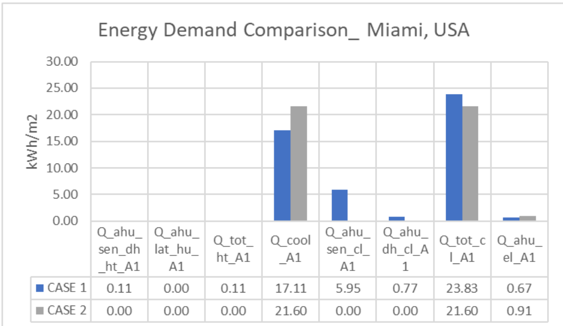

Figure 15 Energy Demand CASE 1 and CASE 2 Comparison for Miami.

The total sensible cooling power in the air node/zone (Q_cool_A1) is 38% higher for Case 2.

The sensible cooling power (Q_ahu_sen_cl_A1) is 5.95kWh/m^2. The Q_ahu_dh_cl_A1 results, indicates a 100% decrease in the Case 2 system. Meaning that additional dehumidification power is not necessary in Case 2.

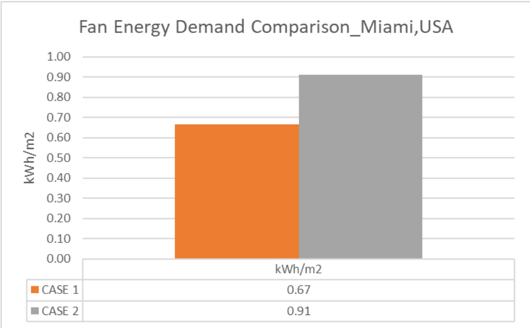

Figure 16 Fan Energy CASE 1 and CASE 2 Comparison for Miami, USA.

Regarding the fan energy demand, as expected the Case 2 system configuration requires higher fan energy demand. The results show a 35% increase in fan electricity usage in the zone.

Finally, the total sensible cooling power in the airnode is 8.50% lower in the DOAS_Membrane system (Case 2).

The results for sensible heating and cooling power demand denote that incorporating the 2-Stage Vacuum Based Membrane Dehumidification system setup alongside the DOAS system is a promising alternative for low energy dehumidification but requires further study to increase its efficiency to allow for higher reductions in latent loads.

4.2 COMFORT

For both climates, the Predicted Mean Vote results indicate that the membrane does impact the comfort level inside the zone. Its dehumidification effect is more evident in the Honduran climate where the PMV results are 1 vote lower, in Case 5.

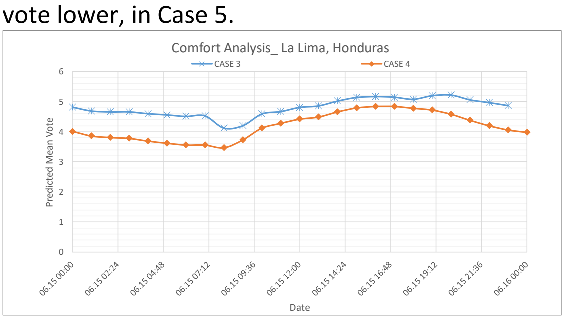

Figure 17 PMV Results La Lima, HN

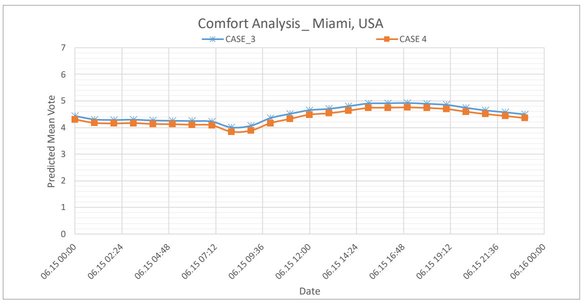

Figure 18 PMV results Miami, USA

Although the membrane-based dehumidification mentioned indicated promising results in comparison to the regular dedicated outside air system, more research work (discharge coefficients for the membrane geometry) is needed to apply the membrane dehumidification system in other ways.

Ideally, the membrane module should be incorporated into the building enveloped, to dehumidify the outside air before this enters the space, further study in the optimization of the shoe box model is recommended to analyse the performance of the membrane system along side other passive design strategies adequate for hot and humid climates.

5. REFERENCES

Cabrera, P. (2019). The Humid Threshold: Cooling hot, humid climates via membrane dehumidification. Harvard University Graduate School of Design.

Chen, T. (2019). Next-Generation Dedicated Outdoor Air Cooling Systems for Low-Energy Buildings. Massachusetts Institute of Technology.

Clark, D. (2013). Information Paper-20: Ventilation rates in offices- mechanical and natural. Cundall Johnston & Partners LLP.

Woods, J. (2014). Membrane processes for heating, ventilation, and air conditioning. Renewable and Sustainable Energy Reviews, 290-304.

Yang, B., Yuan, W., Gao, F., & Guo, B. (2015). A review of membrane-based air dehumidification. Indoor and Built Environment, 11-26.