DEHUMIDIFICATION STRATEGIES AND THEIR APPLICABILITY BASED ON CLIMATE AND BUILDING TYPOLOGY

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ABSTRACT

Dehumidification is a highly energy intensive process, especially in humid climates and for building typologies that require strict space humidity setpoints. Sub-cooling of air to condense out moisture using chilled water or refrigerant is the most common method for dehumidifying. Alternative strategies such as desiccant wheel, dual wheel and wrap around coils could more energy efficiently be used for certain climate zones and project types. Using energy models and results from a customized Excel-based tool, this paper evaluates applicability of each dehumidification strategy based on the local climate and building typology.

INTRODUCTION

Moisture indoors affects occupant comfort, the lifespan of building materials, and the operational effectiveness of program types that handle hygroscopic materials. In certain cases, the selection of mechanical equipment with thermally active surfaces also requires controlled space moisture levels to avoid the risk of surface condensation. Therefore, the ability to maintain strict humidity levels within a desired range by removing moisture from supply air is a critical aspect of air conditioning system design.

The load on the cooling coil associated with removal of moisture that results from occupants, outside air (infiltration, ventilation air), and other processes which generate moisture, is called latent load. Space latent loads typically contribute to about 20-30% of the total building cooling load. Sensible Heat Ratio (SHR) is used as a metric to design mechanical cooling equipment. A lower SHR corresponds to high latent gains and vice versa.

$$SHR = \frac{Sensible\ Load}{Sensible\ Load + Latent\ Load} \qquad (1)$$

Traditionally, moisture removal is achieved by passing air over a chilled coil (water, glycol, or refrigerant) and cooling it below its dew point temperature so the air releases moisture by condensing on the coil surface. This is an energy intensive process (cooling 1 lb of water by 1°F requires about 1 Btu of energy, while condensing 1 lb of water vapor to water requires about 1,000 Btu). This sub-cooling, in many instances, is then followed by re-heating the air up to the desired supply temperature.

Depending on the specifics of the project, strategies such as desiccant dehumidification, dual wheel systems, wrap around coils, and decoupling of sensible and latent loads, may show benefit in terms of annual energy use and reduced system size. To understand the applicability of these strategies, their effectiveness was studied by varying two key parameters: climate and building program type. Multiple energy models and a spreadsheet tool developed by the authors, were used to perform the analysis. Based on the results from this analysis, this paper discusses the benefits and limitations of several such dehumidification strategies and provides recommendations for early phase design considerations.

DESCRIPTION OF STRATEGIES

The following dehumidification strategies, that have shown notable energy savings on existing projects, have been evaluated against a base case of a Dedicated Outdoor Air System (DOAS) with an enthalpy wheel, chilled water cooling coil, and heating hot water reheat.

- Desiccant dehumidification
- Dual wheel system
- Wrap-around coil
- Tiered cooling (chilled water for sensible cooling, direct expansion for latent cooling)

This section discusses the operating principles behind each aforementioned strategy and highlights the differences in how each dehumidifies outside air.

Chilled Water Cooling and Dehumidification

The most common process for dehumidification is to use a chilled water cooling coil. Figure 1 shows the system schematic and psychrometric chart showing the cooling and dehumidification process.

Outdoor air, after exchanging energy with exhaust air (1-2) passes over the cooling coil to cool the air down to the required leaving air humidity ratio (2-3) and then is reheated to the required supply air temperature (3-4).

Desiccant Dehumidification

In this process, a desiccant is used to remove moisture from air. Figure 2 shows the schematic and the psychrometric process for a desiccant dehumidification system with an active desiccant wheel. Outside air, after passing through an enthalpy recovery wheel (1-2), passes over a pre-cooling coil to reduce the air temperature (2-3); pre-cooled air then blows through a desiccant dehumidification wheel where it goes through an isenthalpic process (3-4). During this process the moisture content of the air reduces and increases temperature. The high temperature air then passes over a post-cooling coil to cool it down to the required supply air temperature (4-5). This process, if optimized, can have a lower cooling load compared to the base case.

Desiccant dehumidification systems have the capability to dry the air to any desired humidity level, which is an advantage for certain applications. The limitation of this system is the need for high grade heat (about 180°F) to regenerate the desiccant. Thus, the best fit for this system is if the space needs to be maintained at a low (<50%) relative humidity or if there is a source of waste heat available to regenerate the desiccant.

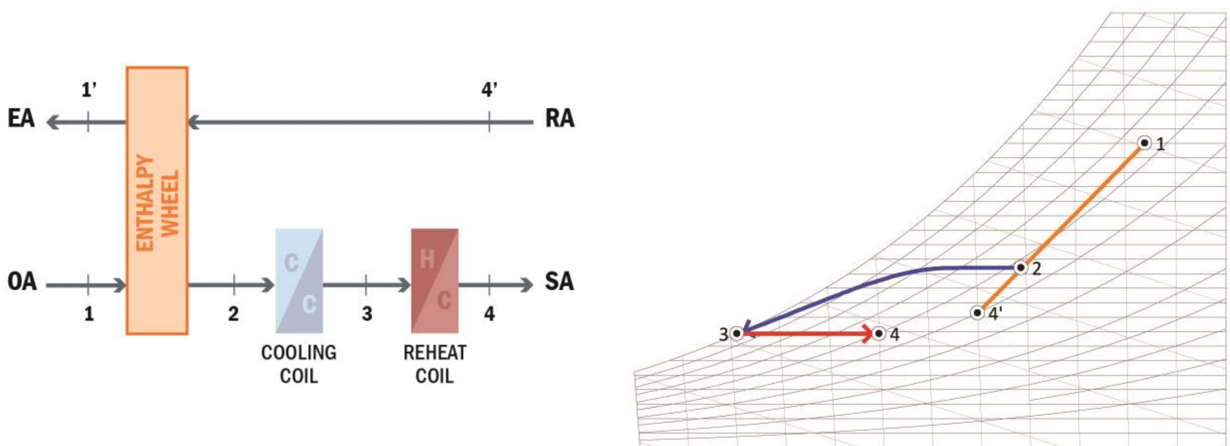

Figure 1 Chilled water cooling/dehumidification: Schematic & Psychrometric chart

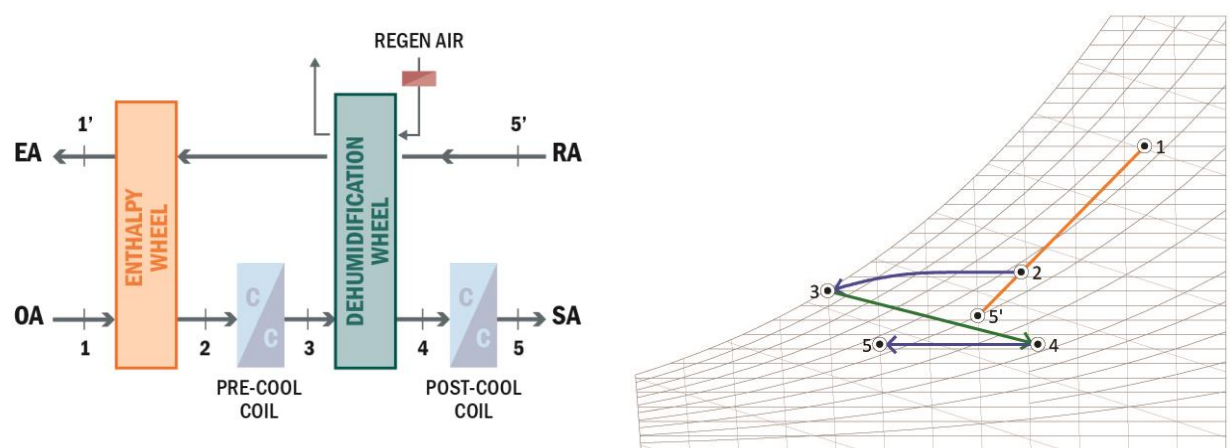

Figure 2 Desiccant dehumidification: Schematic & Psychrometric chart

Dual Wheel System with Cooling Coil

In this process, an additional, sensible heat recovery wheel is introduced after the cooling coil to provide free reheat (refer to Figure 3).

Exhaust air first passes through the sensible wheel (4'-3') where it transfers heat to the supply air (3-4) to heat it to the desired temperature. This cooler exhaust air then passes through the enthalpy recovery wheel to exchange energy with incoming outside air (1-2). The outside air then passes over the cooling coil for cooling and dehumidification (2-3).

Similar to the base case, this method relies on cooling coils for dehumidification but has the advantages of reduced coil load and free reheat.

Wrap Around Coil with Cooling Coil

This strategy employs a wrap around coil in addition to the cooling coil to make the process more energy efficient (see Figure 4).

In this process, outside air, after passing through the enthalpy recovery wheel (1-2), goes over the first sensible coil, which reduces the air temperature (2-3); the air passes through the cooling coil (3-4) for dehumidification and cooling. Then the air passes over a second sensible coil (4-5) to heat it to the desired supply air temperature. The first and second sensible coils are connected and transfer heat from air before the cooling coil to the air after the cooling coil. This helps reduce the cooling load on the primary cooling coil and provides free reheat.

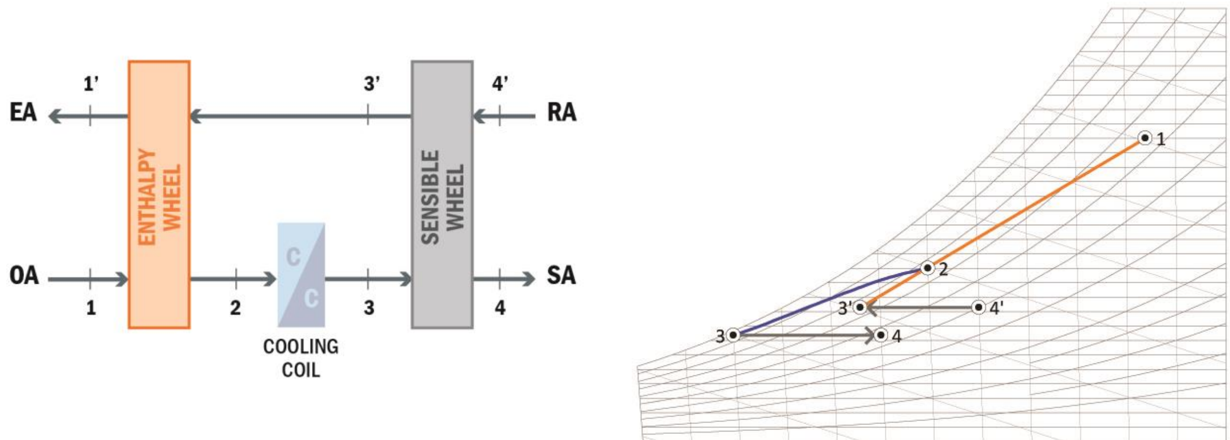

Figure 3 Dual wheel: Schematic & Psychrometric chart

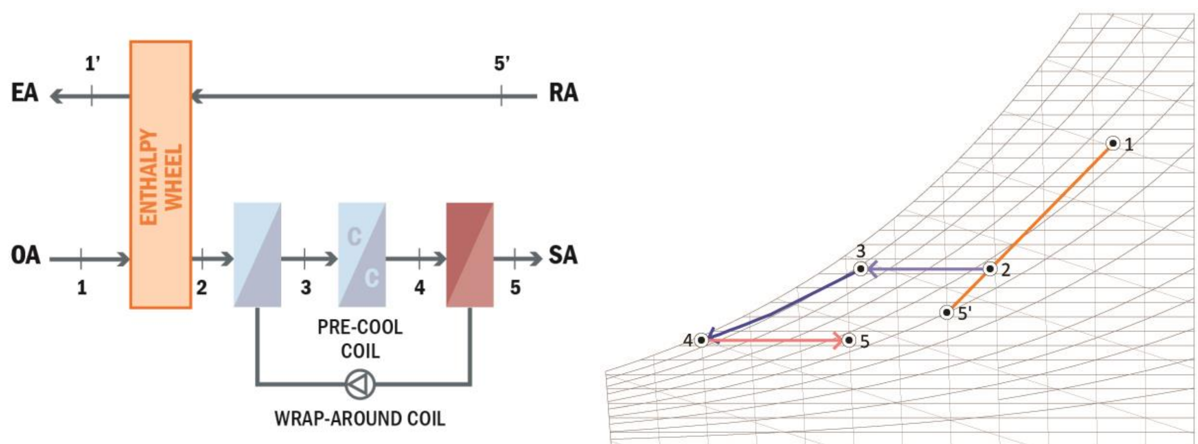

Figure 4 Wrap-around coil: Schematic & Psychrometric chart

Tiered Cooling System (Direct Expansion + CHW)

The level of dehumidification through cooling and condensation is heavily dependent on the temperature of the cooling coil. In chilled water system design, the low coil temperatures required for this process dictate the design chilled water temperature (42-44°F). Designing and operating chillers at low temperatures increases the chiller lift and reduces the efficiency of the chiller. The tiered cooling approach decouples the latent (dehumidification) and sensible cooling loads by using direct refrigerant expansion (DX) for latent cooling at the DOAS, and the chilled water system is designed and operated at a higher temperature (50-55°F), thus achieving building sensible cooling (60-70% of total cooling load) more efficiently compared to a low temperature chilled water system.

An advantage of DX dehumidification, as compared to chilled water dehumidification, is better humidity control. However, the disadvantage is lower efficiency.

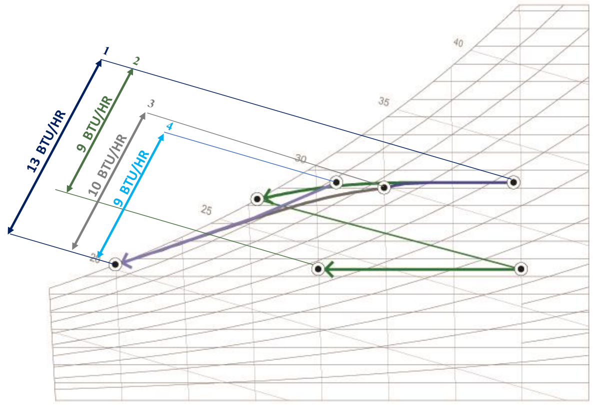

Figure 5 Psychrometric chart showing the cooling process for each strategy and their corresponding cooling load. All strategies show cooling load reduction compared to the base case. (1-Base case, 2-Desiccant dehumidification, 3-Dual wheel, 4-Wrap around coil)

METHODOLOGY

An air conditioning system's latent load is based on outdoor air (infiltration and ventilation air) and humidity gains from occupants and other internal processes. The other factor in latent load calculations is the indoor relative humidity set-point.

$$Q_{latent} = 4840 \text{ x } CFM \text{ x } (W_1 - W_2) \qquad (2)$$

Q_{latent}: *Space latent load* (Btu/h)

CFM: *Air flow in cubic feet per minute*

W_1: *Humidity ratio of return air* (lb_w/lb_a)

W_2: *Humidity ratio of supply air* (lb_w/lb_a)

Analysis parameters

For this study, the factors contributing to latent loads were translated to the following parameters:

- Climate Zone (as an indicator for outdoor air humidity)
- Sensible Heat Ratio (as an indicator for space latent loads)
- Space Relative Humidity (as an indicator of design conditions)

The combination of sensible heat ratio and the space relative humidity can be used as an indicator of building typology. The study focuses on HVAC energy savings and peak cooling load reductions that result from the following permutations and combinations of the above parameters:

- Climate Zone: 4A (Mixed - Humid), 1A (Very hot - humid), 3C (Marine)
- Sensible Heat Ratio: 0.60, 0.80
- Space Relative Humidity: 50%, 60%

Modeling Assumptions

This analysis includes a 250,000 ft^2 office building with typical occupancy and ventilation requirements. To reduce the number of variables and avoid overcomplications in the analysis, the base assumption for all test cases is that the building is served by decoupled systems i.e. a Dedicated Outdoor Air System (DOAS) provides ventilation air and latent cooling, and fan coil units meet space sensible cooling loads. The study assumes the DOAS supplies close to room neutral (65°F) ventilation air directly to the space. On-site water-cooled chillers with ASHRAE 90.1-2013 prescribed minimum efficiencies provide on-site chilled water.

Analysis Tools

Multiple energy model runs, using DOE-2.2 eQuest v3.65 were created, to extract hourly load profiles for the ventilation air flow rate and latent loads, based on different sensible heat ratios. These profiles serve as inputs to a spreadsheet-based tool developed to analyze all the dehumidification strategies discussed in this paper. Other inputs to the tool include hourly outside air conditions, space temperature and humidity set-points, and DOAS supply air conditions.

Using principles of heat and mass transfer, psychrometrics, and appropriate sequences of operation, the tool calculates cooling, heating, and fan energies for each system configuration on an hourly basis for an entire year. Benefits of using the tool are: the tool enables a side-by-side comparison of the annual energy performance associated with all the strategies; it helps optimize controls for each strategy. This tool has been successfully used on several real-world projects as a design tool and for annual energy estimation.

Visualization of Results

Figure 6 shows the whole building annual energy use of a typical office building with decoupled HVAC system in Climate Zone 4A. The whole building energy use has been characterized by end use to identify the major energy drivers in the building. The only energy end uses affected by the dehumidification strategy chosen are DOAS cooling, reheat, and fan energies.

Strategies such as desiccant dehumidification and DX dehumidification do not need chilled water to meet the latent loads, thus enabling the building chilled water loop to only have to meet the space sensible loads. By implementing this strategy, the chilled water system can be designed and operated at a higher chilled water temperature. This would significantly improve chiller performance and hence, affect the sensible cooling energy required for space conditioning. Thus, building sensible cooling energy is also accounted for as an end use affected by dehumidification strategy selection.

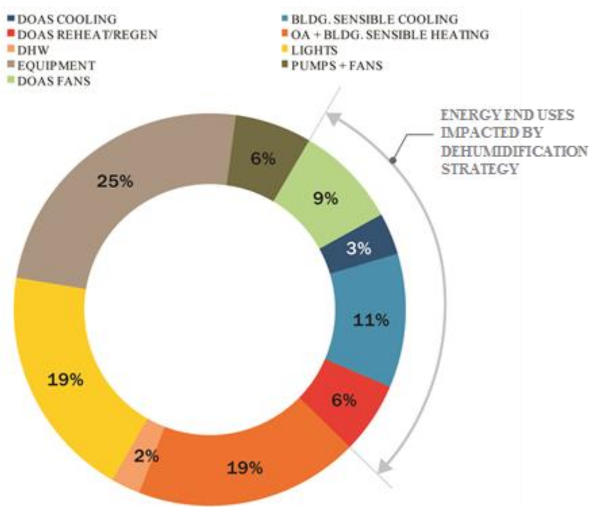

Figure 6 Whole building annual energy end use characterization for a typical office building in a mixed-humid climate

The results and discussion are based on the impact of dehumidification strategy on these selected energy end uses. All results are presented in terms of HVAC source energy, since it normalizes the electricity and gas consumption, thus acting as a suitable metric for comparison. US average source-to-site ratios of 3.34 and 1.047 were used for electricity and natural gas, respectively. (Architecture 2030, 2012; Energy Star)

RESULTS & DISCUSSION

The results are arranged in a matrix format with two varying parameters - sensible heat ratios (SHR) and maximum space relative humidity (RH) set-points, tested for each of the three climate zones of concern.

In all DX dehumidification cases, hot gas by-pass provides reheat, therefore it is considered free and not depicted on the graphs. For the base case and desiccant dehumidification strategies, reheat/regeneration heating is provided by on-site boilers operating at ASHRAE 90.1-2013 minimum efficiency.

Climate Zone 1A (Hot-Humid)

Figure 7 shows the annual HVAC source energy comparison for the dehumidification strategies tested at different relative humidity and sensible heat ratio combinations for Climate Zone 1A.

The results indicate that for any combination of the maximum indoor relative humidity (Max RH) and SHR, the dual wheel system and the wrap around coil provide the greatest energy savings. This is because, in a very hot and humid climate, sub-cooling air for dehumidification is required for a significant number of hours. A dual wheel or wrap around coil can efficiently extract heat from incoming and exhaust air to reduce the cooling load on the coil and provide free reheat for the supply air.

The desiccant dehumidification process also shows notable reduction in cooling energy compared to the base case. But, this process requires significant heating energy to regenerate the desiccant. Thus, this strategy can be implemented only if a renewable source of heat/waste heat is available on-site.

The DX dehumidification strategy shows a significant penalty in all cases due to the hot and humid climate. This is because, latent cooling is a large component of the overall cooling load. Using a less efficient DX unit compared to water-cooled chillers, significantly increases the DOAS cooling energy. Also, the operation of a high temperature chilled water loop for building sensible cooling has limited impact on chiller efficiency improvement and there is no free-cooling potential from the use of a water-side economizer.

As seen in Figure 7, implementation of strategies such as desiccant dehumidification, dual wheel, and wrap around coil, also help in reducing the DOAS peak cooling load. Most of these strategies show about 20% reduction in peak cooling load.

Climate Zone 4A (Mixed-Humid)

Figure 8 shows the annual HVAC source energy comparison for the various dehumidification strategies tested at different relative humidity and sensible heat ratio combinations for Climate Zone 4A.

In a mixed-humid climate, analysis shows that the total source energy consumed by a desiccant dehumidification system can be lower than the base case scenario. This is because, in addition to reduction in DOAS cooling energy, running the building chilled water loop for sensible cooling only at a higher chilled water temperature provides significant improvement in the chiller plant performance.

Similar to the results from desiccant dehumidification, DX dehumidification also provides significant savings compared to the base case. This is also because of the improved plant efficiency.

The strategies including dual wheel and wrap around coil provide savings only for conditions requiring strict space relative humidity control. Savings from these approaches are higher at lower SHR i.e. higher space latent gains.

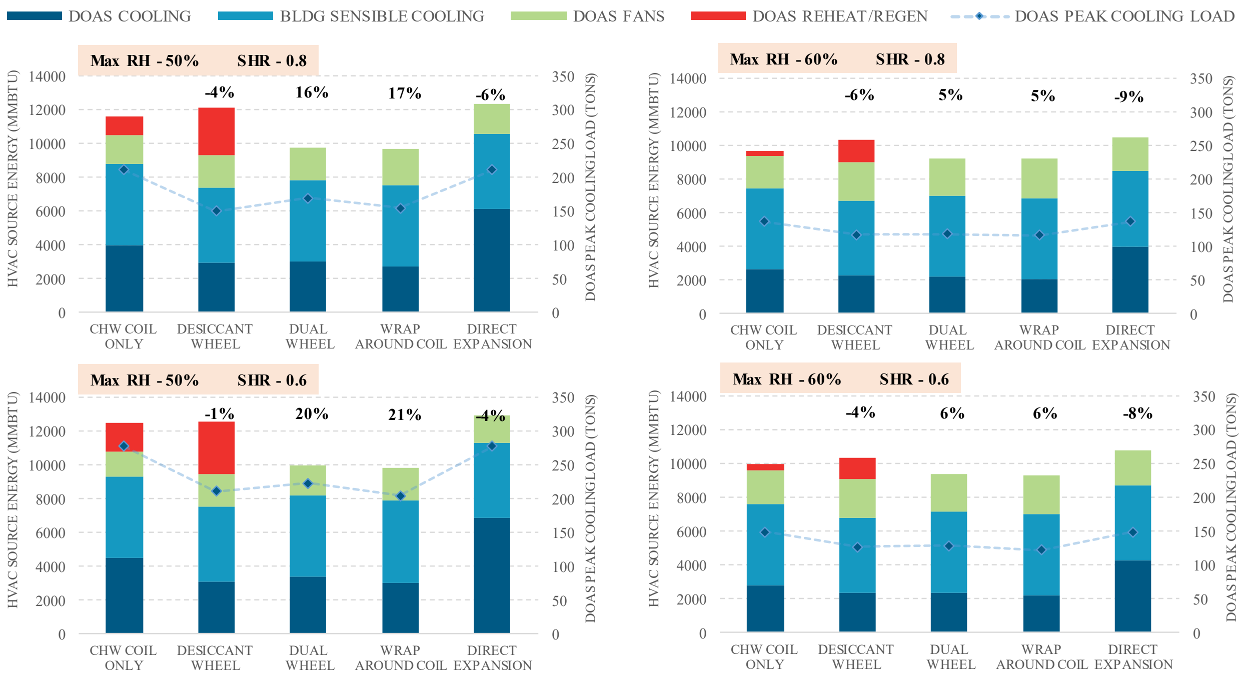

Figure 7 Annual HVAC source energy comparison across all strategies for Climate Zone 1A (Very hot-humid)

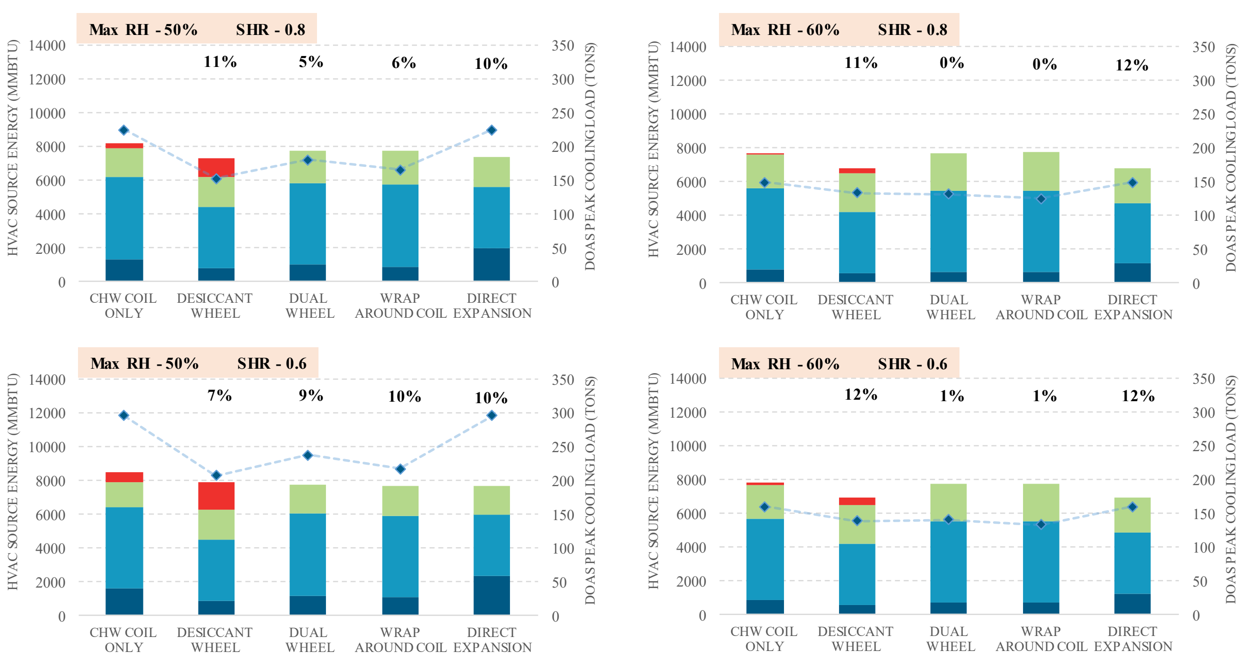

Figure 8 Annual HVAC source energy comparison across all strategies for Climate Zone 4A (Mixed-humid)

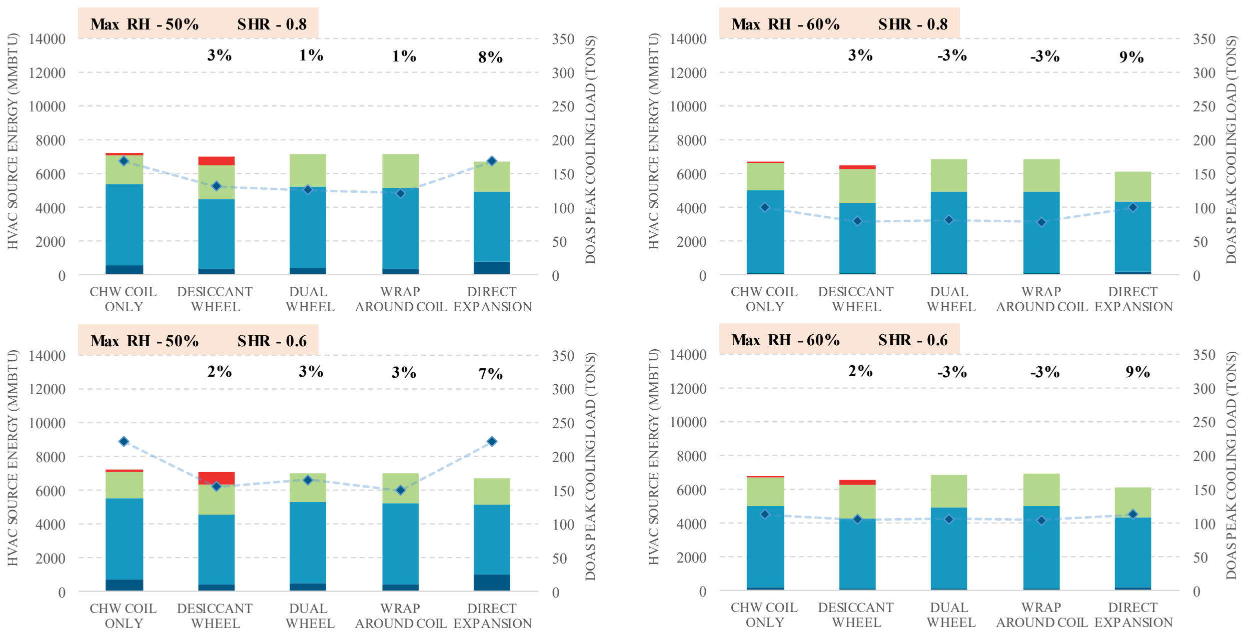

Figure 9 Annual HVAC source energy comparison across all strategies for Climate Zone 3C (Marine)

Similar to the hot-humid climate, use of desiccant dehumidification, dual wheel, or a wrap around coil provides potential reductions in the peak cooling load.

Climate Zone 3C (Marine)

Figure 9 shows the annual HVAC source energy comparison for the various dehumidification strategies tested at different relative humidity and sensible heat ratio combinations for Climate Zone 3C.

In this climate, the energy consumed by the DOAS for cooling and dehumidification is significantly lower compared to the other two Climate zones. For a relaxed space relative humidity set-point, the energy consumption at the DOAS is almost negligible.

Since the DOAS cooling load is small, a tiered approach by incorporating a DX unit for latent conditioning at the DOAS and operating the chilled water loop at a higher temperature for sensible cooling provides significant energy savings across all relative humidity and sensible heat ratio scenarios.

Dehumidification strategies show limited DOAS peak cooling load reduction for the strict 50% RH and 0.6 SHR scenario, but a negligible reduction in peak DOAS cooling load in all other scenarios.

DOAS Sizing Benefits

In case of a decoupled system configuration, dedicated outdoor air systems are sized to meet the higher of ventilation air flow rate or the air flow required to meet the space latent gains. While using the base case for latent cooling, the minimum air temperature that can be achieved is a function of the chilled water temperature. This becomes a limitation on the coil moisture removal capacity. Assuming a typical chilled water supply temperature of 42-44°F, the minimum supply air humidity ratio that can be achieved is about 0.0075-0.008 lb_w/lb_a. Using desiccant or DX based dehumidification strategies, a further reduction in the supply air humidity ratio can be achieved. Table 1 discusses DOAS sizing comparing the base case and desiccant dehumidification strategies.

Table 1 DOAS sizing comparison for two different dehumidification strategies

Building Area	250,000 ft^2
Number of Occupants	1,250
Ventilation air per ASHRAE 62.1	30,000 cfm
Occupant Latent Load	250,000 Btu
Infiltration Latent Load	38,000 Btu
Total Latent Load	**288,000 Btu**
Space Humidity Ratio (75°F, 50%RH)	0.0092 lb_w/lb_a

Sizing Parameters	Base Case	Desiccant Dehumidification
Allowable minimum humidity ratio	0.008	0.005
Airflow to meet latent load (equation 2)	49,600 cfm	14,200 cfm
DOAS Size	**49,600 cfm**	**30,000 cfm**

CONCLUSION

Figure 10 presents an early design phase decision chart summarizing optimal strategy selection across variations of the key parameters (climate, space relative humidity, sensible heat ratio). The following are the key observations from this study:

1. The selection of a particular dehumidification strategy is most dependent on the climate, followed by the space humidity setpoint, followed by the sensible heat ratio (SHR). This is because SHR deviates significantly from the design SHR on an hourly basis during actual operation.
2. In buildings with chilled water cooling, the minimum supply air humidity ratio is dictated by the chilled water temperature. This may impact DOAS sizing under certain design conditions. Also, based on real project data, if not designed correctly, this may affect the ability of the system to maintain desired space relative humidity.
3. For hot and humid climates (Figure 11a), dual wheel/wrap-around coil based approaches are the most relevant since buildings in such a climate are not designed for heating and the primary benefit of these strategies is that they eliminate reheat entirely.
4. For mixed-humid climates (Figure 11b), at stricter humidity setpoints, desiccant dehumidification is more applicable. If there is a source of waste heat available, desiccant dehumidification provides the highest energy savings potential.
5. In a mixed-humid climate, it is always energy efficient to use the tiered approach with direct expansion/desiccant for latent conditioning and high temperature chilled water for sensible conditioning.
6. For the warm-marine climate (Figure 11c), mild outside air conditions reduce the energy consumed for cooling and dehumidification significantly. Therefore, most dehumidification strategies show negligible energy benefit. Using a tiered approach in this climate can help improve the chiller plant efficiency, thus providing overall building energy use reduction.
7. Wrap around coils and dual wheels only provide savings when sub-cooling and reheat is required for dehumidification. They provide the most benefit in hot-humid climates.
8. Desiccant dehumidification, dual wheel and wrap around coil all provide peak cooling load reduction in addition to energy savings.

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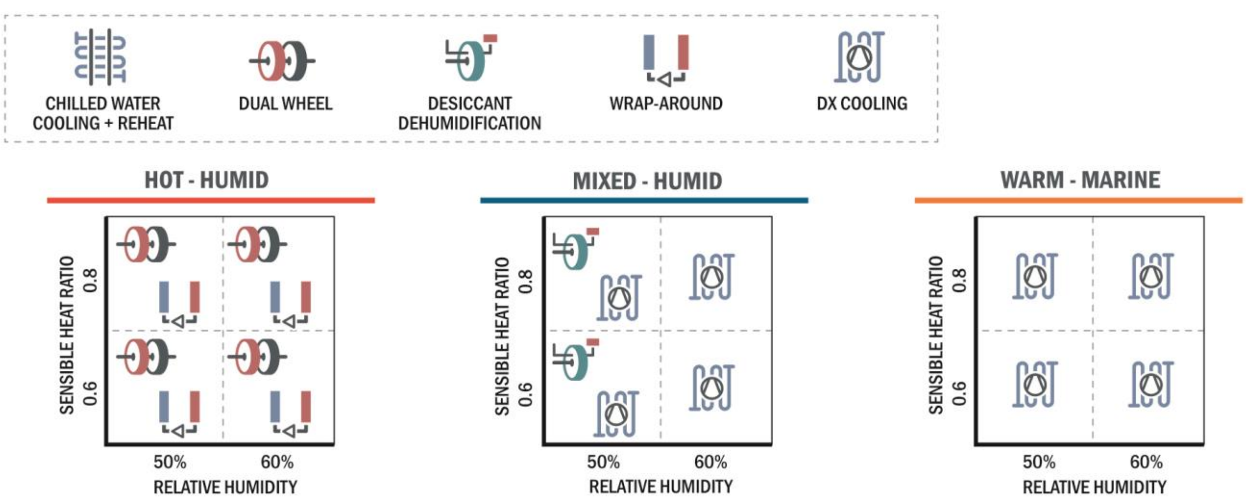

(a) (b) (c)

Figure 10 Dehumidification strategy early design decision matrix