Total Energy Wheel Control In a Dedicated OA System

By John Murphy, Member ASHRAE

With increased focus on reducing energy consumption in buildings, the use of exhaust-air energy recovery in HVAC systems is becoming more common, somewhat prompted by the requirements of ASHRAE Standards 90.1 and 189.1. Proper control of the energy-recovery device is critical to realize the expected energy savings. Although there are several other types of energy-recovery devices, and exhaust-air energy recovery is also applied in mixed-air systems, the focus of this article is on proper control of a total energy wheel (or enthalpy wheel) when applied in a dedicated outdoor air system (DOAS).

Exhaust-Air Energy Recovery

Exhaust-air energy recovery refers to the transfer of energy between the outdoor and exhaust airstreams. For the configuration discussed in this article, a total energy wheel is arranged to precondition the entering outdoor air (OA) by exchanging sensible heat and water vapor (latent heat) with the exhaust air (EA) stream (*Figure 1*).

During the cooling season, when it is hot and humid outside, the total energy wheel pre-cools and "pre-dries" (pre-dehumidifies) the outdoor air by transferring both sensible heat and water vapor to the cooler, drier exhaust airstream. During the heating season, when it is cold and dry outside, this same device pre-heats and pre-humidifies the outdoor air by removing both sensible heat and water vapor from the exhaust air and transferring it to the entering outdoor airstream.

Importance of Proper Wheel Control

Many proponents explain the benefits of exhaust-air energy recovery by focusing on the hottest and coldest days of the year. The more extreme the outdoor conditions, the greater the energy savings and the more that cooling and heating plants can be downsized.

However, during less-severe outdoor conditions, improper operation of the

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energy-recovery device can actually increase overall system energy use. Therefore, proper control of the device is critical for maximizing the energy-saving potential, while avoiding (or minimizing) energy waste.

Proper control of the energy-recovery device depends on whether sensible or total energy recovery is used and what type of HVAC system it is applied to.[1,2] As mentioned previously, this article focuses on control of a total energy wheel when applied in a dedicated outdoor air system (DOAS) (as depicted in *Figure 1*).

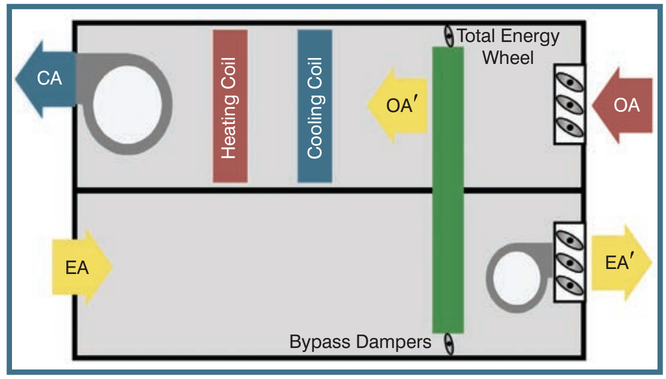

Figure 1: Exhaust-air energy recovery in a dedicated OA system.

Turn the wheel off to avoid transferring unwanted heat to the entering OA. For a total energy wheel, when the enthalpy of the outdoor air drops below the enthalpy of the exhaust air (h_{OA} < h_{EA}), the wheel provides no cooling energy recovery benefit. In fact, unless it is turned off, the wheel will actually increase the load on the cooling coil by increasing the dry-bulb temperature (by transferring sensible heat) and/or increasing the humidity ratio (by transferring water vapor) of the outdoor airstream.

At the example conditions depicted in *Figure 2*, the enthalpy of the outdoor air (h_{OA} = 24.3 Btu/lb [38.5 kJ/kg]) is less than the enthalpy of the exhaust air (h_{EA} = 28.2 Btu/lb [47.7 kJ/kg]). If the total energy wheel continues to operate at this condition, it increases the enthalpy of the air leaving the wheel (OA′) to 27.0 Btu/lb (44.9 kJ/kg), which increases the load on the cooling coil (*Figure 2*).

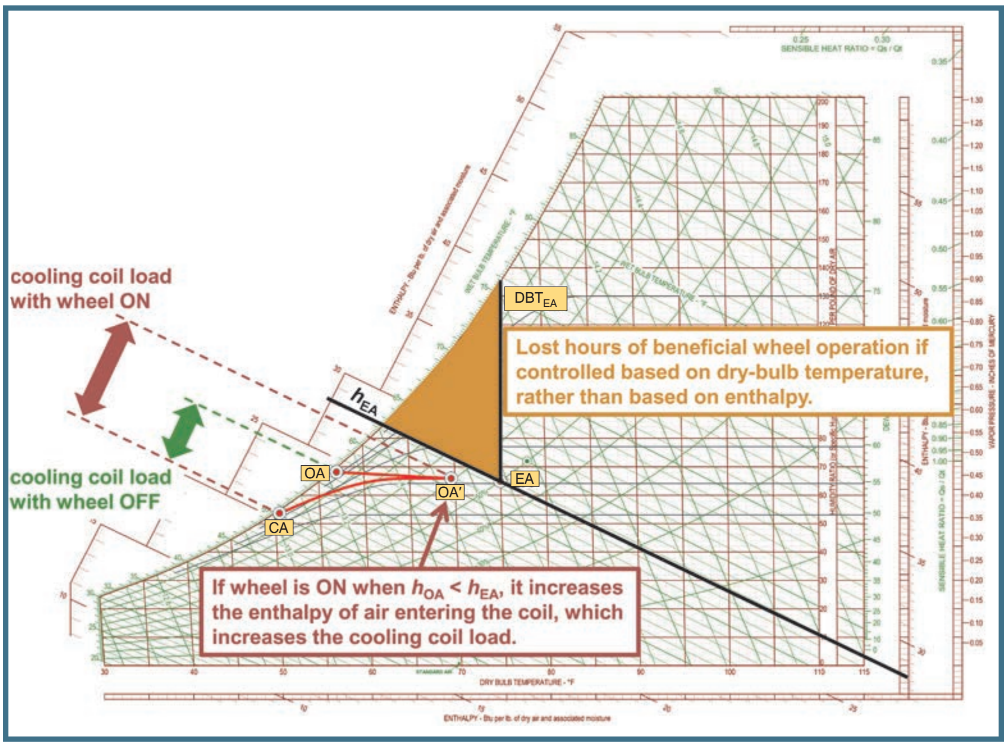

Figure 2: Total energy wheel control on a mild, rainy day.

However, if the wheel is turned off when h_{OA} < h_{EA}, the enthalpy of the air entering the cooling coil is lower, avoiding this increase in coil load. For a 10,000 cfm (4700 L/s) dedicated OA unit, operating the wheel at this condition increases the cooling coil load from 14 tons (50 kW) with the wheel off, to 25 tons (88 kW) with the wheel on … an 80% increase!

In this configuration, consider adding bypass dampers (*Figure 1*) on one or both sides of the wheel. Opening these dampers when the wheel is turned off can reduce the airside pressure drop and minimize fan energy use. *Note: In this operating mode, the wheel is typically cycled on for one or two minutes each hour to help keep it clean.*

Figures 3 and *4* depict the annual occurrences of outdoor conditions, in both Atlanta and Chicago, for a system that operates between 6 a.m. and 6 p.m. every weekday.[3] These charts emphasize the importance of proper total energy wheel control. In Atlanta, there are 1,333 operating hours when h_{OA} > h_{EA}, assuming exhaust air at 75°F (24°C) dry bulb and 50% relative humidity. During these hours, the wheel can operate to reduce cooling energy use. In addition, there are 587 hours when the temperature of the entering outdoor air (DBT_{OA}) is colder than the desired temperature of the conditioned outdoor air (DBT_{CA}), which is assumed to be 50°F (10°C) in this example. During these hours, the wheel can operate to reduce heating energy use. For the remaining 1,200 hours of system operation, the wheel should be turned off to avoid transferring unwanted heat to the entering OA (*Figure 3*).

In Chicago, there are fewer hours (867) when the wheel operates to reduce cooling energy use, but more hours (1,294) when it operates to reduce heating energy use (*Figure 4*). However, there are still 959 hours of system operation when the wheel should be turned off.

Some people choose to control a total energy wheel based on the dry-bulb temperature of the two airstreams, rather than based on enthalpy. Although this avoids the cost and maintenance required to install humidity sensors, it also reduces energy savings during the cooling season.

If the total energy wheel is turned off whenever the dry-bulb temperature of the outdoor air drops below the temperature of the exhaust air (DBT_{OA} < DBT_{EA}), the wheel will be off for many hours when it could have been used to reduce cooling energy use. During those hours when DBT_{OA} < DBT_{EA}, but the enthalpy of the outdoor air is still higher than the enthalpy of the exhaust air (h_{OA} > h_{EA}), the wheel could be operating to reduce the enthalpy of the air entering the cooling coil (orange region in *Figure 2*).

For the example system operating hours depicted in *Figures 3* and *4*, there are 483 hours in Atlanta, and 387 hours in Chicago, when the wheel would be unnecessarily turned off if control is based on dry-bulb temperature, rather than based on enthalpy.[3]

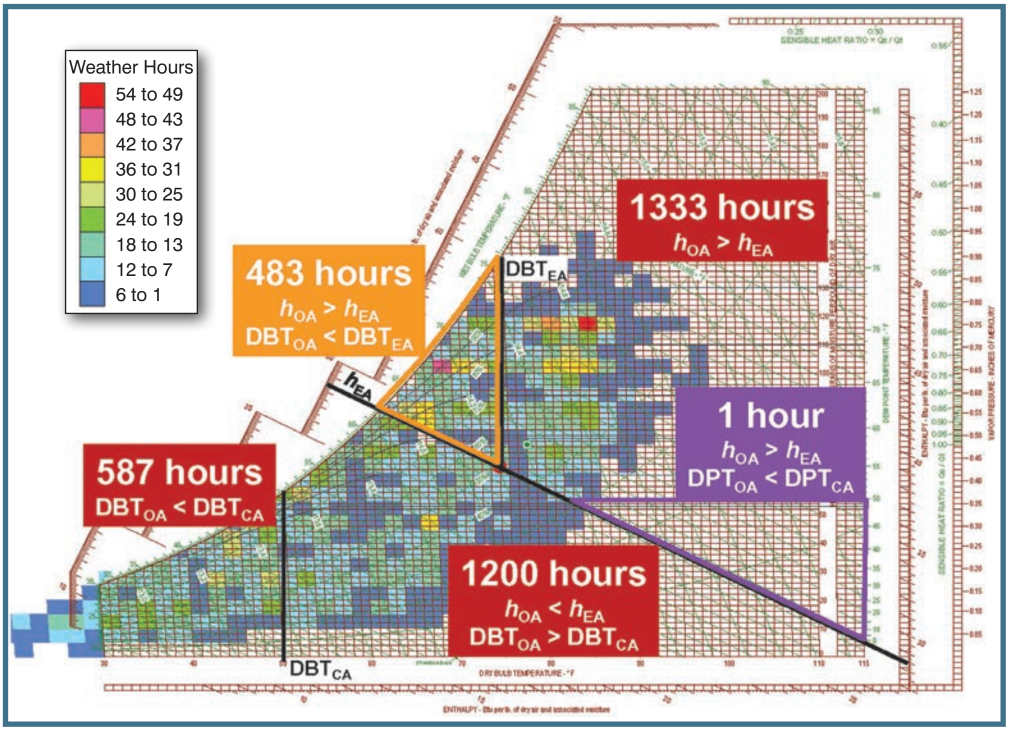

Figure 3: Distribution of total energy wheel operating hours (Atlanta). Monday through Friday 6 a.m. to 6 p.m.

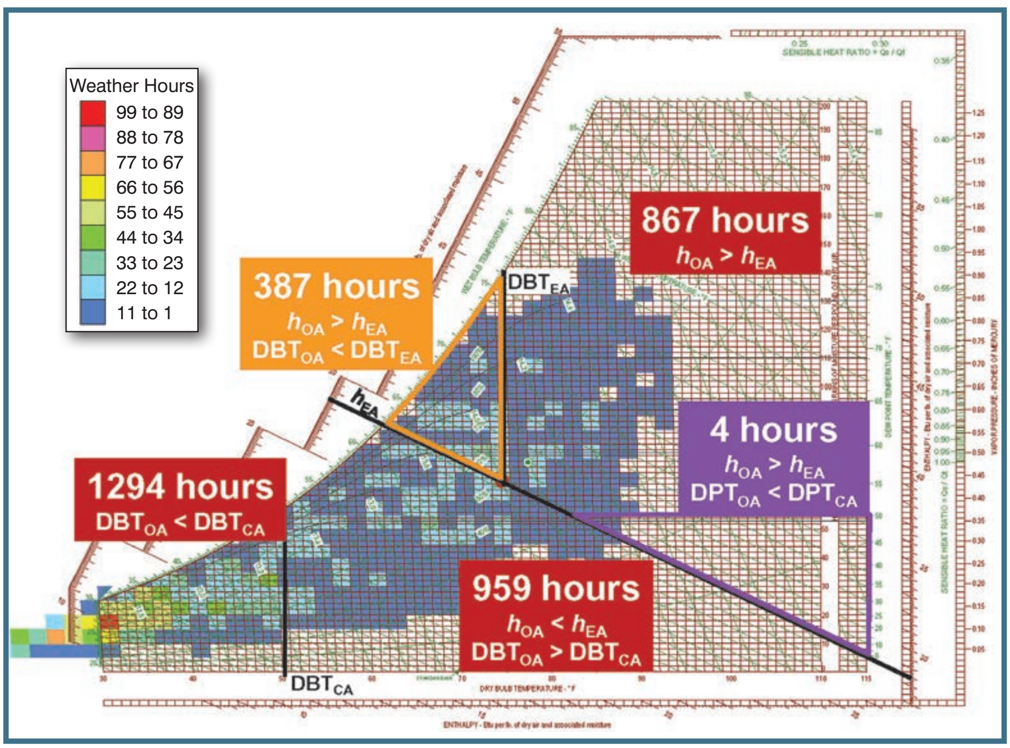

Figure 4: Distribution of total energy wheel operating hours (Chicago). Monday through Friday 6 a.m. to 6 p.m.

Modulate wheel capacity to avoid transferring unwanted water vapor to the entering OA. When it is hot and dry outside, a total energy wheel transfers sensible heat from the entering outdoor air to the cooler exhaust airstream. But it also transfers water vapor from the more-humid exhaust air to the drier outdoor airstream. Some means of controlling the capacity of the total energy wheel may be needed to avoid over-humidifying the entering outdoor air.

If the enthalpy of the outdoor air is higher than the enthalpy of the exhaust air (h_{OA} > h_{EA}), but the outdoor dew-point temperature is less than or equal to the desired dew point of the conditioned outdoor air ($DPT_{OA} \leq DPT_{CA}$), which is 50°F (10°C) in this example, it is possible that the wheel could over-humidify the entering outdoor air, requiring the dehumidification equipment to be activated (*Figure 5*).

Whether this results in energy waste depends on the design and control of the dedicated OA system. If the system is designed to dehumidify the outdoor air to a constant dew-point temperature and then reheat it to a "neutral" dry-bulb temperature, over-humidifying the entering outdoor air could significantly increase system energy use. In the example depicted in *Figure 5*, dehumidifying the over-humidified air (OA′) to 50°F (10°C) requires more energy than the sensible cooling needed to cool the entering outdoor air (OA) to the desired neutral dry-bulb temperature, which is 72°F (22°C) in this case.

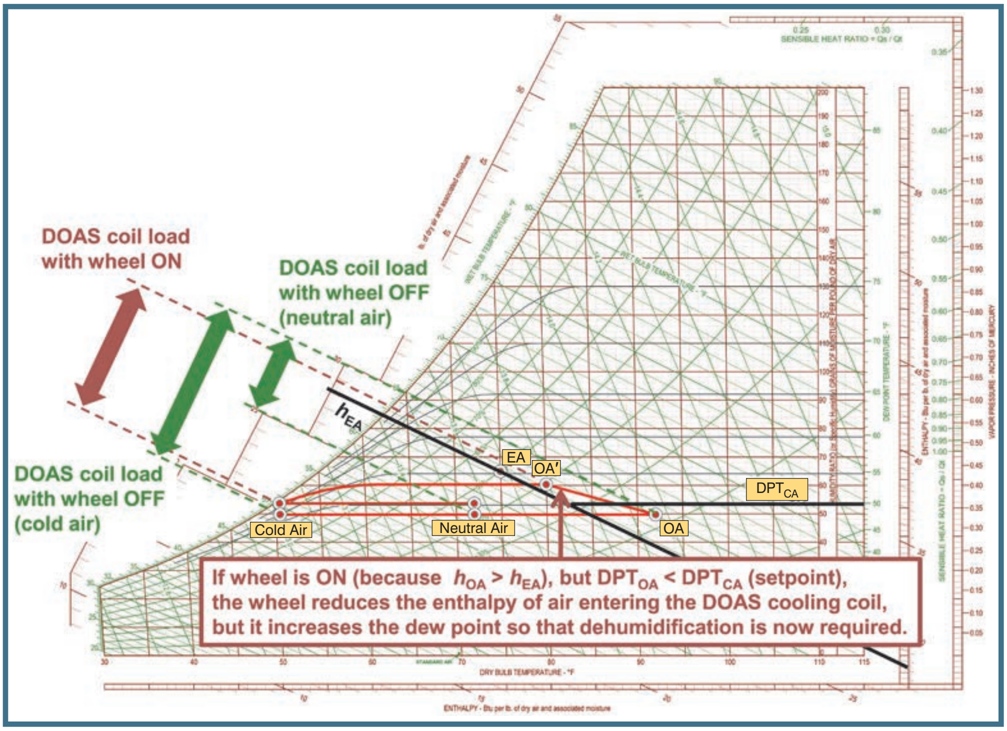

Figure 5: Total energy wheel control on a hot, dry day.

However, if the system is designed to deliver air at a cold temperature (not reheated to neutral), the air would be cooled to 50°F (10°C) whether the wheel is operating or not. In this case, operating the total energy wheel reduces the enthalpy of the air entering the cooling coil, reducing the load on that coil.

Note: At this example operating condition, the load on the DOAS cooling coil appears to be less for the neutral-air system than for the cold-air system. However, the additional cooling done by the DOAS in the cold-air system is useful sensible cooling that reduces the sensible cooling required of the local HVAC equipment out in the zones. For the neutral-air system, this difference in cooling load is simply shifted to the local sensible cooling equipment, so that the overall cooling load is still the same or similar.

Operating at such a condition is probably rare for many applications. For the example system operating hours depicted in *Figures 3* and *4,* there is only one hour in Atlanta, and four hours in Chicago, when this combination of outdoor conditions occur such that the wheel may be over-humidifying the entering outdoor air. (In climates that experience a lot of hours at these conditions,[3] the system is likely to use a sensible energy-recovery technology, rather than a total energy wheel, and this control mode would not apply.)

Modulate wheel capacity to avoid overheating (and possibly over-humidifying) the entering OA during cool weather. When it is cool outside, some means of controlling the capacity of the total energy wheel may be needed to avoid overheating, and possibly over-humidifying, the entering outdoor air.

At the example conditions depicted in *Figure 6,* the dry-bulb temperature of the outdoor air (45°F [7°C]) is colder than the desired temperature of the conditioned OA, which is 50°F (10°C). Therefore, the total energy wheel could be turned on to transfer sensible heat from the warmer exhaust air to preheat the entering outdoor air stream. In this example, if the wheel operates at full heating capacity, the air leaves the wheel (OA′) at 66°F (19°C), which is warmer than desired.

Because a dedicated OA system is accompanied by local HVAC equipment, which provides heating or cooling for each zone, whether this "over-heating" of the outdoor air actually results in wasted energy depends on whether the zones currently require heating or cooling. If a zone served by this dedicated OA unit requires heating at this example condition, then the over-heated OA may be beneficial since it reduces the need of local equipment to add heat to the zone. However, if a zone requires cooling, the over-heated OA may cause the local equipment to use additional "re-cooling" energy.

Note: Over-cooling by the dedicated OA system often occurs when occupancy is low. If this is the case, consider implementing demand-controlled ventilation. By reducing the outdoor airflow delivered to a zone when there are less people in that zone, it may avoid this over-cooling.

Further, others have proposed that if a dedicated OA system serves zones that are dominated by internal cooling loads (thus requiring cooling almost year-around), the wheel should remain off during cool weather.[4] In this case, the cooler air supplied by the dedicated OA unit—unheated at 45°F (7°C) for the example depicted in *Figure 6*, compared to a fixed setpoint of 50°F (10°C)—offsets more of the zone cooling load. For an application dominated by internal cooling loads, this strategy likely reduces overall system energy use. Even though a typical dedicated OA system cannot provide 100% economizer cooling capacity, allowing the system to deliver cooler air at such conditions extends its ability to provide some amount of "free" cooling.

But now consider the impact on humidity. In this ex-

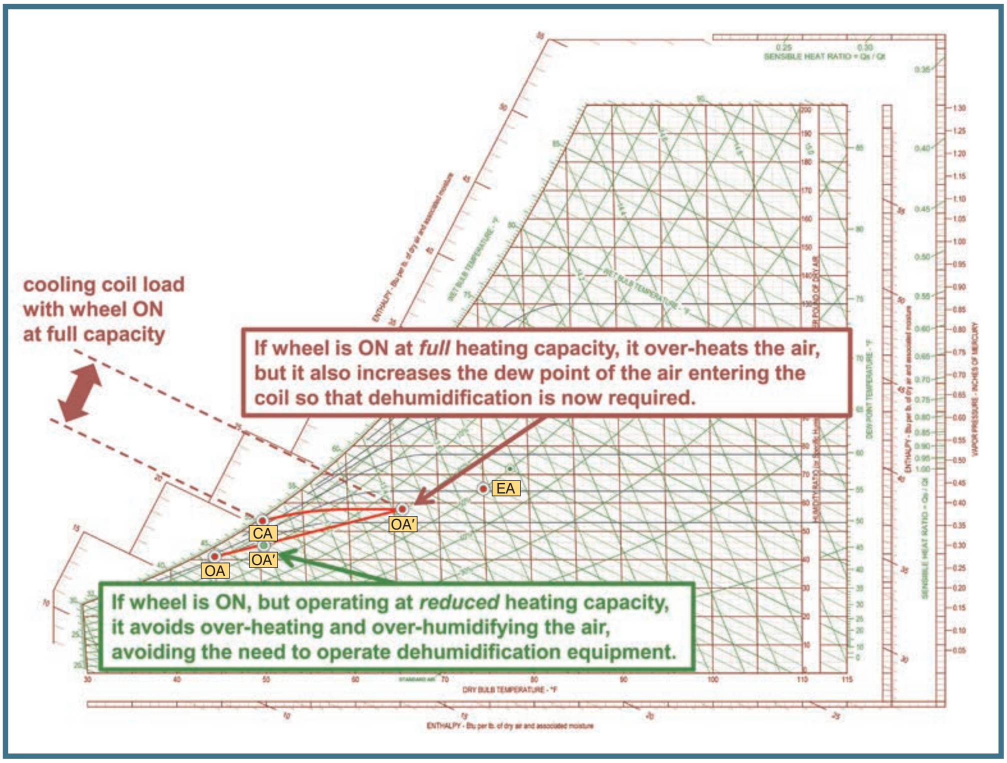

Figure 6: Total energy wheel control on a cool, dry day.

ample, if the total energy wheel operates at full capacity, it transfers water vapor from the more-humid exhaust air and the outdoor air leaves the wheel (OA′) at a 52°F (11°C) dew point, which is higher than the 50°F (10°C) setpoint. The result is that the cooling coil may need to activate to dehumidify the air (*Figure 6*).

Unnecessarily operating the total energy wheel at full heating capacity may require recooling and/or may require operating the dehumidification equipment, both of which are unnecessary uses of energy.

Reducing the capacity of the wheel can prevent both overheating and over-humidifying. Modulating an exhaust-side bypass damper reduces the amount of air passing through the wheel, which decreases the amount of energy recovered. In the example depicted in *Figure 6*, reducing airflow through the exhaust-side of the wheel results in less heat transferred to the outdoor airstream, and air leaves the supply-side of the wheel at the desired 50°F (10°C) dry-bulb temperature, rather than being over-heated.

Modulating wheel capacity also avoids over-humidifying the outdoor air. In this example, air leaves the wheel at a 45°F (7°C) dew point, which is below the 50°F (10°C) setpoint, so dehumidification is not needed.

Others suggest slowing the rotational speed of the wheel as a means to reduce capacity. Although a discussion of these two capacity control methods is beyond the scope of this article, this author recommends modulating an exhaust-side bypass damper because it provides a wider range of capacity control and has a more linear unloading characteristic, which results in simpler and more stable control.[2]

Modulate wheel capacity, or preheat the air, to prevent frosting. When it is very cold outside, an exhaust-air energy-recovery device is subject to frost buildup. Since a total energy wheel transfers sensible heat and water vapor from the exhaust air to the colder, drier outdoor airstream, the exhaust air is cooled and dehumidified. If the condition of the exhaust air passing through the wheel reaches saturation, moisture will begin to condense on the wheel surface. If the surface temperature of the wheel is below 32°F (0°C), this condensed moisture will begin to form frost on the exhaust-side of the wheel. This reduces the energy recovered and may result in structural damage to the device.

The outdoor temperature at which frost begins to form depends on the effectiveness of the wheel, the temperature and humidity of the exhaust airstream, and the outdoor and exhaust airflows.[1,2]

For a total energy wheel, one of two control strategies is typically used to avoid frosting:

1. Reduce the capacity of the wheel. Modulating a supply-side bypass damper decreases the amount of heat transferred, thereby

Understanding Dual-Wheel Configurations

Although this article focuses on control of a total energy wheel in a dedicated outdoor air system (DOAS), realize that a different equipment configuration may result in a different control strategy. Although there are several configurations,[5] one such example is a dual-wheel configuration that combines a total energy wheel and a series desiccant dehumidification wheel (*Figure 7*). The total energy wheel preconditions the entering outdoor air by exchanging energy with the exhaust airstream, while the series desiccant wheel allows the unit to deliver very dry air, efficiently.

For the series desiccant wheel to regenerate, the upstream (regeneration) side of the desiccant wheel must be exposed to air with a relative humidity (RH) of about 70% or less. In the previous example of a mild rainy day, the RH of the entering outdoor air was nearly 100% (*Figure 8*). This is too high to regenerate the desiccant.

One solution could be to preheat the entering outdoor air. In this example, increasing the dry-bulb temperature of the outdoor air by 12°F (7°C) lowers the relative humidity to about 65%, which is low enough for the desiccant to regenerate.

However, in the case of a dual-wheel unit, when high outdoor RH conditions occur, operating the total energy wheel transfers sensible heat from the exhaust air to the entering outdoor airstream (OA). This lowers the relative humidity of the air before it enters the upstream (regeneration) side of desiccant wheel (OA′), allowing it to release water vapor to the air and continue the cycle (*Figure 8*).

For this particular configuration, it is advantageous to continue operating the total energy wheel, even though $h_{OA} < h_{EA}$. Although this increases the enthalpy of the air entering the coil, it eliminates or reduces the need to add regenerative preheat, even at this high RH condition.

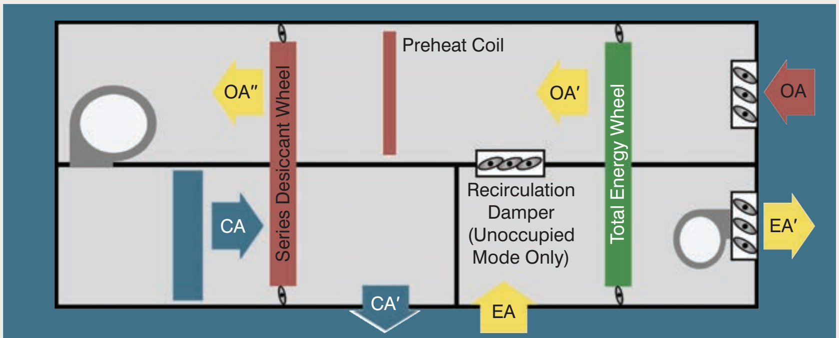

Figure 7: Total energy wheel and a series desiccant dehumidification wheel.

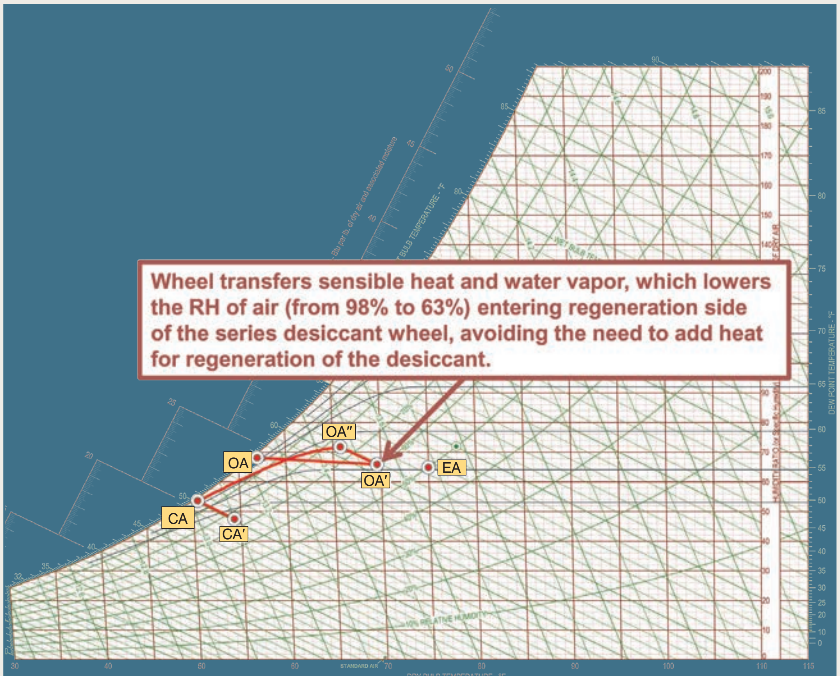

Figure 8: Total energy wheel control on a mild, rainy day for a dual-wheel unit.

raising the surface temperature of the device to prevent frost from forming. This approach is often used in climates and applications where frost formation is expected to be a rare occurrence. In many cases, the bypass dampers are already incorporated into the equipment to reduce fan energy when the wheel is turned off.

2. Preheat the outdoor (or exhaust) air before it enters the wheel. Raising the temperature of the air entering either the supply- or exhaust-side of the wheel prevents the exhaust air from reaching a condition at which frost might begin to form. This approach is used in climates and applications where frost formation is expected to be more common. Although this approach requires the installation of a small preheat coil, it allows the wheel to continue operating at full energy-recovery capacity even during the coldest times of the year.

Modeling Exhaust-Air Energy Recovery

Although proper control of the device is critical for maximizing the economic benefit of exhaust-air energy recovery, some-times these devices are not purchased because the predicted energy savings does not result in an acceptable financial return.

One reason may be that capabilities of energy simulation software to model this strategy differ significantly. It is important to verify that control of the energy-recovery device is being modeled properly to accurately predict the energy-saving benefits.

Figures 9 and *10* depict the simulated operation of a total energy wheel in a dedicated OA system that serves a single elementary school classroom, according to one commonly used energy simulation program.[6] This particular program is capable of modeling proper wheel control, but the user has the ability to change the default settings to model improper wheel control.

Figure 9 displays the simulation results on a mild day, when outdoor conditions are 56°F (13°C) dry bulb and 38°F (3°C) dew point. At this hour, the enthalpy of the outdoor air is 18.7 Btu/lb (25.6 kJ/kg), which is less than the enthalpy of the exhaust airstream.

The top half of *Figure 9* depicts system operation where the wheel is turned off to avoid increasing the enthalpy of the entering outdoor air. The bottom half of this figure depicts operation where the wheel is not controlled properly, and remains turned on. If the wheel continues to operate, it increases the enthalpy of the air leaving the wheel—to 23.3 Btu/lb (36.3 kJ/kg) at this example condition. This increases the load on the cooling coil.

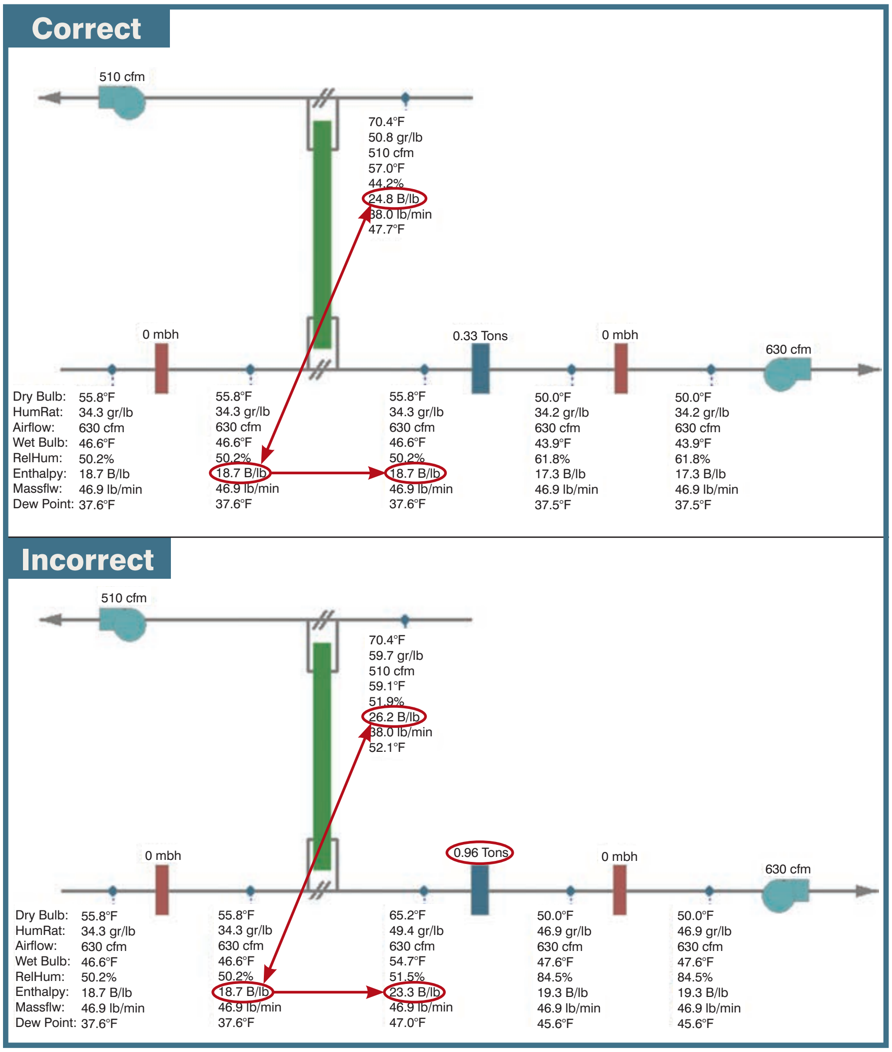

Figure 9: Modeling on/off total energy wheel control on a mild day. **Correct (top):** When $h_{OA} < h_{EA}$ the wheel should be off, and it is off. **Incorrect (bottom):** When $h_{OA} < h_{EA}$ the wheel should be off, but it is on. This increases enthalpy of the air entering the cooling coil, which increases the coil load.

Figure 10 displays the simulation results on a cooler day, when outdoor conditions are 47°F (8°C) dry bulb and 45°F (7°C) dew point. When it is cool outside, the wheel could operate to preheat the entering outdoor air, but wheel capacity may need to be modulated to avoid over-heating or over-humidifying the air.

The top half of the *Figure 10* system depicts operation with modulated wheel capacity. The exhaust-side bypass dampers modulate so the wheel recovers only enough heat to warm the OA to the desired leaving-air temperature, which is a 50°F (10°C) winter setpoint for this example.

The bottom half of this figure depicts operation without wheel capacity modulation. If the wheel continues to operate at full heating capacity, it over-heats the air leaving the wheel—to 60°F (16°C) at this example condition. As discussed previously, this may or may not require re-cooling to the desired 50°F (10°C) setpoint.

The annual energy impact of proper total energy wheel control for a specific building depends on climate, building use, and system design. *Figure 11* depicts the impact of proper wheel control on cooling energy used by the dedicated OA equipment serving a pod of K-12 classrooms. For this example analysis, the dedicated OA system was modeled to deliver the conditioned OA at 50°F (10°C) dry bulb year-round (12 months of occupancy). Proper control of the total energy wheel—turning off the wheel when $h_{OA} < h_{EA}$ and modulating an exhaust-side bypass damper to prevent over-heating—reduced the cooling energy used by the dedicated OA equipment by 5% to 10% in the hotter climates of Houston and Atlanta, and by 15% to 20% in the milder climates of Chicago and Minneapolis. (This equates to about 2% to 3% reduction in the overall energy use for this pod of classrooms.) This difference is primarily due to the fact that Chicago and Minneapolis experience more hours when outdoor enthalpy is low, which is when proper wheel control is important.

For this example, 82% of this difference in cooling energy use in Atlanta is due to operating the wheel when it should be off (when $h_{OA} < h_{EA}$), and 18% of this difference is due to operating the wheel at full heating capacity when capacity should have been modulated. For Chicago, 64% is due to operating the wheel when it should be off, and 36% is due to operating the wheel at full capacity, rather than modulated.

Summary

Achieving maximum energy savings and minimizing the payback period for exhaust-air energy recovery depends on proper control of the energy-recovery device. On the hottest and coldest days of the year, energy savings can be significant. But, during less severe outdoor conditions, improper operation of the energy-recovery device may actually increase system energy use.

Although this article focused on control of a single, total energy wheel in a dedicated OA system, understand that the control strategy may differ depending on the equipment configuration, application, and climate.[1,2,4]

Finally, energy simulation software must be capable of modeling proper control of the energy-recovery device to accurately predict the energy-saving benefits. Since the decision to invest in exhaust-air energy recovery is often based on financial return, underestimating energy savings may result in underuse of this technology.

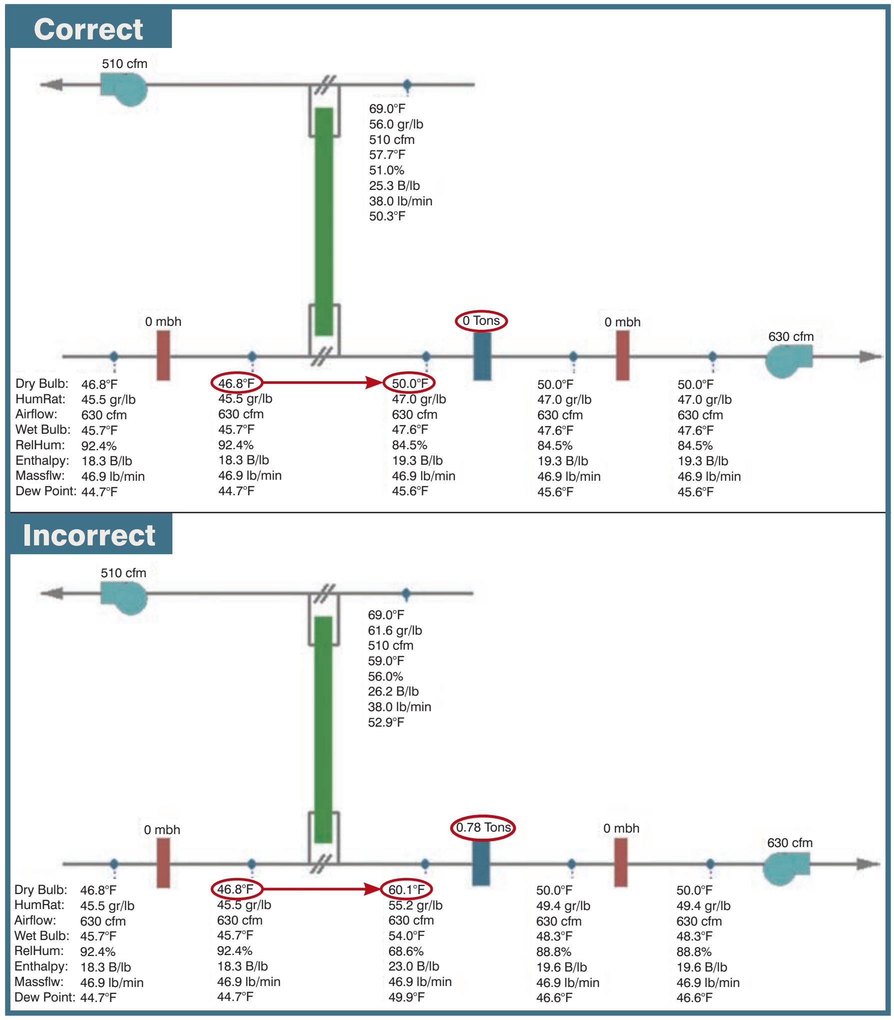

Figure 10: Modeling modulating capacity control on a cool day. **Correct (top):** When it is cool outside, wheel capacity should be modulated to avoid overheating, and it is. Wheel recovers only enough heat to warm the OA to 50°F (10°C) (winter setpoint). **Incorrect (bottom):** When it is cool outside, wheel capacity should be modulated to avoid over-heating, but instead the wheel is operating at full capacity. The result is recovery of too much heat, warming the air above 50°F (10°C) (winter setpoint), which may require re-cooling.

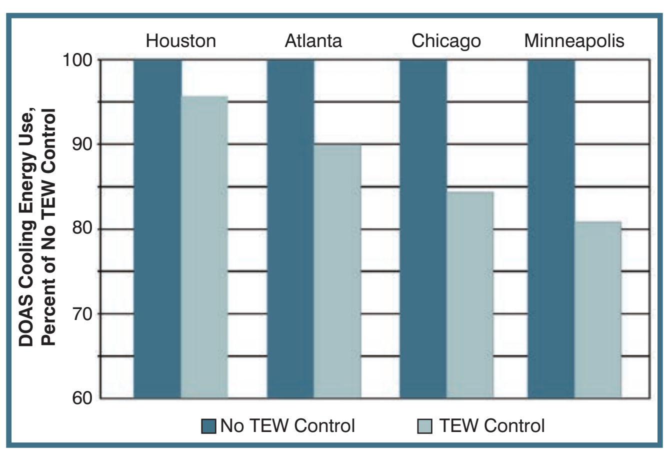

Figure 11: Annual DOAS cooling energy impact of proper total-energy wheel control.

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