Energy Efficient Strategies *to Control* Relative Humidity in Schools

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Southern Energy-Efficiency Center

Building Energy Solutions for the South

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Summary

As heat and water vapor enter a school building, they become sensible and latent cooling loads. By their very nature, AC systems remove both heat and water vapor from the room air, especially at full load. At part-load, some AC systems dehumidify the room air effectively, while others do not. It is important to select AC systems that effectively control humidity.

Even more important than selecting a main AC system with good dehumidification potential, conditioning of ventilation air is critical. Because about 80% of the latent cooling load of a school building comes from the ventilation air (during hot and humid weather), use of a DOAS to strip the moisture from the OA is the most effective means for controlling indoor RH. When hot and humid air flows directly across a cold coil, the latent cooling performance of the system is much better than alternative methods. To achieve an even higher level of system performance and energy efficiency, consider use of a DOAS with a dedicated ADS, which can reduce fan energy, prevent space overcooling, and limit the need for reheat.

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During periods when air conditioning is needed, ideal indoor conditions in school buildings (and in many other buildings as well) are about 75°F and 50% relative humidity (RH). While comfortable temperature conditions generally fall only within a small range, such as 75°F +/– 3°F (e.g., 72 to 78°), comfortable RH conditions extend across a considerably wider range, such as 48% +/– 8% (e.g., 40% to 56%). From an energy efficiency perspective, however, we would like the space to be no colder than necessary and no drier than necessary, because additional energy is required to lower the space temperature or lower the space RH.

Air conditioning systems generally remove both heat (sensible cooling) and water vapor (latent cooling) from the room air. Because of this, AC systems can potentially control both temperature and RH. There is, however, much variability from one AC system to another regarding their ability to provide latent cooling. Some system types remove almost no water vapor from the room air. This is a very important point, which we will come back to later (see Selecting the Main AC System).

Ideal indoor conditions of 75°F and 50% RH also correspond to a dew point temperature of 55°F. Dew point temperature is a measure of the absolute moisture content of the air. When the dew point temperature is 55°F, water vapor represents about 1% (actually 0.92%) of the mass of the air. When the outdoor dew point temperature is higher than 55°F, both ventilation air and air infiltration can introduce moisture (water vapor) into the space and cause an increase in RH. Table 1 illustrates the indoor RH that would result if an AC system provides no latent cooling (and also assuming no internal moisture generation). The higher the outdoor dew point temperature, the higher the potential indoor RH (if the AC system fails to provide the needed latent cooling.)

Table 1. Indoor dew point temperature (T_{dp}) and RH that would result from a specific outdoor dew point temperature, assuming no internal moisture generation and the AC system provides no latent cooling.

Outdoor T_{dp}	Room Temp.	Room RH[1]
50ºF	75ºF	40%
55ºF	75ºF	50%
60ºF	75ºF	60%
65ºF	75ºF	70%
70ºF	75ºF	85%
75ºF	75ºF	100%

[1] Approximate room RH.

From Table 1 we can conclude that when the outdoor dew point temperature is above 55°F, some moisture removal (latent cooling) may be required. The higher the outdoor dew point temperature, the greater the moisture removal that will be required. In part because schools have high occupancy density and therefore require high ventilation rates, good latent cooling performance is very important in classrooms during hot and humid weather. From Table 2 we can see that classrooms have approximately 5 times and 15 times greater ventilation density than office buildings and residences (cfm per 1000 ft^2 of floor area, based on ASHRAE Standard 62), respectively. Because of high ventilation rates and because commonly used AC systems do not have the capability to provide effective humidity control, it is common for schools to have humidity control problems during hot and humid weather.

Table 2. Typical occupancy and ventilation density of a residence, office space, and classroom.

Type of space	Number of persons per 1000 ft^2	Approximate ventilation rate (cfm/1000 ft^2)
Single-family home (4 BR, 2000 ft^2)	2.5	29
Office	5	85
Classroom	29	410

(Note: cfm = cubic feet per minute.)

Water vapor is introduced into the indoor environment from both outside and inside the building.

- Moisture enters the building from outdoors by three mechanisms; 1) air transported water vapor from outdoors to indoors (during hot and humid weather) by means of infiltration or ventilation, 2) vapor diffusion through materials of the building envelope including the slab, and 3) bulk water entry such as rainwater penetration or irrigation overspray.
- Moisture is introduced into the building from interior sources by several mechanisms; 1) water vapor from respiration and perspiration from people, 2) moisture from plants, 3) evaporation from water fixtures such as sinks and toilets, 4) moisture from building materials such as concrete slabs, masonry walls, and materials wetted during construction, 5) plumbing leaks, and 6) cleaning of carpets, mopping, etc.

During hot and humid weather, water vapor introduced into a school by infiltration and ventilation is by far the largest source. In fact, it is common for ventilation air to represent 80% of the total latent cooling load when outdoor dew point temperatures are high (say above 70°F; in Florida, dew point temperatures are above 70°F for most of the period May through October).

We can get an idea of the magnitude of latent cooling load by considering the following discussion. As indicated earlier, water vapor in the indoor air represents about 1% of the mass of the air. During hot and humid weather, when the outdoor dew point temperature is say 76°F, water vapor represents about 2% of the mass of the air. If we know the air flow rate into the building, then we can calculate the water vapor entry rate.

- Consider a 50,000 ft^2 school building with 500 occupants and 150 tons of cooling capacity. If this school has a ventilation rate of 7500 cfm, then the mass flow rate of the ventilation air is about 34,000 lb/hour. *[7500 cfm x 60 min/hr x 0.075 lb/ft^3]*
- Given the 1 percentage point difference in water vapor content (outdoor air versus indoor air), we calculate that 340 lb/hour of water vapor is being introduced into the building (equivalent to 41 gal/hour of condensate removal by the AC system).
- Given that 1050 Btus of cooling is required to convert one pound of water vapor to one pound of liquid water, the latent cooling load associated with this 7500 cfm of ventilation is about 360,000 Btu/hr, or 30 tons. Since only about 25% of the AC system's cooling output is latent cooling (the other 75% is sensible cooling), a 120-ton AC system operating continuously at full capacity would be required to remove the water vapor from this ventilation air. Since the AC system has 150 tons of capacity, we would need the system to operate at full capacity 80% of the time.
- The problem is that the AC system will operate at 80% or greater runtime only during peak periods, such as on hot summer afternoons. During periods with lower sensible cooling loads (this will be about 90% of the time), the cooling capacity will be much less than 120 tons, so the latent cooling output will be considerably less than needed to keep RH at the desired level (say 50%).

There is both good news and bad news regarding the ability of AC systems to control RH in the indoor environment. First, the bad news.

Bad News

1. During typical hot and humid weather, a fundamental problem exists regarding the ability of the central AC system to meet the building's latent cooling load, and it has to do with variability of the sensible and latent cooling loads throughout the day. The latent cooling load is fairly stable from start to end of the school day. By contrast, the sensible cooling load is low during the early hours of the morning (4 AM to 9 AM) and it increases steadily through the day as office equipment is turned on, the outdoor temperture rises, the sun heats the exterior surfaces of the building envelope, and sunlight shines through windows. It is not uncommon for sensible cooling loads to increase by a factor of three from morning to afternoon. By contrast, the latent cooling load may be only 10% to 20% greater at 3 PM compared to 8 AM. Because the AC system runs only in response to the sensible cooling load (the thermostat is a temperature sensing device), latent cooling (moisture removal) occurs therefore only in proportion to the sensible load. If the latent load is fairly constant across the day, but the AC system runtime varies by a factor of three, then we can expect space RH to vary in an unacceptable manner.

2. Many common AC systems used in schools provide little or no latent cooling under part-load operation. Consider two common examples, for DX (Direct eXpansion of the refrigerant at the coil) and for chilled water (CW) systems.

    a. A DX AC unit (such as a roof-top package unit) with the fan operating in fan ON mode, will provide little latent cooling when the runtime fraction (of the compressor) is 60% or less. Moisture remaining on the coil when the compressor shuts off is evaporated during the compressor OFF period. Furthermore, all of the ventilation air introduced into the classroom while the compressor is OFF enters the room completely untreated.

    b. A CW AC unit (the air handler unit [AHU] might be in a mechanical room) with constant volume fan and modulating CW valve will provide little latent cooling when the load factor is 60% or less. As the cooling load diminishes, the flow of chilled water to the coil is reduced, the coil temperature rises, and the ability of the coil to remove water vapor from the air declines and eventually disappears (at about 50% load factor).

3. During periods of low sensible cooling load, the length of time that the AC unit operates is reduced. Shorter ON cycles reduce the latent cooling effectiveness of the system (referring now to DX systems) because the coil is not at full coldness as large a fraction of the time.

There are, however, a number of good news factors which at least in part offset these concerns.

Good News

1. Building occupants are more tolerant of variations in space RH. Whereas a change of a few degrees in the room temperature might bring a chorus of complaints, a change of 10 percentage points in room RH (from say 45% to 55%) may go unnoticed.

2. AC systems become more effective at removing water vapor when room RH is higher. In one set of measured data, the sensible heat ratio (SHR; this is the fraction of the total cooling dedicated to lowering the air temperature) of the AC system declined rapidly as room RH increased, from 0.88 at 45% RH to 0.78 at 55% RH to 0.68 at 65% RH[1].

3. Buildings have thermal mass which allows the building to store heat (sensible load) from the hottest hours of the day and transfers some of that load to cooler hours of the day. As a result, the sensible cooling load seen by the AC system is flatter and more stable across the day, causing the latent cooling output of the AC system to also be more stable.

1 Cummings, J. B. and A. Kamel, "Whole-Building Moisture Experiments and Data Analysis; Task 1 Final Report," FSEC-CR-199-88, Florida Solar Energy Center, Cocoa, FL, February 1988, Figure 9.

4. Building materials and furnishings have considerable moisture capacitance (storage of water vapor) which means that the AC system's greater drying potential during hotter hours of the day can be stored and released during cooler hours of the day when the AC system is running less. This helps to dampen swings in indoor RH.
5. A DX AC system will have greater cooling capacity and therefore a colder coil during cooler hours of the day. The colder coil allows it to more effectively remove water vapor when operating at 8 AM compared to when operating at 3 PM. This helps to bring the latent capacity more in line with the latent load during low-load times of the day.
6. Additionally, the latent cooling performance of the AC system can be improved by reducing the air flow rate across the coil without a substantial drop in energy efficiency. Parker reports that a decrease in air flow from 400 to 300 cfm/ton lowered SHR from 0.65 to 0.60[2] (return at 75°F and 60% RH, outdoors at 95°F) while Palani reports that system energy efficiency declines by only 2.5% for the same reduction in air flow[3]. Lower AC system air flow rates, especially for DX systems, will improve the latent cooling performance of the AC system for two reasons. First, the lower air flow rate across the coil results in a colder coil and shifts more capacity from sensible to latent. Second, the lower air flow rate de-rates the sensible capacity of the AC system so it runs longer. Longer run times tend to produce improved latent cooling performance. Some AC systems that have variable speed fan capabilities can, when combined with humidistat control, adjust fan speed and better adapt to the latent load requirements of the building.

Having said all this, there still remains a major humidity control problem if the AHU fan runs continuously (we are talking here about a constant volume (CV) system, not a variable air volume (VAV) system), for two reasons. 1) Moisture that collects on the cooling coil when the compressor is active, evaporates when the compressor is off. 2) The OA that passes over a warm coil (when the compressor is off) is not dehumidified, and a great deal of untreated high dew point temperature air is delivered directly into the space.

Even Better News

There is, however, an ideal and elegant solution to the latent cooling problems described above, which involves separating the V from the HVAC (heating, ventilating, and air conditioning). Instead of an integrated heating, ventilating, and air conditioning system, the ventilation part operates separately. In this approach, outdoor air would be introduced into the building and conditioned by means of a dedicated outdoor air system (DOAS). This system would condition the OA continuously, lowering the dew point temperature of the OA to say 53°F. The key factor is that the OA would pass over a cold cooling coil at all times (during hot and humid weather). If the dew point temperature of the OA is already low (say 58°F or lower), then the cooling coil of the DOAS could be deactivated (compressor shut off) to save energy and reduce the potential of overcooling the space.

It is the continuously cold coil of the DOAS in contact with the very moist OA that produces the greatest improvement in humidity control. While a normal AC system has an SHR in the range of 0.72 to 0.78 (meaning only 22 to 28% of the capacity goes toward latent cooling), the cooling coil of the DOAS would operate with an SHR of about 0.39, meaning that 61% of the cooling goes toward latent cooling.

Generally, there are two types of DOAS; 1) a system that conditions the OA and then injects it into the central AC air distribution system or 2) a system that conditions the OA and then distributes it by means of a separate dedicated air distribution system (ADS). Both types provide excellent latent cooling of the ventilation air, but the second provides the potential for considerable energy savings.

2 Parker, D., Sherwin, J., Raustad, R., Shirey, D., "Impact of Evaporator Coil Air Flow in Residential Air Conditioning Systems," Presented at the 1997 ASHRAE Annual Meeting, June 28-July 2, Boston, MA. Figure 6.

3 Palani, M., O'Neal, D., and Haberl, J., 1992. "The Effect of Reduced Evaporator Air Flow on the Performance of a Residential Central Air Conditioner," Proceedings of the 1992 Symposium on Building Systems in Hot-Humid Climates, Energy Systems Laboratory, Texas A&M University.

The first DOAS type, with integrated ADS, requires that the AHU of the main AC system runs continuously to distribute the ventilation air. If the main AHU is CV, then its cooling coil will need to modulate to a warmer temperature to prevent overcooling the space during part-load. Even if the main AHU is VAV, there will be a minimum air flow rate (often set to 30% or so of full air flow) below which the air flow will not fall. This 30% of maximum air flow, provided to the space at 55°F, may overcool the space during low-load conditions. This wastes energy by overcooling the space, which then creates further energy waste by requiring reheat to raise the space temperature back to the setpoint. A variation on the first DOAS type is a CV dual-path AHU. In the dual-path system, there are separate cooling coils for the OA and the return air (RA) within the same AHU. The OA coil can remain cold all of the time, therefore effectively stripping away the latent cooling load of the ventilation air. The RA coil temperature can be modulated from warm to cold depending upon the space cooling load.

The second DOAS type, with a dedicated ADS, provides greater control flexibility, because the central AHU does not need to provide ventilation air. This allows greater optimization of the overall HVAC system. In this optimized DOAS, the OA ventilation rate would be varied based on sensing of occupancy (CO^2 sensor or occupancy sensor). There are two big advantages that result from using a dedicated ADS; 1) the OA can be metered to individual spaces using a CO^2 controller and a modulating damper, and 2) the main AC system can be operated in a more energy efficient manner. Specifically, if this is a CV system, the main AHU fan can be cycled off (fan AUTO) when the thermostat is satisfied, saving fan energy and improving the latent cooling performance of the main AC system. If this is a VAV system, the AHU fan speed can be varied from 100% to near 0%, saving fan energy and reducing the potential that overcooling will occur and that reheat would be required.

Selecting The Main AC System

The most important factor in humidity control is how ventilation air is controlled and conditioned. As indicated, excellent RH control can be achieved by running the hot and humid OA directly across a continuously cold coil. Since about 80% of the total latent cooling load of a school originates from the ventilation air, successful stripping out of this moisture takes us most of the way toward successful control of indoor humidity. Beyond using a DOAS, however, it is important to select a main AC system that will effectively dehumidify the room air.

As suggested earlier, latent cooling performance varies greatly from one type of AC system to another. Table 3 presents characteristics of 12 AC system types, eight of which are DX and four of which are CW.

Table 3. Humidity control performance of 12 types of AC systems.

No.	System Type	Air Flow Rate	Fan Status	Cooling Source	Cold Source Duty	Coil Temp	Humidity Control
1	standard DX	contant	on/off	compressor	cycled	cold	good
2	standard DX	contant	continuous	compressor	cycled	warm	poor
3	standard DX	contant	continuous	compressor	continuous	cold with reheat	very good
4	variable DX	variable	continuous	compressor	variable	cold	very good
5	two-stage (face split) (DX)	constant	continuous	compressor	variable	cold	good
6	two-stage (row split) (DX)	constant	continuous	compressor	variable	warm	very poor
7	two-stage (face split) (DX)	constant	on/off	compressor	variable	cold	very good
8	two-stage (row split) (DX)	constant	on/off	compressor	variable	warm	poor
9	face and bypass (CW)	constant	continuous	chilled water	continuous	cold	very good
10	zoned (CW)	constant	continuous	chilled water	continuous	cold + hot	excellent
11	valve (3-way) modulation (CW)	constant	continuous	chilled water	continuous	warm	poor
12	variable air volume (CW)	variable	continuous	chilled water	continuous	cold	very good

Let's focus on some of the key issues in Table 3. "Air Flow Rate" indicates whether the AHU blower is variable speed or constant speed. "Fan Status" indicates whether the AHU blower cycles ON/OFF or is continuous. "Cold Source Duty" indicates whether the cold source is cycled ON/OFF, is continuously at full capacity, or is modulated (variable). "Coil Temp" indicates the typical or average cooling coil temperature that occurs during normal operation.

"Humidity Control" indicates the effectiveness of this AC system type in controlling indoor RH, ranging from very poor to excellent. The key factor determining humidity control effectiveness is whether the cooling coil is cold when air is flowing across it.

Of the 12 AC system types, four are rated as poor or very poor, two are rated as good, and six are rated as very good or excellent at controlling indoor RH. Obviously, you should avoid those system types that are rated poor or very poor, while selecting those that are rated good, very good, or excellent. The key to effective moisture removal and good RH control is for the cooling coil to be cold when air is moving across the coil, because a cold coil strips away moisture. A warm or even cool coil does not effectively remove moisture.

A brief discussion of each system type follows. An estimate of likely average indoor RH that would result from the operation of this system during hot and humid weather is presented (in parentheses) after the name of each system type.

1. *Standard Direct Expansion (DX) – fan AUTO (54% RH)*. This is the type of system that most of us have in our home with fan control set to AUTO. A constant volume AHU fan is cycled ON/OFF in sync with the compressor operation. Apart from the first 30 to 60 seconds after compressor start up, the cooling coil is cold whenever the fan moves air across the coil causing latent cooling performance to be good.
2. *Standard DX – fan ON (70% RH*). This is the same as System Type 1 except with fan control set to ON. A constant volume AHU fan operates continuously while the compressor cycles. After the compressor shuts off, the cooling coil becomes warm within about 30 seconds, after which the mixed return air and outdoor air are not conditioned. Furthermore, moisture that has accumulated on the coil evaporates into the warm air stream returning moisture to the room air and producing elevated room RH.
3. *Standard DX – continuous cold coil with reheat (46% RH)*. This is the same as System Type 2 except that the compressor is forced to run continuously. Because of continuous compressor operation, the cooling coil remains cold and therefore provides excellent dehumidification. To prevent overcooling of the space, a heating source such as electric resistance elements, a hydronic coil, or hot gas reheat (waste condenser heat) is activated.
4. *Two-stage DX with two speed fan – fan AUTO (50% RH).* This is similar to System Type1 except there is a two-stage compressor and two fan speeds. If there is no cooling load, then the compressor and AHU fan turn off. If the cooling load is small, then the first-stage compressor will operate and the AHU fan will operate at low fan speed. Since the fan speed is proportional to the compressor capacity, the coil remains cold whenever air flows across the coil causing latent cooling performance to be good.
5. *Two-stage DX with face-split coil, constant fan – fan ON (54% RH)*. This system has a two-stage compressor, a face-split cooling coil (in effect, two separate coils, typically one above the other), and one fan speed. If there is no cooling load, then the compressor is off but the AHU fan continues to run. If the cooling load is small, then the first-stage compressor will operate and make the first-stage coil cold. At full capacity, both the first and second stage compressors operate and both the first and second stage coils are fully cold. Because the first-stage coil is cold most of the time, latent cooling performance is good. When the second stage coil ceases to be active, the moisture that remains on that coil evaporates, causing some introduction of water vapor to the space and increase in room RH.
6. *Two-stage DX with row-split coil, constant fan – fan ON (80% RH)*. This system is the same as System Type 5 except that it has a row-split cooling coil. The row-split coil is one coil,

but alternating rows of the coil are active. In a four-row coil, for example, coil rows 1 and 3 would be active in first stage operation while 2 and 4 would be active in second stage. If there is no cooling load, then the compressor is off but the AHU fan continues to run. If the cooling load is small, then the first-stage compressor will operate and make the coil cool but not cold. At full capacity, both the first and second stage compressors will operate and the coil will be fully cold. Because the system will operate in first-stage the majority of the time, the coil will be cool but not cold most of the time, so little moisture will be removed from the air stream. During the intermittent periods when the system goes to second stage operation, moisture will condense on the cooling coil, but then evaporate when the system returns to first stage. Since first-stage provides little or no latent cooling and much of the moisture remaining on the coil after second stage operation evaporates back into the room air, the end result is very high indoor RH.

7. *Two-stage DX with face-split coil, constant fan – fan AUTO (50% RH*). This is the same as System 5 but with fan AUTO. Performance-wise the only difference is that the AHU fan shuts off when there is no cooling load, thus eliminating most of the evaporation of moisture from the first-stage coil when the first-stage compressor shuts off. As a result, indoor RH is slightly lower.

8. *Two-stage DX with row-split coil, constant fan – fan AUTO (75% RH)*. This is the same as System 6 but with fan AUTO. Performance-wise the only difference is that the AHU fan shuts off when there is no cooling load, thus eliminating some evaporation of moisture from the coil when the compressors are off. As a result, indoor RH is slightly lower.

9. *Face and bypass Chilled Water (CW) system with constant and continuous fan (50% RH)*. In this system, there are two air flow pathways. One path takes the air through a cooling coil (the "face") that remains cold all of the time. The other path allows air to bypass the cooling coil – this air is therefore not conditioned at all. A thermostat senses room temperature and modulates the face and bypass dampers. As the damper in front of the coil modulates towards closed the bypass dampers modulate towards open. Conversely, when the dampers in front of the coil open, the bypass dampers close. Because the coil remains cold all of the time, the air that passes through the "face" is well dehumidified and as a result indoor RH is well controlled most of the time. Latent cooling performance is enhanced if the OA is directed to the face rather than the bypass.

10. *Zoned CW system with constant and continuous fan (44% RH)*. This system, which is sometimes called "hot deck, cold deck", also has two air flow pathways. One path takes the air through a cooling coil ("cold deck") that remains cold all of the time. The other path takes air across a heating coil ("hot deck") that remains hot all of the time. A matrix of mixing dampers (controlled by zone thermostats) meter a mixture of the cold and hot air streams into individual supply ducts that serve specific zones within the building. If the heating source of the hot deck were turned off, this system would operate much like a face and bypass system. Because of the heat provided to the space by the hot deck, a greater proportion of the air flow goes across the cooling coil (compared to a face and bypass system). Therefore, the resulting indoor RH is even lower than that from the face and bypass system, but the energy use is higher. It is possible for the Building Automation System to modulate the temperature of the hot deck in real time in response to space RH (e.g., move toward no heat source if space RH is below the desired setpoint).

11. *Constant Volume Modulating Valve CW system with continuous fan (70% RH)*. This system modulates cooling output by raising the temperature of the coil during reduced load periods. This is done by modulating the flow rate of chilled water through the coil. Because the coil is warm or cool but not cold, a majority of the time, this system is not effective at removing water vapor from the room air.

12. *Variable Air Volume (VAV) CW system with continuous fan (50% RH)*. This system modulates cooling output by increasing or decreasing the air flow rate across the cooling coil. The coil is maintained at a cold temperature to provide (typically) 55°F supply air to the

space. In theory, the air flow rate can modulate from 0% to 100% of full flow. However, because OA is normally integrated into the system, the minimum air flow rate is often around 30% of full flow. If 30% of full flow (with 55°F air) provides too much cooling then two options are available. First, reheat can be used to warm the supply air to prevent space overcooling. Second, the cooling coil temperature can be raised (by reduced CW flow) to prevent space overcooling. The first provides the greatest RH control but at a considerable energy penalty. The second saves energy but tends to produce somewhat higher indoor RH during low-load periods, because the coil is too warm to dehumidify effectively. If a DOAS is used, as discussed earlier in this paper, then the AHU fan speed can be controlled down to near 0% reducing the overcooling potential.

Acknowledgements

This work has been funded by the U.S. Department of Energy's Building Application Center. Learn more at www.SouthernBuildings.org. The opinions expressed are those of the authors and not necessarily those of the funding agency.

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