



Using Direct Evaporative + Chilled Water Cooling

By Rick Phillips, P.E., Associate Member ASHRAE

Using evaporative cooling is a great way to save energy. It can be used in drier climates to provide a significant amount of the overall cooling requirements for a building. When it is coupled with chilled-water cooling, all the cooling requirements for any type of building can be achieved along with the energy savings. This article examines how to maximize the energy savings in HVAC systems using direct evaporative cooling (DEC) combined with chilled-water coils. Arranging the components in different sequences in an air-handling unit (AHU) has a significant effect on overall energy savings.

A number of advantages exist to combining a chilled-water cooling coil with DEC. The primary reason is that the DEC is unable to provide all the cooling needed in most climates. With the addition of a cooling coil (CC), the use of evaporative cooling can be extended to many more climates.

If one is designing an HVAC system using DEC combined with indirect evaporative cooling alone to provide all the cooling needs of a building, typical values used for the design supply air temperature for the Denver area are 60°F to 63°F (15.6°C to 17.2°C). With the addition of a CC, the traditional value of

55°F (12.8°C) can be used. If the 60°F (15.6°C) supply air temperature was used, compared to a 55°F (12.8°C) value, the supply fan cfm must be increased by 33% to provide the same amount of cooling, when trying to maintain a room temperature of 75°F (23.9°C). This also results in a 33% increase in fan horsepower if two fans with the same efficiency are selected, as well as a larger air-handling unit and ducts.

The use of a CC allows the air-handling unit to provide all the needed cooling on days when there is high humidity outdoors. On those days, the DEC is ineffective by itself so the CC can provide the cooling. By the same means, if the indoor humidity level is too high, the DEC can be shut down and allow the CC to provide the cooling until the humidity levels are reduced to an acceptable level.

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With the combination of a CC and DEC, the DEC can be thought of as an add-on energy conserving module, rather than as the primary cooler. The evaporative cooling pad has a low-pressure drop (0.2 in. w.c. at 500 fpm [50 Pa at 2.5 m/s] face velocity for a 12 in. [305 mm] thick pad), so the parasitic cost due to additional fan energy is low compared to other energy saving add-ons such as heat pipes and air-to-air heat exchangers. A small sump pump, typically one-third horsepower, is the other parasitic cost. DEC modules are also relatively inexpensive, typically costing \$0.25 to \$0.50/cfm (\$0.53 per L/s to \$1.06 per L/s) for a high quality unit.

Another benefit of having a DEC unit in the air-handling unit is that it allows the chiller to be kept off until the wet-bulb temperature reaches the 50°F to 55°F (10°C to 12.8°C) range. Under these conditions, the DEC can provide all the needed cooling. In a drier climate that can correspond to a 70°F to 75°F (21.1°C to 23.9°C) dry-bulb temperature.

Affect of DEC Position on Performance

The primary question is whether positioning the DEC upstream of the CC results in the need for more or less chiller energy compared to placing the DEC downstream. Chiller energy demand will be represented by the total enthalpy change across the CC, which will account for latent and sensible loads.

Conventional practice is to place the DEC downstream of the CC. Intuitively, one would think that placing a DEC upstream of the CC would add latent load to the CC and result in an increase of chiller energy. The other reason this is done is that the CC is essentially replacing the indirect evaporative cooling coil in a system with indirect and direct evaporative cooling. In indirect/direct evaporative cooling systems, it is mandatory to place the indirect coil upstream of the DEC to get the psychrometric benefits of this combination.

In working with evaporative cooling systems over the years, it was noticed that for certain ambient weather conditions the CC energy was less if the DEC was located upstream, defying conventional practice. This raised the question about which position would result in the lowest overall CC operating energy on a yearly basis. The only way to resolve the question is to analyze the combinations on a yearly basis, using hourly weather data. The configuration of the components and psychrometrics of the two conditions are shown in *Figures 1 and 2*.

DEC Downstream of the Cooling Coil

Case 1 in *Figure 1* shows the conventional condition with the DEC downstream of the CC. The starting Point A is for a mild ambient condition of 77°F (25°C) DB and 55°F (12.8°C) WB. All calculations are for Denver at an elevation of 5,280 ft (1609 m) above sea level. The intent is to produce a final leaving air temperature of 55°F (12.8°C) DB. As the airstream passes through the CC, it is sensibly cooled along a horizontal line of the psychrometric chart to Point B (*Figure 2*). From Point B, the airstream enters the DEC and is adiabatically cooled along the constant wet-bulb line to Point C, where it reaches 55°F (12.8°C) DB. Point C is determined by the effectiveness of the evaporative cooling media. For a 90% effective media,

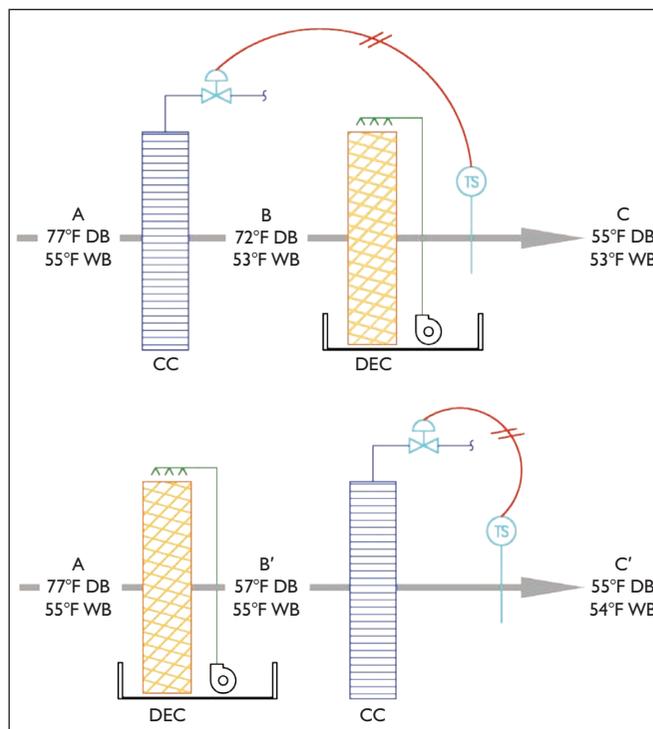


Figure 1: Case 1 (top)—DEC downstream of cooling coil. Case 2 (bottom)—DEC upstream of cooling coil.

the point will be located at 90% of the length of the wet-bulb line segment extending from Point B to the saturation curve.

Chilled-water flow through the CC is modulated to maintain the final 55°F (12.8°C) DB supply air temperature. The temperature sensor would be located downstream of the DEC. Point B in Case 1 is determined by iterative calculations. Starting at Point A, a lower dry-bulb temperature is assumed for the airstream, with a constant humidity ratio (HR). The assumed air temperature is then passed through the DEC and the leaving air temperature is calculated. A solution is reached when the leaving air temperature for the DEC reaches the desired setpoint of 55°F (12.8°C) DB, within a small window of error. Point B is the CC discharge air condition (DB/WB) that produces a leaving air temperature of 55°F (12.8°C) DB at the DEC. A DEC consisting of a 12 in. (305 mm) thick evaporative cooling pad, with an effectiveness of 90%, is used in the calculations.

DEC Upstream of the Cooling Coil

Case 2 in *Figure 1* shows the unconventional condition with the DEC upstream of the CC. The starting Point A is the same as for the previous case, as are all other general conditions. As the airstream passes through the DEC it is adiabatically cooled along the constant wet-bulb line from Point A to Point B' (*Figure 2*), the location of which is governed by the effectiveness of the evaporative cooling pad. From Point B', the airstream enters the CC and follows a sensible cooling line until it reaches Point C', where the dry-bulb temperature is 55°F (12.8°C). Only the amount of additional cooling needed to reach 55°F (12.8°C) is added by the CC.

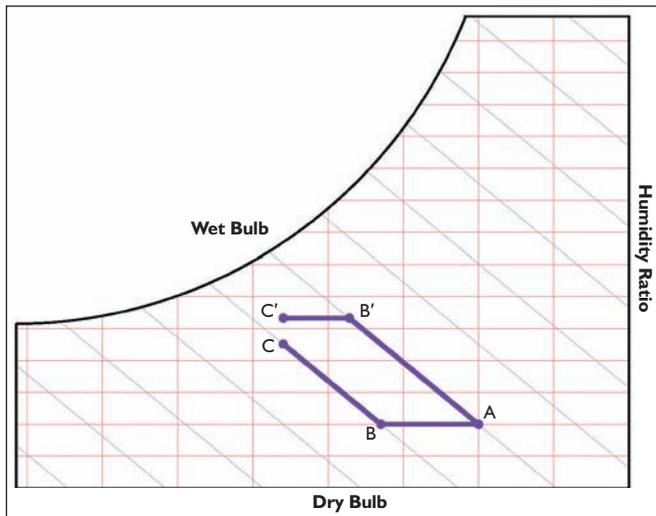


Figure 2: Psychrometric process.

The ambient condition used in Figure 1 was chosen to illustrate the situation where the energy expended at the CC is greater in the conventional case where the DEC is downstream of the CC. The change in enthalpy across the CC in Case 1 is 1.35 Btu/lb_m (3.14 kJ/kg) compared to 0.62 Btu/lb_m (1.44 kJ/kg) for Case 2. Case 2 uses only 46% of the coil energy required by Case 1. If the airflow rate across the coils was 20,000 cfm (9439 L/s), the energy exchanged for Case 1 would be 98,900 Btu/h (28 985 W) compared to 46,940 Btu/h (13 757 W) for Case 2. If the ambient conditions were changed to 90°F (32.2°C) DB/50°F (10.0°C) WB, the case with the CC upstream of the DEC would result in lower coil energy.

Results From Yearly Calculations

Since ambient conditions exist where the CC upstream of the DEC results in less coil energy and cases where the opposite is true, a year's worth of hourly calculations are needed to determine the optimal position. Hourly weather data from the ASHRAE Typical Meteorological Year, 2nd Revision (TMY2) database for Denver was used. Four arrangements of components were analyzed as illustrated in Figure 3. Arrangements 1 and 2 have the supply fan positioned downstream of the CC and DEC, while Arrangements 3 and 4 have the supply fan upstream. The fan position was included since the sensible temperature rise across the fan has a significant impact on the DEC performance. Arrangements 1 and 3 have the CC upstream of the DEC and Arrangements 2 and 4 have the CC downstream of the DEC. In all cases, the analysis looked at the energy use to produce a constant 55°F (12.8°C) supply air temperature (SAT).

Table 1 summarizes the results of the yearly calculations. For the case where the fan is downstream (Arrangements 1 and 2), placing the CC downstream of the DEC results in 10.2% less CC energy. Compared to the base case of chilled-water cooling only, this results in an additional 5% annual savings. For the case where the fan is upstream (Arrangements 3 and 4), placing the CC upstream of the DEC results in 6.3% less CC energy.

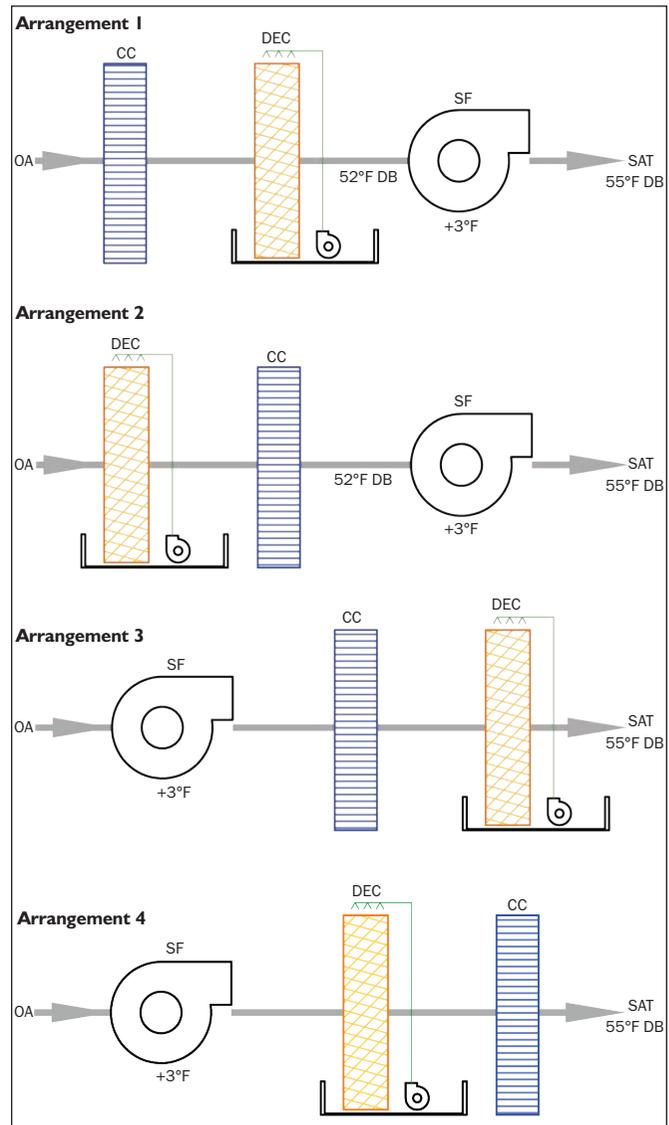


Figure 3: Coil and fan arrangements used for calculations.

Compared to the base case of chilled-water cooling only, this results in an additional 2% annual savings.

Comparing the arrangement with the fan upstream with the fan downstream arrangement shows that with the fan upstream there is a much greater benefit from the DEC. Comparing the two best arrangements from each case (Arrangements 2 and 3), the case with the fan upstream uses 35% less CC energy than the case with the fan downstream. With the fan upstream, the dry-bulb temperature is raised before it enters the DEC, which helps its performance, but the wet-bulb temperature is also raised, which hurts its performance. When using a 3°F (1.7°C) dry bulb rise across the fan, the wet bulb typically rises only 1°F (0.6°C), so the greater dry-bulb increase overcomes the smaller wet-bulb increase.

Greater evaporative cooling benefit can be achieved with a higher supply air temperature. Table 1 also includes performance values for a 58°F (14.4°C) SAT (in parentheses) for Arrangements 1 and 2. In both cases, the higher SAT provides much greater savings than with the 55°F (12.8°C) SAT: 54% versus 46% for

	Base Case (No Evaporative Cooling)		With Evaporative Cooling		
	Yearly Summation (Btu/lb _m)	Peak Coil Load (Btu/lb _m)	Yearly Summation (Btu/lb _m)	Peak Coil Load (Btu/lb _m)	Savings Compared To Base Case
Arrangement 1	16,300 (11,400)	12.60 (6.0)	8,900 (5,200)	12.70 (10.70)	46% (54%)
Arrangement 2	16,300 (11,400)	12.60 (6.0)	8,000 (4,360)	12.70 (10.60)	51% (73%)
Arrangement 3	15,800	11.40	5,200	10.60	67%
Arrangement 4	15,800	11.40	5,550	11.40	65%

Table 1: Summation of yearly cooling coil Δh values for 100% outside air base condition, with 55°F (13°C) supply air temperature (values in parentheses are for a 58°F [14°C] SAT).

Arrangement 1 and 73% versus 51% for Arrangement 2. In this case, Arrangement 2 also is much better than Arrangement 1, with a 19% improvement. The downside of using a 58°F (14.4°C) SAT is that the required airflow rate (cfm) increases for a given amount of cooling, which increases fan horsepower and duct size.

When applying the case with the fan upstream, the designer must ensure there is enough space for uniform air velocity to develop across the CC or DEC to attain good performance results. Using a plenum fan is one method that aids in accomplishing this goal.

The results presented above are a simplified method for comparing different component arrangements to see the effects on energy demand. They do not represent full energy consumption models. For example, the analysis sums the hourly CC energy use for a year per lb_m of air, but doesn't analyze the energy use for a given airflow, whether it is constant flow or variable flow. The analysis also does not account for energy use by a chiller, which is providing the cooling for the CC. If the avoided chiller energy was included, the savings for use of DEC over CC would be much greater, but they would be dependent on the efficiency of the chiller used.

Summary

The effect on energy consumption of the relative position of components for an air-handling system using a chilled-water coil in conjunction with a direct evaporative cooling pad has been analyzed over a year's worth of hourly weather data for the Denver climate. The results show:

- If the supply fan is positioned downstream of the cooling components, placing the CC downstream of the DEC results in less CC energy consumption.
- If the supply fan is placed upstream of the cooling components, less CC energy is consumed if the CC is placed upstream of the DEC.
- Positioning the fan upstream of the cooling components saves a significant amount of CC energy over placing it downstream.

Adding a DEC as an add-on component to an air-handling unit with mechanical refrigeration is a means of saving significant amounts of energy in many climates, not just dry climates.¹ In any climate where there are significant hours where the wet-bulb temperature is below the dry-bulb discharge temperature a DEC allows an owner to keep the chiller off or to run at a lower capacity

during these periods. DEC units are also relatively inexpensive. For the Denver climate, using a DEC in conjunction with a CC will typically result in a 35% energy savings for the mechanical system of a building compared to a base case with a CC only, using a DOE-2 computer model. For a LEED-NC rated building, this equates to four credits for energy conservation.

References

1. Lentz, M.S. 1991. "Adiabatic saturation and VAV: a prescription for economy and close environmental control." *ASHRAE Transactions* 97(1).

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