Methods of Calculating Water Recovery From Air-Conditioning Cooling Coils, Part 1 of 2

A detailed analysis of five procedures used to calculate water-vapor removal

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In traditional building cooling, air passes through chilled cooling coils in air-handling units prior to entering a facility. As air passes over the coils, moisture in the air condenses into water on the coils. The water drips into a collection pan below and is sent to a sewer drain. Today, however, particularly in areas where water is scarce and rates are high, many building owners are collecting this water and using it to replenish cooling towers for irrigation and other uses.

At the Winship Cancer Institute of Emory University in Atlanta, for example, 900,000 gal. of water is collected from buildings and fed to cooling towers each year, reducing the cost for tower makeup water.[1] And at Rice University in Houston, 12 million gal., which represents 5 percent of the university's total water consumption in a typical year, is collected from eight buildings and pumped to a central plant's cooling towers for use as makeup water.[2] If we assume Houston charges a combined fee (fresh water and sewer) of $8 per 1,000 gal., the university sees a savings of $96,000 per year. There are many other projects like these, which have shown economic viability, which is why engineers are taking a close look at condensate-recovery systems.

To determine a project's viability, engineers must estimate how much water comes from the building's air-conditioning systems annually. Factors that influence the amount of water collection include climate, percentage of outside-air intake (percentage of total circulation airflow) that brings water vapor to the cooling coil, ambient humidity ratio (pounds of water vapor per pound of dry air), and number of hours per year the air-conditioning system is required to run.

Over the last 10 years or so, a number of articles about methods for calculating water-vapor removal have been written. Many of these methods focus solely on water vapor that enters a building via outside-air intakes. There are, however, other sources, such as people; air infiltration; the opening of outside doorways; water-vapor transmission through walls, floors, and ceilings; cooking; plants; cleaning; bathrooms; and pools.

This article will provide a detailed review of five procedures used to calculate the amount of water coming off cooling coils. Some of the methods are approximate (though they may not be advertised as such) and easy to use, while others are highly accurate, but require a lot of calculation time and a lot of experience in psychrometrics and mass-flow analysis. Figure 1 shows a typical commercial-building air system, which will be used in our discussion.

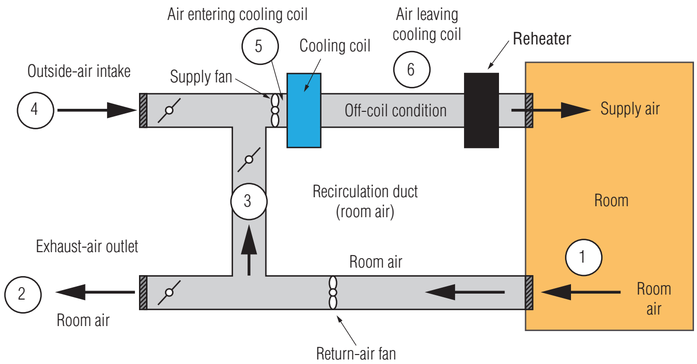

FIGURE 1. Commercial-building airflow.

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Equation 1a:

$$\frac{0.10 \text{ gal. removed/hr}}{\text{Total tons of cooling}} \text{ to } \frac{0.30 \text{ gal. removed/hr}}{\text{Total tons of cooling}} \text{ or } \frac{0.8339 \text{ lb water removed/hr}}{\text{Total tons of cooling}} \text{ to } \frac{2.5017 \text{ lb water removed/hr}}{\text{Total tons of cooling}}$$

Note: 8.3391 lb water per gallon at 58°F

Example:
- Design full cooling load: 500 tons
- Actual cooling load: 400 tons

Additional information:
Gallons per ton-hour is a representation of latent-heat ratio (LHR). The value of 0.10 gal. per ton-hour is a building with a LHR of approximately 0.0748, or 7.48 percent latent-heat removal, which is a sensible-heat ratio (SHR) of 0.9252, or 92.52 percent sensible-heat removal. The value of 0.30 gal. per ton-hour is a building with a LHR of 0.2243, or 22.43 percent latent-heat removal, which is a SHR of 0.7753, or 77.53 percent sensible-heat removal. To approximate LHR, use Equation 1b.

From: $\frac{\text{gallons}}{\text{hour}} = \frac{0.10 \text{ gal.}}{\text{ton-hour}} \times 400 \text{ tons} = \frac{40.0 \text{ gal.}}{\text{hour}}$

To: $\frac{\text{gallons}}{\text{hour}} = \frac{0.30 \text{ gal.}}{\text{ton-hour}} \times 400 \text{ tons} = \frac{120.0 \text{ gal.}}{\text{hour}}$

From: $\frac{\text{pounds}}{\text{hour}} = \frac{0.8339 \text{ lb}}{\text{ton-hour}} \times 400 \text{ tons} = \frac{333.56 \text{ lb}}{\text{hour}}$

To: $\frac{\text{pounds}}{\text{hour}} = \frac{2.5017 \text{ lb}}{\text{ton-hour}} \times 400 \text{ tons} = \frac{1{,}000.68 \text{ lb}}{\text{hour}}$

Equation 1b:

$$LHR = \frac{\frac{\text{Btu latent}}{1{,}076 \text{ lb water removed}} \times \text{value } \frac{\text{gal. water removed/hr}}{(\text{total tons of cooling})} \times 8.3391 \frac{\text{lb water}}{\text{gal.}}}{(12{,}000 \text{ total Btu/hr}) \div \text{total tons of cooling}}$$

$$LHR = \frac{\text{latent-heat removal, Btu/hr}}{\text{total heat removal, Btu/hr}}$$

where:
LHR percentage = LHR × 100
SHR percentage = SHR × 100
SHR = 1.0 – LHR

Approximate values of SHR and LHR for commercial buildings:

Building type	SHR	LHR	Using LHR and Equation 1b, gallons per ton-hour
School	0.65 to 0.80	0.20 to 0.35	0.2675 to 0.4681
Supermarket	0.65 to 0.85	0.15 to 0.35	0.2006 to 0.4681
Hospital	0.75 to 0.85	0.15 to 0.25	0.2006 to 0.3343
Kitchen	0.60 to 0.70	0.30 to 0.40	0.4012 to 0.5349
Library	0.80 to 0.90	0.10 to 0.20	0.1337 to 0.2675
Computer room	0.80 to 0.95	0.05 to 0.20	0.0669 to 0.2675

Cities with high summer outdoor humidity ratios (pounds water vapor per pound dry air), such as Miami, tend to have lower SHRs (for a particular building type) and higher LHRs than cities with low outdoor humidity ratios, such as Oakland, Calif. In other words, SHR varies with building location.

TABLE 1. Equation 1 for total cooling-coil water-vapor removal. Note: Equation 1b and table of approximate values of SHR and LHR for commercial buildings developed by William G. Acker.

Equation 1

The first equation in our review (Table 1) is an approximate equation using 0.10 to 0.30 gal. of water per ton of air conditioning for every hour of operation.[3] The value of 0.10 gal. per ton-hour occurs when the latent-heat ratio (LHR, the percentage of latent-heat removal) is 7.48 percent. The value of 0.30 gal. per ton-hour occurs when the LHR is 22.43 percent. Table 1 shows how LHR is calculated.

Table 1 also shows approximate LHR values for some commercial-building types. Kitchens have LHRs of 30 percent to 40 percent of the cooling-coil load; in other words, they would exceed the 0.30-gal.-per-ton-hour maximum. A kitchen with a LHR of 0.40, for instance, would produce around 0.5349 gal. per ton-hour.

What is unique about this equation is that it is easy to use and requires very little calculation time to get an approximation of the water removed by a cooling coil. It is helpful to know the cooling-coil design sensible-heat ratio (or LHR), which equates directly to gallons per ton-hour.

Table 1 provides gallons per ton-hour for different building LHRs. It is important to note that for most commercial buildings, cooling total load or tons varies significantly over the course of a year. Because the summer months generally are more humid and a lot of latent heat or water vapor comes in via outside-air intakes, the amount of water removed by a cooling coil will be greater during summer. At Memorial Hermann Medical Plaza in Houston, for example, the amount of water collected during summer (June, July, and August) is approximately 95,000 gal. per month; the remainder of the year, it varies from about 7,000 gal. to 42,000 gal. per month.[3] In summary, then, if you want to predict monthly water collection using these factors, you need to know the average total cooling tons on an hour-by-hour or day-by-day basis.

Equation 2

The second equation in our review (Table 2) can be found in a number of psychrometrics books. It is an approximate equation that yields good results, but requires knowledge of cooling-coil latent-heat removal (British thermal units per hour or latent-removal tons). Equation 1 requires only total coil load (tons) because it assumes the amount of latent-heat removal (which is why the factor varies from 0.10 gal. per ton-hour to 0.30 gal. per ton-hour). If you know only the total amount of heat (British thermal units per hour) removed by a cooling coil, you can estimate latent-heat removal by multiplying the total amount of heat removed by an assumed LHR. Approximate LHRs for certain building types can be found in Table 1. Determining monthly water removal with Equation 2 requires knowledge

Equation 2a:

$$m\text{ (lb water per hour)}_{\text{removed}} = \frac{Q\text{ (Btu/hr)}_{\text{latent heat entering cooling coil}} - Q\text{ (Btu/hr)}_{\text{latent heat leaving cooling coil}}}{1{,}076\text{ Btu latent removed per lb water removed}}$$

$$= \frac{\text{Delta } Q\text{ (Btu/hr)}_{\text{latent heat}}}{1{,}076\text{ Btu latent removed per lb water removed}} = \frac{Q\text{ (Btu/hr)}_{\text{latent heat removed by cooling coil}}}{1{,}076\text{ Btu latent removed per lb water removed}}$$

Equation 2b:

$$\frac{g\text{ (gal.)}}{\text{(hour)}_{\text{removed}}} = \frac{Q\text{ (Btu/hr)}_{\text{latent heat removed by cooling coil}}}{1{,}076\text{ Btu latent removal per lb water removed}} \times \frac{1.0\text{ gal.}}{8.3391\text{ lb water}}$$

Notes:

- The differential of 1,076 Btu of latent heat removed per pound of water vapor removed will vary slightly from case to case because of varying psychrometric properties across cooling coils.
- The value of 8.3391 lb of water per gallon of water is based on 58°F water coming off the cooling coil.
- $Q\text{ (Btu/hr)}_{\text{latent-heat removal by cooling coil}} = Q\text{ (Btu/hr)}_{\text{total heat removal by cooling coil}} \times \text{(latent-heat-removal percentage} \div 100)$

$$= Q\text{ (ton)}_{\text{total heat removal by coil}} \times \frac{12{,}000\text{ Btu/hr}}{\text{ton}} \times \frac{\text{latent-heat-removal percentage}}{100}$$

- $Q\text{ (ton)}_{\text{total cooling-coil load}} = Q\text{ (ton)}_{\text{sensible cooling-coil load}} + Q\text{ (ton)}_{\text{latent cooling-coil load}}$
- $Q\text{ (ton)}_{\text{latent cooling-coil load}} = Q\text{ (ton)}_{\text{total cooling-coil load}} \times \text{(latent-heat-removal percentage} \div 100)$
- $Q\text{ (Btu/hr)}_{\text{latent cooling-coil load}} = Q\text{ (ton)}_{\text{latent cooling-coil load}} \times 12{,}000\text{ Btu/hr per ton}$

TABLE 2. Equation 2 for total cooling-coil water-vapor removal.

Note:
Some engineering units and details were added for illustrative purposes. Care was taken to ensure those additions did not change the equations or the results obtained with them.

Equation 3a:

$$\frac{g\ (\text{gal.})}{(\text{min})_{removed}} = \frac{T\ (\text{ton}) \times \frac{375\ \text{ACFM}_{\text{coil inlet}}}{\text{ton}} \times \frac{\%OA\ \frac{(\text{ACFM}_{\text{outside-air intake}})}{(\text{ACFM}_{\text{coil inlet}})}}{100} \times (W_{\text{outside-air intake}} - W_{\text{cooling-coil discharge}}) \frac{\text{lb water vapor}}{\text{lb dry air}}}{V_{da}\ \text{air specific volume of outside-air-intake airflow (cu ft wet air per lb dry air)} \times 8.33\ \text{(lb water per gal. water)}} \quad \text{(3aa) (approx.)}$$

$$\frac{g\ (\text{gal.})}{(\text{hour})_{removed}} = \frac{g\ (\text{gal.})}{(\text{min})} \times \frac{60\ \text{min}}{\text{hour}} = \frac{\text{ACFM}_{\text{outside-air intake}}\ \text{(cu ft wet air per min)} \times \text{delta W (lb water vapor per lb dry air)} \times 60\ \text{min per hr}}{13.70\ \text{(cu ft wet air per lb dry air)} \times 8.33\ \text{(lb water per gal. water)}} \quad \text{(3ab) (approx.)}$$

$$\frac{m\ (\text{lb water})}{(\text{hour})_{removed}} = \frac{\text{ACFM}_{\text{outside-air intake}}\ \text{(cu ft wet air per min)} \times \text{delta W (lb water vapor per lb dry air)} \times 60\ \text{min per hr}}{13.70\ \text{(cu ft wet air per lb dry air)}} \quad \text{(3ac) (approx.)}$$

$$\frac{m\ (\text{lb water})}{(\text{hour})_{removed}} = \frac{m\ (\text{lb dry air})_{\text{outside-air intake}}}{(\text{hour})} \times \frac{(\text{lb water vapor})}{\text{delta W (lb dry air)}} \quad \text{(3ad) (exact)}$$

Equation 3b (approximate):

$$\frac{g\ (\text{gal.})}{(\text{min})_{removed}} = \frac{\text{ACFM}_{\text{outside-air intake}}\ \text{(cu ft wet air per min)} \times 4.5 \times \text{delta W (lb water vapor per lb dry air)}}{500}$$

Notes:

1. T (ton): Cooling load on a cooling coil. Design full load (tons) or actual test load (tons) can be used.

$$T(\text{ton})_{\text{total heat removed by coil}} = \frac{Q\ (\text{Btu/hr})_{\text{sensible-heat removal}} + Q\ (\text{Btu/hr})_{\text{latent-heat removal}}}{12{,}000\ \text{Btu/hr per ton}}$$

2. 375 ACFM per ton: Approximate equation for determining the flow of air entering a cooling coil
   ACFM (cu ft wet air per min)$_{\text{entering cooling coil}}$ = 375 ACFM$_{\text{coil inlet per ton}}$ × T (ton)

3. %OA: The amount of outside-air intake expressed as a percentage of the total air entering a cooling coil.

   a. OA Ratio Method 1 $= \frac{(\text{ACFM}_{\text{outside-air intake}})}{(\text{ACFM}_{\text{coil inlet}})}$

   b. OA Ratio Method 2 $= \frac{m\ (\text{lb dry air per hr})_{\text{outside-air intake}}}{m\ (\text{lb dry air per hr})_{\text{coil inlet}}}$

Note: The method employing mass-flow analysis ensures a more accurate determination of outside-air-intake percentage because ACFM$_{\text{outside-air intake}}$ and ACFM$_{\text{coil inlet}}$ have different air densities (or different specific volumes). In most cases, however, the methods produce very similar results.

4. $W_{\text{outside-air intake}}$ (lb water vapor per lb dry air): Humidity ratio of the outside-air intake.

5. $W_{\text{cooling-coil disch}}$ (lb water vapor per lb dry air): Humidity ratio of cooling-coil discharge air.

6. 13.70 (cu ft wet air per lb dry air): Specific volume of air.
   a. These equations demand use of outside-air-intake specific volume. The book suggests a standardized value of 13.70 based on a psychrometric plot for Dallas, which is coil-intake-air specific volume.
   b. The book also mentions use of 13.8.

7. 8.33 (lb water per gal. water): Occurs at about 68.90°F, which is a little warm for water leaving a cooling coil. A value of 8.3391 occurs at about 58°F, which is closer.

8. ACFM (cu ft wet air per min)$_{\text{outside-air intake}}$ = T (ton) × 375 (ACFM per ton)$_{\text{coil inlet}}$ × (%OA ÷ 100)
   a. ACFM$_{\text{outside-air intake}}$ at design full-load tons.
   b. ACFM$_{\text{outside-air intake}}$ at actual test-load tons.

9. Equation 3b assumes the specific air volume is 13.3333 cu ft of wet air per pound of dry air and uses 8.34 lb of water per gallon of water.

10. Equations 3aa, 3ab, and 3ac are labeled approximate because of the method used to estimate ACFM$_{\text{outside-air intake}}$ or because of the use of 13.70 as the value for outside-air-intake specific air volume.

11. Each of the equations in this table calculates only outside-air-intake water-vapor removal by a cooling coil. Removal of water vapor from people is not included.

Equation 3c (approximate):

$$\frac{g\ (\text{gal.})}{(\text{year})_{removed}} = \frac{g\ (\text{gal.})}{(\text{hour})_{removed}} \times \text{EFLCH (full-load cooling hours per year)}$$

Notes:

1. g (gal. per hour)$_{\text{removed}}$: Must be determined using design full-load tons for T (ton) in Equation 3a, or ACFM$_{\text{outside-air intake}}$ must be at the design full-load condition for Equation 3a or 3b.

2. EFLCH (full-load cooling hours per year): Data taken from the 2007 edition of ASHRAE Handbook—HVAC Applications, Chapter 32, Table 8. Values are provided in Table 4 of this article. The use of EFLCH is an approximate relationship used to obtain annual loads.

3. The value of gallons per year represents only removal of water vapor entering through outside-air intakes.

TABLE 3. Equations for the removal of water vapor entering via an air-handling unit's outside-air intake. Note: Equation 3aa developed by William G. Acker based on E.W. Bob Boulware's calculation; Equation 3ad is William G. Acker's exact equation.

of latent-heat removal on an hourly basis for each month of the year.

Equation 3

The third equation in our review (Table 3) is extrapolated from a book by E.W. Bob Boulware.[4] It is a type of mass-flow analysis for calculating the amount of outside-air-intake water vapor removed by a cooling coil. It does not address other sources of water vapor in buildings.

The accuracy of equations 3ab and 3ac can be improved by:

• Using the specific volume (cubic feet of wet air per pound of dry air) of air at outside-air-intake properties, rather than the specific volume of air entering the cooling coil. For Dallas, the outside-air-intake properties are 95°F dry bulb, 75°F wet bulb for a specific volume of 14.36. The book advocates a standardized value of 13.7 or 13.8 (see equations 3ab, 3ac, and 3b), which results in a loss of accuracy. Using the actual specific volume and actual cubic feet per minute (ACFM) of the outside-air intake in the following equation will produce an accurate value of the mass dry-air flow:

$$m\text{ (lb dry air per hr)}_{\text{outside-air intake}} = \text{ACFM (cu ft wet air per min)}_{\text{tested outside-air intake}} \times (1 \div \text{specific volume [cu ft wet air per lb dry air]})_{\text{outside-air intake}} \times 60\text{ min per hr}$$

• Using the mass dry-air flow of the outside-air intake in the following equation, which will produce an accurate mass water-vapor-removal rate:

$$m\text{ (lb water per hr)}_{\text{removed}} = m\text{ (lb dry air per hr)} \times (W_{\text{outside-air intake}} - W_{\text{cooling-coil discharge}})\text{ lb water per lb dry air}$$

• Using the more-exact volume-to-mass conversion of water of 8.3391 lb per gallon. The book uses the value of 8.33 lb per gallon.

• Using actual outside-air-intake ACFM, if known, instead of the equation in Note 8 in Figure 3.

With these changes, the approximate equation becomes exact Equation 3ad. Next month, in Part 2 of this article, we will discuss why this mass-flow equation works.

Equation 3b, also from the book, is less accurate than Equation 3a because it assumes a standard outside-air-intake specific volume of 13.3333, which is lower than actual outside-air specific volume typically. Actual outside-air specific volume can be found on most psychrometric charts by plotting outside-air properties (dry bulb and wet bulb, dry bulb and relative humidity, or dry bulb and humidity ratio).

Location	School	Office	Retail	Hospital	Annual cooling degree-days
Atlanta, Ga.	690 to 830	1,080 to 1,360	1,380 to 1,860	2,010 to 2,850	1,841
Baltimore, Md.	500 to 610	690 to 1,080	880 to 1,480	1,340 to 2,340	1,228
Bismarck, N.D.	150 to 250	250 to 540	340 to 780	540 to 1,290	539
Boston, Mass.	300 to 510	450 to 970	610 to 1,380	1,020 to 2,330	750
Charleston, W.Va.	430 to 570	620 to 1,140	820 to 1,600	1,260 to 2,560	1,066
Charlotte, N.C.	650 to 730	1,060 to 1,340	1,350 to 1,830	1,990 to 2,820	1,669
Chicago, Ill.	280 to 410	420 to 780	550 to 1,090	870 to 1,780	842
Dallas, Texas	830 to 890	1,350 to 1,580	1,660 to 2,090	2,320 to 3,100	2,719
Detroit, Mich.	230 to 360	390 to 820	530 to 1,170	870 to 1,950	775
Fairbanks, Alaska	26 to 54	64 to 200	110 to 320	210 to 600	71
Great Falls, Mont.	130 to 220	210 to 490	290 to 710	500 to 1,210	328
Hilo, Hawaii	1,360 to 1,390	2,440 to 2,580	2,990 to 3,370	4,060 to 4,910	3,258
Houston, Texas	940 to 1,000	1,550 to 1,770	1,870 to 2,290	2,540 to 3,320	3,001
Indianapolis, Ind.	380 to 560	560 to 1,000	730 to 1,410	1,120 to 2,250	1,055
Los Angeles, Calif.	780 to 910	1,280 to 1,670	1,740 to 2,350	2,740 to 3,770	1,153
Louisville, Ky.	550 to 670	770 to 1,250	1,000 to 1,720	1,480 to 2,690	1,390
Madison, Wis.	210 to 310	320 to 640	420 to 900	680 to 1,490	608
Memphis, Tenn.	700 to 830	1,090 to 1,350	1,350 to 1,780	1,910 to 2,680	2,214
Miami, Fla.	1,260 to 1,300	1,980 to 2,150	2,350 to 2,740	3,110 to 3,890	4,458
Minneapolis, Minn.	200 to 300	320 to 610	430 to 870	680 to 1,420	751
Montgomery, Ala.	840 to 910	1,260 to 1,510	1,550 to 1,990	2,170 to 2,950	2,282
Nashville, Tenn.	570 to 740	830 to 1,280	1,030 to 1,710	1,490 to 2,620	1,683
New Orleans, La.	920 to 990	1,500 to 1,720	1,820 to 2,240	2,500 to 3,280	2,846
New York, N.Y.	360 to 550	540 to 1,040	720 to 1,480	1,160 to 2,440	978
Omaha, Neb.	310 to 440	480 to 820	610 to 1,130	920 to 1,780	1,109
Phoenix, Ariz.	950 to 1,020	1,340 to 1,610	1,630 to 2,090	2,220 to 3,040	4,557
Pittsburgh, Pa.	300 to 530	440 to 920	600 to 1,310	960 to 2,160	751
Portland, Maine	190 to 300	310 to 630	410 to 900	700 to 1,520	365
Richmond, Va.	630 to 730	880 to 1,310	1,110 to 1,770	1,650 to 2,760	1,348
Sacramento, Calif	680 to 850	1,080 to 1,430	1,460 to 2,020	2,250 to 3,180	1,251
Salt Lake City, Utah	410 to 710	510 to 1,090	660 to 1,520	1,060 to 2,470	1,193
Seattle, Wash.	260 to 460	440 to 1,200	710 to 1,860	1,340 to 3,270	177
St. Louis, Mo.	460 to 550	680 to 1,100	850 to 1,500	1,260 to 2,330	1,631
Tampa, Fla.	1,050 to 1,110	1,800 to 2,000	2,170 to 2,580	2,910 to 3,710	3,517
Tulsa, Okla.	580 to 770	830 to 1,300	1,030 to 1,730	1,470 to 2,630	2,060

Notes:
1. Values of EFLCH are from Table 8, Chapter 32, of the 2007 edition of ASHRAE Handbook—HVAC Applications, as well as a December 2000 ASHRAE research-project report (RP-1120) by Steven Carlson. The latter has equations using values of average annual cooling degree-days to estimate EFLCH values for cities not on the above list.
2. Average annual cooling degree-days were added to this table and are not part of Table 8, Chapter 32, of the 2007 edition of ASHRAE Handbook—HVAC Applications.

TABLE 4. Equivalent full-load cooling hours (EFLCH) per year.

Equation 3c is used to calculate the amount of outside-air-intake water vapor removed by a cooling coil annually. This equation requires multiplication of an input value of gallons per hour removed by equivalent full-load cooling hours per year (EFLCH). If the gallons per hour in Equation 3a or Equation 3b is used, the gallons per year will represent only the outside-air-intake water vapor removed.

Values of EFLCH for four building types—school, office, retail, and hospital—in 35 U.S. cities are given in Table 4. This is a great procedure for estimating water removal without going through many hours of calculation. The alternative is to calculate the gallons removed each hour the air conditioner operates and add them, which may involve 1,000 to 5,000 individual calculations, depending on the location and annual operating hours of the air conditioner.

Equation 4

The fourth equation in our review (Table 5) is taken from mass-flow-analysis equations, which are accurate equations. It requires use of the ACFM of outside-air-intake airflow, which can be obtained from a field test or from building design-load analysis.

Equation 4c is approximate because of the use of EFLCH (hours per year). When using Equation 4c,

Equation 4a (exact equation for removal of outside-air-intake water vapor only):

$$\frac{\text{m (lb water)}}{\text{(hr)}_{\text{removed}}} = \frac{\text{ACFM (cu ft wet air per min)}_{\text{outside-air intake}} \times (W_{\text{outside-air intake}} - W_{\text{cooling-coil discharge}})\ \frac{\text{lb water vapor}}{\text{lb dry air}} \times \text{60 min per hr}}{\text{Specific volume (cu ft wet air per lb dry air)}_{\text{outside-air intake}}}$$

$$= \text{m (lb dry air per hr)}_{\text{outside-air intake}} \times (W_{\text{outside-air intake}} - W_{\text{cooling-coil discharge}})\ \frac{\text{lb water vapor}}{\text{lb dry air}}$$

$$= \text{m (lb dry air per hr)}_{\text{outside-air intake}} \times W_{\text{outside-air intake}} \text{ (lb water vapor per lb dry air)} - \text{m (lb dry air per hr)}_{\text{outside-air intake}} \times W_{\text{cooling-coil discharge}} \text{ (lb water vapor per lb dry air)}$$

$$= \text{m (lb water vapor per hr)}_{\text{outside-air intake}} - \text{m (lb water vapor per hr)}_{\text{remaining outside-air-intake water vapor leaving cooling coil}}$$

Notes:

1. ACFM (cu ft wet air per min)$_{\text{outside-air intake}}$: The amount of outside air drawn into the air-handling unit.
2. W (lb water vapor per lb dry air)$_{\text{outside-air intake}}$: Humidity ratio of the outside-air intake. This can be obtained by plotting the outside-air properties on a psychrometric chart, or it can be calculated using equations in Chapter 6 of ASHRAE Handbook—Fundamentals.
3. W (lb of water vapor per lb dry air)$_{\text{cooling-coil discharge}}$: Humidity ratio of the cooling-coil discharge. This can be obtained by plotting the air properties of the cooling-coil discharge on a psychrometric chart.
4. Specific volume (cu ft wet air per lb dry air)$_{\text{outside-air intake}}$: Specific volume of outside-air intake. This can be obtained by plotting the outside-air-intake properties on a psychrometric chart.
5. m (lb dry air per hr)$_{\text{outside-air intake}}$: This is the mass dry-air flow entering the HVAC system through the outside-air intake. It is obtained as follows: m (lb dry air per hr) = (ACFM ÷ specific volume) × 60 min per hr. This procedure of breaking air into mass flows of dry air and water vapor is taught in Chapter 6 of ASHRAE Handbook—Fundamentals. Mass flows of dry air around the air-system circuit can be added or subtracted (two ACFM air streams cannot be added or subtracted). Mass-flow analysis is the procedure used to find air-mixture properties when two air streams combine. This procedure breaks airflow into two separate mass flows: dry air and water vapor. ACFM will change if dry-bulb temperature changes; mass flow of dry air will not change because of a change in dry-bulb temperature. The addition or removal of water vapor from an air stream will cause a change in ACFM, but it will not change the mass flow of dry air.
6. m (lb dry air per hr)$_{\text{cooling-coil discharge}}$: This is the mass flow of dry air leaving the cooling coil. In this equation, only outside-air-intake dry-air mass flow across the cooling coil is analyzed because the only source of water vapor entering the building is the outside-air intake. Therefore, in this case only, the mass flow of dry air entering the coil or leaving the coil is equal to the outside-air-intake dry-air flow. Recirculation-duct dry-air mass flow is not included in this equation because there was no water vapor added to it; therefore, the humidity ratio of the recirculation-duct airflow is equal to the humidity ratio of the cooling-coil discharge. In other words, analysis of recirculation-duct airflow across the cooling coil would show no water-vapor removal because the delta humidity ratio ($W_{\text{recirculation duct}} - W_{\text{cooling-coil discharge}}$) is zero for this airflow stream. Therefore, recirculation-duct airflow is left out of this analysis because it is not needed, as it does not have any excess water vapor to be removed by the cooling coil.
7. m (lb water vapor per hr)$_{\text{outside-air intake}}$: This is the amount of water vapor entering with the outside-air intake.
8. m (lb water vapor per hr)$_{\text{remaining outside-air-intake water vapor leaving cooling coil}}$: This is the amount of water vapor that entered with the outside-air intake minus the amount removed by the cooling coil.
   8.1. m (lb water vapor per hr)$_{\text{outside-air intake}}$ – m (lb water vapor per hr)$_{\text{outside-air-intake water vapor removed by cooling coil}}$ = m (lb water vapor per hr)$_{\text{remaining outside-air-intake water vapor leaving cooling coil}}$
9. m (lb water per hr)$_{\text{removed}}$: The amount of water vapor removed by the cooling coil. In this case, it is assumed the only water vapor entering the building is from the outside-air intake. In this equation, then, the water vapor removed is water vapor that entered with the outside-air intake. It is important to note that for most commercial buildings, a lot of cooling-coil water-vapor removal is water vapor that entered with the outside-air intake. Some commercial buildings, such as office buildings, can have significant water vapor from other sources, such as people, which could add a lot of water-vapor load onto the cooling coil, requiring a higher amount of cooling-coil water-vapor removal. Other sources of water vapor are cooking, transmission through construction, air infiltration (mass flow of exhaust exceeds mass flow of supply), indoor pools, and wet-surface evaporation related to floor cleaning, bathrooms, and plants. These sources usually show up in building return-air flow.

TABLE 5. Equation for calculating water-vapor removal from a cooling coil (continues on next page).

Equation 4b (exact equation for removal of outside-air-intake water vapor only):

$$\frac{g\ (\text{gal. water})}{(\text{hr})_{removed}} = \frac{\text{ACFM (cu ft wet air per min)}_{\text{outside-air intake}} \times (W_{\text{outside-air intake}} - W_{\text{cooling-coil discharge}}) \frac{\text{lb water vapor}}{\text{lb dry air}} \times 60 \text{ min per hr}}{\text{Specific volume (cu ft wet air per lb dry air)}_{\text{outside-air intake}} \times P \text{ (lb water per gal. water)}}$$

Notes:

1. g (gal. water per hr)$_{removed}$: This is Equation 4a, with pounds of water converted to gallons of water.
2. P (lb water per gallon of water): The temperature of water coming off cooling coils usually is very close to the dry-bulb temperature of the air leaving the coils. The temperature of the water dripping off cooling coils usually is close to 58°F, which has 8.3391 lb of water per gallon of water. The value of P (lb per gal.) can be obtained from water tables using the following equation:

$$P\ \frac{(\text{lb water})}{(\text{gal. water})} = \frac{\text{Water density (lb per cu ft)}}{7.4805195 \text{ gal. water per cu ft water}}$$

Equation 4c (approximate equation for annual water-vapor removal):

$$\frac{g\ (\text{gal. water})}{(\text{year})_{removed}} = \frac{g\ (\text{gal. water})}{(\text{hr})_{removed}} \times \text{equivalent full-load cooling hours (full-load cooling hours per year)}$$

Notes:

1. EFLCH data taken from 2007 ASHRAE Handbook—Fundamentals, Chapter 32, Table 8. In this article, values are provided in Table 4. EFLCH is an approximate relationship used in this case to calculate annual water removal.
2. When using EFLCH, the value of g (gal. water per hr) must be determined using system design-load data. In other words, the value of outside-air-intake ACFM or outside-air-intake mass flow must be at design-load conditions.
3. Gallons per year represents only outside-air-intake water-vapor removal.

TABLE 5 (continued from previous page)

you need to use building-design-load-analysis ACFM$_{\text{outside-air intake}}$ to calculate gallons per hour.

It is very important to note that when using Equation 4a or 4b, the ACFM must be at the psychrometric properties and specific volume of the outside-air intake. In other words, you cannot calculate dry-air mass flow using the ACFM$_{\text{outside-air intake}}$ and specific volume of the air at the inlet to a cooling coil. Also, when you have two airflows, such as outside-air intake and building recirculation-duct return air, mixing together, you cannot add the ACFMs together. You can, however, add the dry-air mass flows of the two airflow streams to get the dry-air flow of the mixture. You also can add the two water-vapor mass flows to get the water-vapor mass flow of the mixture.

What is unique about equations 4a and 4b is that we are analyzing only outside-air-intake mass dry-air flow and mass water-vapor flow through the cooling coil. Normally, outside-air-intake flow is mixed with recirculation-duct return-air flow, which makes up cooling-coil-inlet mass dry-air flow and water-vapor flow. In this case, however, outside-air-intake and recirculation-duct airflows are analyzed separately across the cooling coil, which is allowed in mass-flow analysis. In this equation or process, we assume the only source of water vapor entering the building is the outside-air intake. Because the recirculation-duct return air has no added water vapor (its humidity ratio is equal to that of the cooling-coil discharge), it can be left out of the calculations. This occurs only when the lone source of water vapor is the outside-air intake. This will become very clear next month, when, in Part 2 of this article, we analyze equations 4a and 4b using a complete building-air-system airflow diagram.

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Methods of Calculating Water Recovery From Air-Conditioning Cooling Coils, Part 2 of 2

A detailed analysis of five procedures used to calculate water-vapor removal

ROBERTIEZ/ISTOCK

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Last month, in Part 1 of this article (*http://bit.ly/Acker_0415*), we evaluated four equations used to determine the amount of water vapor removed from cooling coils in condensate-recovery applications. The accuracy of those equations varies, as some calculate only the removal of water vapor entering with the outside-air intake. This month, we will discuss more-accurate methods of water-vapor removal and the removal of all water-vapor loads by a cooling coil.

Equation 5

Unlike the previously discussed equations, Equation 5 (Table 6) calculates total cooling-coil water-vapor removal, or the removal of water vapor from all sources, such as people; air infiltration; the opening of outside doorways; water-vapor transmission through walls, floors, and ceilings; cooking; plants; cleaning; bathrooms; and pools. The problem is that it requires a considerable amount of information that engineers may not have or may not know how to obtain. Significant skill in psychrometrics, thermodynamics, and mass-flow analysis—not to mention considerable engineering time to produce an air-system diagram—is needed.

Equations 5a, 5b, and 5c are exact, while Equation 5d is approximate because of the use of EFLCH (equivalent full-load cooling hours per year). If Equation 5d is used, the gallons-per-hour value should come from a mass-flow analysis using air properties and ACFM (actual cubic feet per minute) airflows obtained through building design analysis and used in equations 5a, 5b, and/or 5c. Gallons per year can be obtained by calculating the gallons removed each hour of the year and totaling them, but this requires the selection of outside-air properties for each hour the air conditioner operates, a very time-consuming process of data collection and calculation. Equations 5aa and 5ab are similar to Equation 5a but approximate because they assume air specific volume is 13.3333 cu ft of wet air per pound of dry air.

In Chapter 3 of the book "Alternative Water Sources and Wastewater Management,"[4] an example calculation of cooling-coil water-vapor removal is given for an office building in Dallas. Additional detail on this system was extrapolated and used to develop the mass-flow-analysis diagram in Table 7. Some of the psychrometric air properties and airflows were provided, while the rest were calculated using provided information. The diagram shows the psychrometrics, including ACFM airflow, mass dry-air flow, mass water-vapor flow, and energy flow, at six points in the system. Heat from fans was not included to keep the analysis simple. In this case, the only source of water vapor is outside-air intake, at a rate of 20.2737 lb per hour. The building exhaust removes 14.4507 lb of water per hour, leaving 5.8230 lb to be removed by the cooling coils.

The easiest way to calculate cooling-coil water-vapor removal involves the use of Method A (Equation 5a), which utilizes the properties of air at the inlet to and leaving a cooling coil. In the case of the Dallas office building, the outside-air-intake and recirculation-duct airflows were added together (using mass-flow analysis) and analyzed to determine the air-property mixture, or coil-inlet airflow (Point 5 on the diagram). Then, using Method A (Equation 5a), the amount of water-vapor removal by the cooing coil (5.8230 lb per hour) was determined.

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Equation 5a (exact):

$$\frac{m\ (\text{lb water})}{(\text{hr})_{removed}} = \frac{ACFM_{into\ coil} \times W\ (\text{lb water vapor per lb dry air})_{into\ coil} \times 60\ \text{min per hr}}{\text{specific volume (cu ft wet air per lb dry air)}_{into\ coil}} - \frac{ACFM_{leaving\ coil} \times W\ (\text{lb water vapor per lb dry air})_{leaving\ coil} \times 60\ \text{min per hr}}{\text{specific volume (cu ft wet air per lb dry air)}_{leaving\ coil}}$$

$$= (m\ [\text{lb dry air per hr}]_{into\ coil} \times W\ [\text{lb water vapor per lb dry air}]_{into\ coil}) - (m\ [\text{lb dry air per hr}]_{leaving\ coil} \times W\ [\text{lb water vapor per lb dry air}]_{leaving\ coil})$$

$$= m\ (\text{lb water vapor per hr})_{into\ coil} - m\ (\text{lb water vapor per hr})_{leaving\ coil}$$

$$= m\ (\text{lb dry air per hr})_{into\ coil} \times \text{delta } W\ (\text{lb water vapor per lb dry air})$$

$$= m\ (\text{lb dry air per hr})_{leaving\ coil} \times \text{delta } W\ (\text{lb water vapor per lb dry air})$$

$$= \frac{ACFM\ (\text{cu ft wet air per min})_{into\ coil} \times 60\ \text{min per hr}}{\text{specific volume (cu ft wet air per lb dry air)}_{into\ coil}} \times (W_{into\ coil} - W_{leaving\ coil})\ \text{lb water vapor per lb dry air}$$

$$= \frac{ACFM\ (\text{cu ft wet air per min})_{leaving\ coil} \times 60\ \text{min per hr}}{\text{specific volume (cu ft wet air per lb dry air)}_{leaving\ coil}} \times (W_{into\ coil} - W_{leaving\ coil})\ \text{lb water vapor per lb dry air}$$

Notes:

1. ACFM (cu ft wet air per min)$_{into\ coil}$: airflow entering coil at entering-air properties.
2. W (lb water vapor per lb dry air)$_{into\ coil}$: humidity ratio at coil entering-air properties.
3. Specific volume of air (cu ft wet air per lb dry air)$_{into\ coil}$: specific volume at coil entering-air properties.
4. ACFM (cu ft wet air per min)$_{leaving\ coil}$: airflow leaving coil at leaving-air properties.
5. W (lb water vapor per lb dry air)$_{leaving\ coil}$: humidity ratio at coil leaving-air properties.
6. Specific volume of air (cu ft wet air per lb dry air)$_{leaving\ coil}$: specific volume at coil leaving-air properties.
7. m (lb dry air per hr)$_{into\ coil}$ = m (lb dry air per hr)$_{leaving\ coil}$, no air leakage or air bypass.
8. No coil bypass factor assumed.
9. There are approximate equations in some books and articles (equations 5aa and 5ab) that were developed using an assumed specific volume of 13.3333 cu ft per pound.

Equation 5aa (approximate):

$$m\ (\text{lb water per hr})_{removed} = \frac{ACFM_{into\ coil} \times \text{delta } W\ \frac{(\text{grains water vapor})}{(\text{lb dry air})} \times 4.5}{7{,}000\ (\text{grains water vapor per lb water vapor})}$$

$$= ACFM_{into\ coil} \times \text{delta } W\ (\text{lb water vapor per lb dry air}) \times 4.5$$

Equation 5ab (approximate):

$$m\ (\text{lb water per hr})_{removed} = ACFM_{into\ coil} \times \text{delta } W\ (\text{lb water vapor per lb dry air}) \times 4.5$$

Note: The value of 4.5 is derived from: (60 min per hr) ÷ specific volume 13.3333 cu ft wet air per lb dry air = 4.5

Equation 5b (exact) (for the diagram in Table 7):

$$\frac{m\ (\text{lb water})}{(\text{hr})_{removed}} = \frac{ACFM_{outside\text{-}air\ intake} \times (W_{outside\text{-}air\ intake} - W_{leaving\ coil})\ \text{lb per lb}}{\text{specific volume (cu ft wet air per lb dry air)}_{outside\text{-}air\ intake}} + \frac{ACFM_{recirculation\ duct} \times (W_{recirculation\ duct} - W_{leaving\ coil})\ \text{lb per lb}}{\text{specific volume (cu ft wet air per lb dry air)}_{recirculation\ duct}}$$

$$= \frac{m\ (\text{lb dry air})}{(\text{hr})_{outside\text{-}air\ intake}} \times (W_{outside\text{-}air\ intake} - W_{leaving\ coil})\ \text{lb per lb} + \frac{m\ (\text{lb dry air})}{(\text{hr})_{recirculation\ duct}} \times (W_{recirculation\ duct} - W_{leaving\ coil})\ \text{lb per lb}$$

$$= \frac{m\ (\text{lb water})}{(\text{hr})_{removed\ from\ outside\text{-}air\text{-}intake\ water\ vapor}} + \frac{m\ (\text{lb water})}{(\text{hr})_{removed\ from\ recirculation\text{-}duct\ water\ vapor}}$$

Note: $\frac{m\ (\text{lb dry air})}{(\text{hr})_{into\ coil}} = \frac{m\ (\text{lb dry air})}{(\text{hr})_{outside\text{-}air\ intake}} + \frac{m\ (\text{lb dry air})}{(\text{hr})_{recirculation\ duct}}$

Recirculation-duct dry-air mass flow is determined by subtracting building exhaust dry-air mass flow from return-air dry-air mass flow (ACFM cannot be added or subtracted). Recirculation-duct dry-air mass flow then can be added to outside-air-intake dry-air mass flow to get the dry–air mass flow of air entering a cooling coil. Therefore, calculating the amount of water-vapor removal from each mass-flow stream by a cooling coil is possible. It is important to mention these two airflows have different delta-Ws (pounds per pound). In the case of Equation 4a (Table 5 in Part 1 of this article), the delta-W for the recirculation-duct airflow is zero because there is no internal building water-vapor addition. In Equation 4a, the only source of water vapor is the outside-air intake.

Equation 5c (exact):

$$\frac{g\ (\text{gal.})}{(\text{hr})_{removed}} = \frac{m\ (\text{lb water vapor per hr})_{into\ coil} - m\ (\text{lb water vapor per hr})_{leaving\ coil}}{P\ (\text{lb water per gal. water})}$$

Equation 5d (approximate):

$$\frac{g\ (\text{gal. water})}{(\text{year})_{removed}} = \frac{g\ (\text{gal.})}{(\text{hr})_{removed}} \times \text{EFLCH (hr per year)}$$

TABLE 6. Equation for calculating cooling-coil water-vapor removal. This equation calculates removal of water vapor from all sources using mass-flow-analysis equations and procedures.

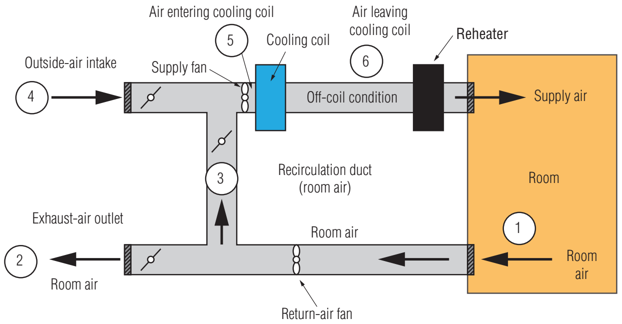
Like Method A, Method B is accurate, but breaks air entering a cooling coil into two streams—recirculation-duct return (Point 3 in the diagram in Table 7) and outside-air intake (Point 4)—and analyzes them separately as they pass through the cooling coil. The results for Method B in Table 7 show the water-vapor removal

Data from example in Chapter 3 of the book "Alternative Water Sources and Wastewater Management"[4]:

- Building design cooling load: 60,000 Btu/hr (5 tons)
- ASHRAE outside-air-intake air properties at 1-percent coincidence for Dallas:
  a. Dry bulb: 98.4°F (rounded to 98°F in the book)
  b. Wet bulb: 74.6°F (rounded to 75°F in the book)
- Percent outside-air intake: 20
- Outside-air-intake ACFM: 375 per ton × 5 tons × (20% ÷ 100) = 375
- Building type: office
- Water vapor generated internally:
  a. From people: none
  b. From air infiltration: none
  c. From permeance: none
  d. From cooking: none
  e. From plants and/or building cleaning: none
  f. From outside doorways: none
- Equivalent full-load cooling hours (EFLCH) per year:
  a. For office building in Dallas: 1,350 to 1,580
  b. Average: 1,465

Cooling-coil heat removal from Point 5 to Point 6

1. Delta Q $(\text{Btu/hr})_{\text{dry air}}$ = 161,653.96 – 108,930.56 = 52,723.40
2. Delta Q $(\text{Btu/hr})_{\text{water vapor}}$ = 85,825.45 – 78,548.85 = 7,276.60
3. Delta Q $(\text{Btu/hr})_{\text{total}}$ = 247,479.41 – 187,479.41 = 60,000.00 (5.00 tons)
4. Mass water-vapor removal (lb per hr) = 78.0765 – 72.2535 = 5.8230
5. Volume water-vapor removal (gal. per hr) = m (lb per hr) ÷ 8.3391 lb per gal.
   = 5.8230 lb per hr ÷ 8.3391
   = 0.698



	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6
tdb	82.97°F	82.97°F	82.97°F	98.40°F	86.07°F	58.00°F
twb	66.16°F	66.16°F	66.16°F	74.60°F	68.50°F	56.78°F
RH	38.44%	38.44%	38.44%	33.08%	37.56%	90.00%
W (lb water vapor per lb dry air)	0.009225	0.009225	0.009225	0.012942	0.009968	0.009225
V (cu ft wet air per lb dry air)	13.8846	13.8846	13.8846	14.3635	13.9804	13.2457
ACFM (cu ft wet air per min)	1,812.48	362.50	1,449.9847	375.00	1,824.99	1,729.08
m (lb dry air per hr)	7,832.3505	1,566.4701	6,265.8804	1,566.4701	7,832.3505	7,832.3505
m (lb water vapor per hr)	72.2535	14.4507	57.8028	20.2737	78.0765	72.2535
$Q\ (\text{Btu/hr})_{\text{dry air}}$	155,857.47	31,165.46	124,692.01	36,961.95	161,653.96	108,930.56
$Q\ (\text{Btu/hr})_{\text{water vapor}}$	79,298.37	15,865.66	63,432.71	22,392.74	85,825.45	78,548.85
$Q\ (\text{Btu/hr})_{\text{total}}$	235,155.84	47,031.12	188,124.72	59,354.69	247,479.41	187,479.41

Methods of calculating cooling-coil water-vapor removal:

1. Method A (Equation 5a): Use total airflow (outside-air-intake airflow + recirculation-duct airflow) entering the coil and the differential humidity ratio across the coil

$$m\ (\text{lb water vapor per hr})_{\text{removed by coil}} = \frac{\text{ACFM}_{\text{coil inlet}} \times 60 \text{ min per hr}}{V\ (\text{cu ft wet air per lb dry air})_{\text{coil inlet}}} \times (W_{\text{coil inlet}} - W_{\text{coil discharge}}) \text{ lb water vapor per pound dry air}$$

$$\begin{aligned} m\ (\text{lb water vapor per hr})_{\text{removed by coil}} &= m\ (\text{lb dry air per hr})_{\text{coil inlet}} \times \text{delta } W \text{ (lb water vapor per lb dry air)} \\ &= 7{,}832.3505 \text{ lb dry air per hr} \times (0.009968 - 0.009225) \text{ lb water vapor per lb dry air} \\ &= 5.8230 \text{ lb per hr} \end{aligned}$$

2. Method B (Equation 5b): This method breaks coil-inlet air into two separate air steams (outside-air intake and recirculation duct)

$$\begin{aligned} m\ (\text{lb per hr})_{\text{removed by coil}} &= \frac{\text{ACFM}_{\text{outside-air intake}} \times 60 \text{ min per hr}}{V\ (\text{cu ft wet air per lb dry air})_{\text{outside-air intake}}} \times (W_{\text{outside-air intake}} - W_{\text{coil discharge}}) \text{ lb per lb} \\ &+ \frac{\text{ACFM}_{\text{recirculation duct}} \times 60 \text{ min per hr}}{V\ (\text{cu ft wet air per lb dry air})_{\text{recirculation duct}}} \times (W_{\text{recirculation duct}} - W_{\text{coil discharge}}) \text{ lb per lb} \\ &= m\ (\text{lb dry air per hr})_{\text{outside-air intake}} \times \text{delta } W + m\ (\text{lb dry air per hr})_{\text{recirculation duct}} \times \text{delta } W \\ &= 1{,}566.4701 \times (0.012942 - 0.0092250) + 6{,}265.8804 \times (0.009225 - 0.009225) \\ &= 5.8230 \text{ lb per hr} + 0.0 \text{ lb per hr} \\ &= 5.8230 \text{ lb per hr} \end{aligned}$$

Summary of the water-vapor flows in system diagram:

Outside-air-intake water vapor	Amount of water vapor entering building		Amount removed by building exhaust		Amount of water vapor removed by cooling coil
	20.2737 lb per hr	–	14.4507 lb per hr	=	5.8230 lb per hr

TABLE 7. Analysis of Dallas office-building air system using psychrometrics, mass-flow analysis, and thermodynamics.

related to outside-air-intake flow over the cooling coil is 5.8230 lb per hour and the water-vapor removal associated with recirculation-duct airflow across the cooling coil is 0 lb per hour for a total water-vapor removal of 5.8230 lb per hour, which is the same as Method A. It should be noted that, in this case, there is no internal building water-vapor generation (from people, etc.); therefore, there is no water-vapor removal from recirculation-duct airflow. In other words, the humidity ratio of the recirculation-duct airflow is equal to the humidity ratio of the air leaving the coil; therefore, there is no excess water vapor to be removed.

Method B uses Equation 5b, which calculates water-vapor removal for the two air steams (outside-air intake and recirculation duct) separately. You can see that Method B calculated the same water-vapor removal as Method A, which uses only the air entering the cooling coil. This proves Method B is accurate. Method A and Method B worked very well in this case, in which the only water-vapor source was the outside-air intake; it works just as well for buildings with multiple sources of water vapor because it uses the principles of mass-flow analysis.

As mentioned earlier, the airflow diagram in Table 7 is an extrapolation of provided data. Cooling-coil heat removal was given as 5 tons (60,000 Btu/hr). Because the amount of water-vapor removal is rather small, the bulk of the heat removal is sensible-heat removal. The temperature and relative humidity of the air leaving the cooling coil were stated to be 58°F and 90 percent, respectively, which allowed us to calculate the properties of the air entering the cooling coil. This allowed the calculation of the recirculation-duct air properties. The exhaust airflow was chosen to be 1,566.4701 lb of dry air per hour, the same as the outside-air intake and, thus, balancing the air in the building. With the exhaust airflow identified, iterations were completed to identify the return-air properties. The return-air dry bulb of 82.97°F is slightly elevated over a common air-conditioning-season comfort set point of 75°F and 50 percent RH (W = 0.009236 lb per pound). The humidity ratio of the return air is very comfortable. The reason for the high dry bulb is the small amount of water-vapor removal, which means the bulk of the 60,000-Btu/hr heat removal is sensible heat. A typical office building usually has more latent-heat removal than this analysis shows, but that is because this example assumes the only water-vapor source is the outside-air intake.

Next, we will consider the impact of water vapor from people. The Dallas office building has an outside-air intake of 375 ACFM, which suggests occupancy of 18 or 19 people (375 ACFM ÷ 20 ACFM per person = 18.75 people). The average air-conditioning load for a typical office building is about 42.86 Btu/hr per square foot, or 280 sq ft per ton. With a design load of 5 tons, or 60,000 Btu/hr, the building square footage is around 1,400 (280 sq ft per ton × 5 tons = 1,400 sq ft). With an assumed occupancy of 18, then, the water-vapor load from people is around 4.1814 lb per hour. If we input this added water-vapor load into the building mass-flow analysis, we get the results in Table 8.

In summary, the addition of water vapor from people increased cooling-coil water-vapor removal 57.44 percent, from 5.8230 lb per hour to 9.1679 lb per hour. Excluding pool rooms, outside-air intake and people usually are the two greatest sources of water vapor in commercial buildings. This review shows the importance of looking beyond outside-air-intake water vapor when estimating the amount of water vapor removed annually by a cooling coil. It also shows the importance of mass-flow analysis and psychrometrics, which allow engineers to develop a diagram like the one in Table 7 to fully understand system operation and the load on a cooling coil.

	Entering building	Removed by building exhaust	Removed by cooling coil
Water vapor from people	4.1814 lb per hr	0.8365 lb per hr	3.3449 lb per hr
Outside-air intake	20.2737 lb per hr	14.4507 lb per hr	5.8230 lb per hr
Total	24.4551 lb per hr	15.2872 lb per hr	9.1679 lb per hr

TABLE 8. Water-vapor mass-flow analysis.

There are computer programs to help engineers perform these calculations. One such program is TRACE from Trane. This program develops airflow diagrams and calculates mass flows. Also, it has hourly psychrometric air properties for different cities in the United States.

Work by Lawrence

Just before the completion of this article, the author came across some in-depth work[5,6,7] led by Thomas Lawrence, PhD, PE, LEED AP, program coordinator for mechanical engineering at the University of Georgia. What is unique about this work is the amount of effort put into getting accurate values of gallons per year and then developing that data into *(gal. per year)* ÷ $ACFM_{outside\text{-}air\ intake}$.

Table 3 in a May 2012 article co-written by Lawrence[5] summarizes this data for 46 cities in two columns: "Weather Data Predicted" and "Regression Equation Predicted Values." The values in the first column came from a very time-consuming spreadsheet analysis calculating water removal for each hour of the year. Gallons collected per year then were divided by outside-air-intake ACFM. The equation used in the spreadsheet analysis is:

$$\frac{\text{gal.}}{\text{hr}} = \frac{0.90 \times \text{ACFM} \times 60 \text{ min per hr} \times 1.0 \text{ hr} \times (W_{\text{outside-air intake}} - 0.008) \text{ lb w.v. per lb d.a.} \times 0.0765 \text{ lb d.a. per cu ft wet air}}{8.34 \text{ lb water per gal. water}}$$

This equation assumes the air leaving a cooling coil will be at a humidity ratio of 0.008 lb water vapor per pound of dry air. The equation also assumes only 90 percent of the water is captured. The ACFM (cu ft wet air per min) is the outside-air-intake airflow bringing in the water-vapor load.

To determine gallons of water-vapor removal per year, the above equation uses outside-air humidity ratio ($W_{outside\text{-}air\ intake}$) for each of the 8,760 hr in a year, using historical hourly psychrometric data. The ACFM in the above equation is $ACFM_{outside\text{-}air\ intake}$, which is assumed to remain constant over the course of a year. Outside-air-intake air density is an assumed 0.0765 lb of dry air per cubic foot of wet air. If you instead use actual outside-air-intake air density for each hour of the year with an assumed ACFM, you will get a slightly lower gallons-per-hour or gallons-per-year value.

Another method of calculating gallons per year is offered in the May 2012 article, which has factors for use with $ACFM_{outside\text{-}air\ intake}$ in the following:

$$\frac{\text{gal.}}{\text{year}} = \text{ACFM}_{\text{outside-air intake}} \times \text{factor for city } \frac{\text{(gal. per year)}}{\text{ACFM}_{\text{outside-air intake}}}$$

If a system is not allowed to run for certain hours or days, when the outside-air humidity ratio is above 0.008 lb of water vapor per pound of dry air, consider developing your own spreadsheet to calculate gallons per year.

Once data for each city were established, Lawrence developed an equation that uses weather data to produce a value of gallons per year per ACFM. Results of that equation can be found in the "Regression Equation Predicted" column of Table 3 in the May 2012 article. The "Regression Equation Predicted" data fared well in comparison with the highly accurate "Weather Data Predicted" (detailed spreadsheet method) data. The regression equation is:

$$\frac{\text{(gal. per year)}}{\text{ACFM}_{\text{outside-air intake}}} = 0.4777 \times \text{dew-point temperature}_{\text{average}} + 0.00204 \times \text{CDD} + (0.32596 \times \text{in. rainfall}) - 22.50$$

where:

dew-point temperature = average annual dew-point temperature, degrees Fahrenheit

CDD = cooling degree-days, 65°F basis

in. rainfall = accumulation from April through October, inches

It is important to note that this series of calculations is for outside-air-intake water vapor condensed and collected only; it does not include any other sources of water vapor.

A Fall 2010 article co-written by Lawrence[6] has a map of the United States showing values of condensate-collection potential for different regions of the country. The values are in (gal./year)/$ACFM_{outside\text{-}air\ intake}$.

Lawrence conducted a spreadsheet analysis for a research laboratory in Athens, Ga., with 100-percent-outside-air intake of 19,400 ACFM. The air-handling system ran all year long. According to the hourly outside-air humidity ratios, the air conditioner dehumidified for 4,593 hr over the course of a year, which is the number of hours the outside-air humidity ratio exceeded 0.008 lb of water vapor per pound of dry air. The value of 4,593 hr of cooling per year is interesting compared to the EFLCH for Atlanta in Table 4 (Part 1 of this article).

Conclusion

This article analyzed equations engineers use to calculate the amount of water vapor removed from cooling coils. Some of the equations are accurate, while others are approximate. Many are for only one source of water vapor: outside-air intake. This article explained procedures that consider water vapor from other sources. It is hoped this article provided insight into the many procedures used to calculate water-vapor removal from cooling coils.

References

4) Boulware, E.W. B. (2012). *Alternative water sources and wastewater management* (ch. 3). New York: McGraw-Hill Professional.

5) Lawrence, T., Perry, J., & Alsen, T. (2012, May). AHU condensate collection economics. *ASHRAE Journal*, pp. 18-25.

6) Lawrence, T., & Perry, J. (2010, Fall). Capturing condensate. *High Performing Buildings*, pp. 56-61. Available at http://www.hpbmagazine.org/attachments/article/12072/10F-CapturingCondensate.pdf

7) Lawrence, T., Perry, J., & Dempsey, P. (2010, January). Capturing condensate by retrofitting AHUs. *ASHRAE Journal*, pp. 48-54.

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audience. To the best of my recollection, the stories received little, if any, of that; they just started appearing in newsletters like any other piece of content. As a result, they never really caught on with readers, and the series eventually fizzled out. I always regretted that.

With the growing popularity of online photo galleries and the explosion of social media, the time for a revival of Johnny Tundra seems right. With that, I am pleased the announce the "rebooting of the franchise," to use a Hollywood expression, as a series of "graphic galleries." Please check out the first installment—"Don't Shoot the Boiler"—at *http://bit.ly/JT_01*. Share it with colleagues, and let us know what you think by either posting in the comments section or dropping me a line at *scott.arnold@penton.com*.