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Dehumidification and Cooling Loads From Ventilation Air

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Ninety five years since Willis Carrier began the modern era of air conditioning by dehumidifying a printing plant, our industry is becoming more concerned with the importance of controlling humidity in buildings. In part, this concern stems from indoor air quality problems associated with excess moisture in AC systems. But more universally, the need for ventilation air has forced HVAC equipment originally optimized for high efficiency in removing sensible heat loads to remove high latent (moisture) loads .(1)

To assist cooling equipment and meet the challenge of larger ventilation loads, several technologies have become successful in commercial buildings. Newer technologies such as subcool/reheat and heat pipe reheat show promise. These increase latent capacity of cooling-based systems by reducing their sensible capacity. Also, desiccant wheels have traditionally provided deeper-drying capacity by using thermal energy to remove the latent load.(2)

Regardless of which mix of technologies is best for which applications, there is a need for a more effective way of thinking about the cooling loads created by ventilation air. It is clear from the literature that all-too-frequently, HVAC systems do not perform well unless the ventilation air loads have been effectively addressed at the original design stage.(3,4) This article proposes an engineering shorthand, an annual load index for ventilation air to help improve the ability of HVAC systems to deal efficiently with the amount of fresh air our industry has decided is useful for maintaining comfort in buildings.(5)

The proposed **"ventilation load index" (VLI)** is the load generated by one cubic foot per minute of fresh air brought from the weather to space-neutral conditions over the course of one year. It consists of two numbers, separating the load into dehumidification and cooling components: latent ton-hours per cfm per year + sensible ton-hours per cfm per year.

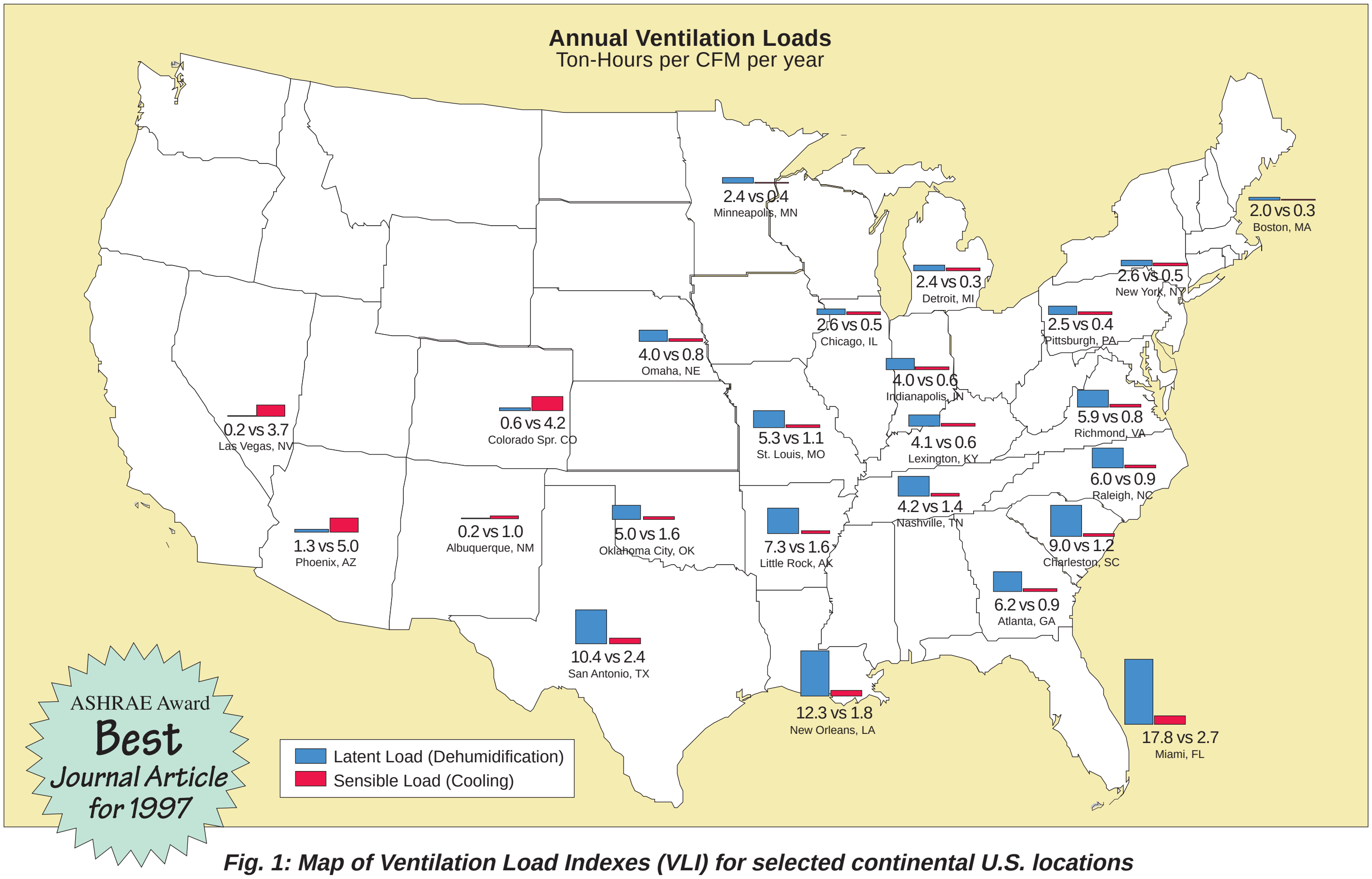

Fig. 1: Map of Ventilation Load Indexes (VLI) for selected continental U.S. locations

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For example, a ventilation air load index of 6.7 + 1.1 means that the total annual latent load is 6.7 ton-hours per cfm, and the annual sensible load is 1.1 ton-hours per cfm.

The "VLI" is proposed in the same spirit that led to the use of the "degree-day" as shorthand for expressing heating and cooling loads on the envelope of a building, or the "SEER" as a means of expressing the relative efficiency of cooling equipment over time. Those engineering shorthand values reduce great complexity to simple terms. Although they cannot replace detailed examination of the phenomena they represent, they allow rapid comparisons between similar items. In the same way, the ventilation load index allows for quick comparisons between loads in different geographic locations. As a result, the index can help an engineer consider how the HVAC system design and equipment selection should vary according to climate and amount of outside air.

Latent vs. Sensible Ton-hours per SCFM per Year

To calculate the index for a given location, one must compare the temperature and humidity levels in the weather to the temperature and humidity in the conditioned space. Then a calculation is made for every hour of the year. One must also must decide what values to use for "space-neutral" temperature and humidity set points to compare with the weather conditions. In calculating the indexes contained in this article, we have chosen to define the "space-neutral" conditions as 75°F, 50%rh (65 gr/lb). One could equally-well choose different set points for specialty applications, but 75°F, 50%rh seems to represent an upper level of tolerance of many commercial building users based on informal input from engineers and owners of commercial buildings. Those values seem consistent with human comfort research findings. This set point is at the middle of the combined summer and winter comfort zones with respect to dry bulb temperature, and towards the upper limit of 60%rh for moisture in the combined zones.(6)

The latent ton-hours per scfm in a given hour are calculated as follows:

$$\textbf{Latent}\text{ ton-hours per scfm per hour} = \frac{(\text{Outside air humidity ratio - 65 gr/lb}) \times 4.5 \times 1{,}050}{7{,}000 \times 12{,}000}$$

Where 4.5 is the lbs of air per hour per cfm, 7000 is the grains of water vapor per lb, 1050 is the heat of vaporization of water at standard temperature and pressure in Btu per lb, and 12000 represents the Btu's per hour of one ton of air conditioning capacity. The values for each of the 8760 hours of the year are calculated and summed to form the latent (dehumidification) load portion of the index.

Similarly, the sensible ton-hours per cfm in a given hour are calculated as follows:

$$\textbf{Sensible}\text{ ton-hours per scfm per hour} = \frac{(\text{Outside dry bulb temp - 75°F}) \times 1.08}{12{,}000}$$

Where the outside dry bulb is the average dry bulb temperature in degrees Fahrenheit, and 1.08 is the specific heat of air at standard temperature and pressure in Btu per degree Fahrenheit per lb, and 12000 represents the number of Btu's per hour of one ton of air conditioning capacity. To arrive at the value for the annual sensible heat load, separate calculations are made for each of the 8760 hours of typical weather observations for a given location.

Note that the index does not consider hours when no load exists. If, for example, the outdoor dry bulb temperature is 75°F, then there is no sensible load added to the cumulative total from that hour's observation. Likewise, the index does not consider either "free cooling" or "free dehumidification". For example, if the humidity ratio in the weather air is below the indoor set point of 65 gr/lb, then no "credit" is subtracted from the cumulative total annual latent load for that hour.

Advantages of the VLI

There are several useful advantages of this index. Perhaps most importantly, it represents the cumulative annual load, as opposed to the load at only a single point of operation. It seems useful to know the entire 8760-hour load rather than just the load at peak design conditions, which by definition are only representative of the load for 35 hours in a year. In addition, the index has other advantages:

- **Small numbers in both I-P and S-I units**

As can be seen from the values in Table 1, the index yields values which are small numbers, making variations between different locations apparent at a glance. Also, when the index is recalculated using S-I units (kWh/l/sec per year) the values are similarly small.

City	State	Ventilation Load Index (Ton-hrs/scfm/yr) Latent + Sensible	Total	Cumulative Load Ratio Latent:Sensible
Albuquerque	NM	**0.2 + 1.0**	1.2	0.2:1
Boston	MA	**2.0 + 0.3**	2.3	6.4:1
Detroit	MI	**2.4 + 0.3**	2.7	7.4:1
Minneapolis	MN	**2.4 + 0.4**	2.8	6.2:1
Pittsburgh	PA	**2.5 + 0.4**	2.9	5.8:1
New York	NY	**2.6 + 0.5**	3.1	5.1:1
Chicago	IL	**2.6 + 0.5**	3.1	5.0:1
Las Vegas	NV	**0.2 + 3.7**	3.9	0.04:1
Indianapolis	IN	**4.0 + 0.6**	4.6	6.6:1
Lexington	KY	**4.1 + 0.6**	4.7	7.4:1
Colorado Spr.	CO	**0.6 + 4.2**	4.8	0.1:1
Omaha	NE	**4.0 + 0.8**	4.8	5.3:1
Phoenix	AZ	**1.3 + 5.0**	6.2	0.3:1
St. Louis	MO	**5.3 + 1.1**	6.4	4.7:1
Oklahoma City	OK	**5.0 + 1.6**	6.6	3.2:1
Richmond	VA	**5.9 + 0.8**	6.7	7.2:1
Raleigh	NC	**6.0 + 0.9**	6.9	6.8:1
Atlanta	GA	**6.2 + 0.9**	6.9	6.7:1
Nashville	TN	**6.2 + 1.4**	7.6	4.6:1
Little Rock	AK	**7.3 + 1.6**	8.8	4.7:1
Charleston	SC	**9.0 + 1.2**	10.3	7.3:1
San Antonio	TX	**10.4 + 2.4**	12.8	4.4:1
New Orleans	LA	**12.3 + 1.8**	14.1	6.8:1
Miami	FL	**17.8 + 2.7**	20.5	6.7:1

Table 1: Ventilation Load Indexes (VLI) for selected Continental US Locations

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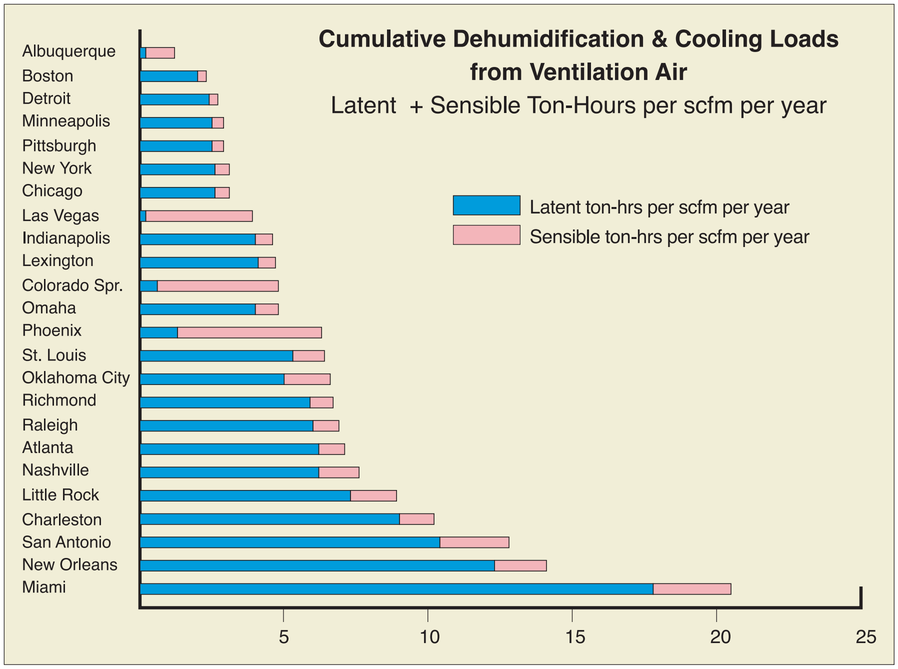

Fig. 2: Cumulative dehumidification and cooling loads from ventilation air for selected continental US locations

• Encourages examination of system behavior in different operating modes

In the weather, temperature and moisture levels are related, but they vary independently. Therefore an air conditioning system will often be cooling without dehumidifying, or have a need to dehumidify the air without cooling. By separating and quantifying the annual loads for the latent and sensible components of the total load, the index encourages the engineer to consider whether the ventilation system is in fact capable of controlling temperature and humidity independently, as suggested by weather variations.

Calculation Methodology

To calculate the indexes displayed in Table 1, we used the TMY-2 data set of hourly weather observations and a newly-developed computer program which accesses those data sets in order to perform annual summaries.

Annual data set - TMY-2

The TMY-2 data set was selected for several reasons. First, it contains complete records for 239 locations within the U.S, by far the largest number of credible and complete annual records available at the present time. Secondly, the data shows observed values, rather than averaged values, and the methodology for constructing a TMY-2 data set is well-documented and repeatable. Finally the records were produced for the U.S. Department of Energy using public funds, and as such, are nonproprietary, in the public domain and readily available to the public through the National Technical Information Service. (7)

The acronym TMY stands for "Typical Meteorological Year". The "2" designator represents the fact that this 239-file data set was produced using the second—current—format for TMY methodology. That methodology is based on the concept of selecting "typical" months of weather observations from a long-term record of hourly observations. A "typical" month is selected from the 30-year record based on how closely it conforms to the mean values of a given variable for that month over the 30-year period. So the TMY-2 file for a specific site may consist of its January record from 1962, February from 1975, March from 1981, and so forth. Then, to join different monthly records together smoothly, interpolation is applied at the end of one month and the beginning of another.

The methodology allows for weighting different values more or less heavily for "typicality". In the current set, for example, solar observations are weighted slightly more heavily than the dry bulb temperature and the dewpoint. Consequently, the months selected contain solar data which is slightly "more average" than the dry bulb and dewpoint data, and the temperature and humidity is slightly "more average" than the remaining values of wind-speed, precipitation and so forth. Given that 24 simultaneous variables can never have "typical" values in every one of the 8760 hours per year, the TMY-2 record containing "typical months" of actual observed data represents weather behavior better than older methodologies, which selected a single variable and then calculated averages for some of the other variables rather than recording the actual simultaneous observed data.

Calculation engine - BIN calculation program

The computer program which calculated the indices was developed initially to produce custom BIN data and joint-frequency tables of temperature, dewpoint and wind speed for use in estimating annual energy consumption of HVAC systems and unitary equipment. A public version of the program is under development, funded by the Gas Research Institute in cooperation with committees of ARI and ASHRAE.(8)

The program is written in a popular graphical version of the BASIC programming language. It runs on the presently most widely-used operating system for personal computers, when they are equipped with at least 8 Megabytes of RAM and a CD-ROM drive. The program and all 239 TMY-2 files are contained on a single CD-ROM .

The "ventilation air pretreatment" routine looks at each hour's dry bulb temperature and humidity ratio, and calculates the difference from the building's set points for temperature and humidity. The program allows the user to select the set point values for air delivered to the building. For these indexes, we chose 75°F, 50%rh, 65 gr.lb. Then the program totals loads for each of the 8760 hours in the TMY-2 file selected by the user. The routine accumulates the loads for sensible and latent heat separately, because there are many hours when one load is present without the other. For example if the outdoor temperature is 74°F in a given hour, there is no sensible load. But if the moisture outdoors during that same hour is 85 gr/lb, then there is a moisture load to be removed when ventilation air is brought to the target value of 65 gr/lb.

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	Ton-Hours per SCFM Per Year	
	Latent	Sensible
Alabama		
Birmingham	7.1	1.2
Huntsville	6.4	1.1
Mobile	11.2	1.7
Montgomery	9.4	1.6
Arkansas		
Fort Smith	6.9	1.6
Little Rock	7.3	1.6
Arizona		
Flagstaff	1.0	1.8
Phoenix	1.3	5.0
Prescott	0.2	0.9
Tucson	1.5	3.0
California		
Arcata	0.1	0.0
Bakersfield	0.3	2.4
Daggett	0.3	3.3
Fresno	0.3	2.1
Long Beach	2.2	0.4
Los Angeles	2.1	0.1
Sacramento	0.2	1.1
San Diego	2.4	0.2
San Francisco	0.1	0.1
Santa Maria	0.1	0.1
Colorado		
Alamosa	0.0	0.1
Boulder	0.2	0.6
Colorado Springs	0.6	4.2
Eagle	0.0	0.3
Grand Junction	0.1	1.0
Pueblo	0.5	1.1
Connecticut		
Bridgeport	3.2	0.3
Hartford	3.0	0.6
Delaware		
Wilmington	4.3	0.7
Florida		
Daytona Beach	12.3	1.7
Jacksonville	12.2	1.8
Key West	21.6	3.5
Miami	17.8	2.7
Tallahassee	11.6	1.7
Tampa	14.2	2.3
West Palm Beach	17.0	2.3
Georgia		
Athens	7.1	1.0
Atlanta	6.2	0.9
Augusta	7.7	1.3
Columbus	9.1	1.5
Macon	8.6	1.5
Savannah	10.1	1.5
Iowa		
Des Moines	2.9	0.7
Mason City	2.5	0.3
Sioux City	3.0	0.7
Waterloo	2.8	0.4

	Ton-Hours per SCFM Per Year	
	Latent	Sensible
Idaho		
Boise	0.0	0.8
Pocatello	0.0	0.6
Illinois		
Chicago	2.6	0.5
Moline	3.1	0.7
Peoria	3.4	0.6
Rockford	3.0	0.4
Springfield	4.5	0.8
Indiana		
Evansville	5.6	1.0
Fort Wayne	3.1	0.4
Indianapolis	4.0	0.6
South Bend	3.4	0.5
Kansas		
Dodge City	2.4	1.3
Goodland	0.9	0.9
Topeka	5.2	1.0
Wichita	4.2	1.5
Kentucky		
Covington	4.0	0.6
Lexington	4.1	0.6
Louisville	5.0	0.9
Louisiana		
Baton Rouge	11.3	1.7
Lake Charles	13.5	1.7
New Orleans	12.3	1.8
Shreveport	9.7	1.7
Massachusetts		
Boston	2.0	0.3
Worchester	1.9	0.2
Maryland		
Baltimore	4.7	0.8
Maine		
Caribou	1.0	0.1
Portland	1.9	0.2
Michigan		
Alpena	1.2	0.1
Detroit	2.4	0.3
Flint	1.8	0.3
Grand Rapids	2.0	0.3
Houghton	1.6	0.1
Lansing	2.4	0.4
Muskegon	1.8	0.2
Sault Ste. Marie	0.9	0.1
Traverse City	1.7	0.3
Minnesota		
Duluth	0.8	0.1
Minneapolis	2.4	0.4
Rochester	2.3	0.3
Saint Cloud	1.8	0.3
Missouri		
Columbia	4.3	0.9
Kansas City	5.3	1.1

	Ton-Hours per SCFM Per Year	
	Latent	Sensible
Missouri (Continued)		
Springfield	5.6	1.0
St. Louis	5.3	1.1
Missippi		
Jackson	9.9	1.7
Meridian	8.9	1.5
Montana		
Billings	0.1	0.6
Cut Bank	0.0	0.1
Glasgow	0.2	0.4
Great Falls	0.0	0.4
Helena	0.0	0.4
Kalispell	0.0	0.2
Miles City	0.1	0.6
Missoula	0.0	0.4
North Carolina		
Asheville	4.6	0.4
Cape Hatteras	9.0	0.7
Charlotte	5.8	1.0
Greensboro	5.8	0.7
Raleigh	6.0	0.9
Wilmington	9.8	1.2
North Dakota		
Bismarck	1.0	0.4
Fargo	1.7	0.4
Minot	0.6	0.3
Nebraska		
Grand Island	2.6	0.8
Norfolk	2.4	0.8
North Platte	1.3	0.8
Omaha	4.0	0.8
Scottsbluff	0.5	0.8
New Hampshire		
Concord	2.0	0.4
New Jersey		
Atlantic City	4.1	0.6
Newark	3.1	0.6
New Mexico		
Albuquerque	0.2	1.0
Tucumcari	1.0	1.3
Nevada		
Elko	0.0	0.6
Ely	0.0	0.4
Las Vegas	0.2	3.7
Reno	0.0	0.8
Tonopah	0.0	0.9
Winnemucca	0.1	1.0
New York		
Albany	2.3	0.4
Binghamton	2.2	0.1
Buffalo	1.9	0.2
Massena	2.1	0.2
New York City	2.6	0.5
Rochester	2.4	0.4
Syracuse	2.1	0.3

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	Ton-Hours per SCFM Per Year	
	Latent	Sensible
Ohio		
Akron	2.5	0.3
Cleveland	2.4	0.4
Columbus	2.8	0.5
Dayton	2.9	0.4
Mansfield	2.5	0.4
Toledo	2.5	0.4
Youngstown	2.6	0.3
Oklahoma		
Oklahoma City	5.0	1.6
Tulsa	6.5	2.0
Oregon		
Astoria	0.2	0.0
Burns	0.0	0.3
Eugene	0.2	0.3
Medford	0.0	0.9
North Bend	0.1	0.0
Pendleton	0.1	0.7
Portland	1.8	2.3
Redmond	0.0	0.4
Salem	0.1	0.3
Pennsylvania		
Allentown	3.2	0.4
Bradford	1.5	0.1
Erie	2.4	0.2
Harrisburg	3.2	0.7
Philadelphia	4.1	0.6
Pittsburgh	2.5	0.4
Wilkes-Barre	2.5	0.3
Williamsport	3.4	0.4
Rhode Island		
Providence	2.4	0.3
South Carolina		
Charleston	9.0	1.2
Columbia	7.8	1.4
Greenville	5.8	0.9
South Dakota		
Huron	2.1	0.5
Pierre	1.3	0.8
Rapid City	0.3	0.5
Sioux Falls	1.9	0.8
Tennesee		
Bristol	4.2	0.5
Chattanooga	6.3	1.2
Knoxville	6.4	0.8
Memphis	7.8	1.6
Nashville	6.2	1.4
Texas		
Abilene	4.2	2.1
Amarillo	1.4	1.2
Austin	10.4	2.4
Brownsville	16.4	2.6
Corpus Christi	16.7	2.5
El Paso	1.2	2.2
Fort Worth	7.6	2.1
Houston	13.3	2.1
Lubbock	2.3	1.3
Texas (Continued)		
Lufkin	10.8	1.9
Midland	2.4	2.0
Port Arthur	14.0	1.9
San Angelo	4.4	2.0
San Antonio	10.4	2.4
Victoria	13.8	2.2
Waco	8.2	2.3
Wichita Falls	6.4	2.4
Utah		
Cedar City	0.0	0.7
Salt Lake City	0.1	1.1
Virginia		
Lynchburg	4.0	0.7
Norfolk	6.5	0.8
Richmond	5.9	0.8
Roanoke	4.1	0.6
Sterling	4.6	0.7
Vermont		
Burlington	1.8	0.3
Washington		
Olympia	0.2	0.2
Quillayute	0.1	0.0
Seattle	0.1	0.1
Spokane	0.0	0.4
Yakima	0.0	0.5
Wisconsin		
Eau Claire	2.1	0.3
Green Bay	2.0	0.3
La Crosse	2.8	0.4
Madison	2.2	0.4
Milwaukee	2.2	0.3
West Virginia		
Charleston	4.0	0.5
Elkins	2.8	0.2
Huntington	4.5	0.6
Wyoming		
Casper	0.0	0.4
Cheyenne	0.0	0.3
Lander	0.0	0.4
Rock Springs	0.0	0.3
Sheridan	0.0	0.5

By using an hour-by-hour calculation, the procedure avoids the distortion of traditional BIN summaries. Although useful for many purposes, a BIN summary averages the values for either temperature or humidity, and consequently underestimate the loads of the averaged value. For example, we have found that when weather observations are “BINned” by temperature with mean coincident (average) values for moisture, annual latent loads are underestimated by 25 to 35% of their true dimension. Likewise, BINning the observations by dewpoint and averaging the coincident values for dry bulb temperature would underestimate the sensible load by 10 to 20%. This is why, although the program is also capable of producing BIN summaries, we chose to use the separate, more accurate hour-by-hour approach. The program’s ventilation air subroutine produces more meaningful indexes because they are non-averaged, separate values for latent and sensible loads.

Validation of ventilation pretreatment subroutine results

To ensure that the program provided accurate values for the indexes, a separate program, operated by a second programmer was used to generate values for all stations, and to compare them to results produced by the BIN program. The check-program used was a general-purpose statistical analysis program designed to run on workstations, and on personal computers of the type used by the BIN data program. (9) The check program was customized by the addition of commercially-available psychrometric subroutines which are frequently used as the calculation engine in popular psychrometric calculators and equipment selection programs running on personal computers.(10) The agreement between the BIN program and the statistical analysis program was good. Specifically, the R^2 value for the sensible load values was 0.98 and the R^2 value for latent loads was 0.97.

Ventilation Load Indexes

Table 1 contains the index values calculated by the BIN program. Several interesting points become clear from the information presented in the table:

Large differences between latent loads and sensible loads

One might expect that sensible heat loads and moisture loads generated by ventilation air would be similar, but that is not the case. None of the locations shown here have equal latent and sensible loads. In fact, all locations have loads that differ by at least 3:1, and loads at most locations differ by 4:1 or greater.

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Predominance of latent loads compared to sensible loads

Except for desert climates, the latent loads are always higher than the sensible loads. Even in San Antonio, TX and Oklahoma City, OK, which most would assume have arid climates, the annual latent load exceeds the sensible load by 4 and 5 times, respectively.

Geographic differences and similarities between annual loads

As one would expect, the total annual cooling loads are larger in southern climates and smaller in northern locations. For example, the sum of the latent and sensible loads in Miami, FL are 20.5 ton-hours per scfm per year, and loads in Boston only total 2.3 ton-hours per scfm per year—Miami's load is nearly 9 times that of Boston. However, the ratio of latent to sensible loads does not always vary by similar amounts between locations. In "humid" Miami, the latent load exceeds the sensible by 6.7 to 1. But in "dry" Boston, the latent load still exceeds the sensible load by 6.4 to 1.

Possible Implications for System Design

The implications of the indices for system design will vary according to the importance of controlling humidity and the volume of outside air needed for a given application. Where ventilation air is a high proportion of the total air flow, latent loads probably require more attention in the future than they have received in the past. Examples would include high-occupancy areas such as classrooms, or a theatre, restaurant, retail store or a health-care facility. In these applications, the ventilation air requirement may be more than 15% of the total system flow. With that much ventilation air, packaged rooftop equipment optimized for sensible heat removal may need assistance from a separate subsystem for ventilation air, or modification to trade part of its sensible capacity for increased latent removal capacity.

Where there is an economic benefit to controlling humidity combined with large ventilation loads, the ventilation air should be examined carefully, and perhaps singled-out for attention separate from the balance of the system. This suggestion is supported by the fact that the latent and sensible loads are so different in dimension, and are seldom concurrent. Independent control of temperature and humidity would allow closer control of each variable. Where there is an economic benefit to such control, a moisture removal system for ventilation air, combined with a sensible heat removal system for the combined supply air would reduce variation in temperature and moisture levels. Examples might include laboratory systems, where temperature or moisture excursions might cost money, or printing and electronic assembly, where humidity variations can slow or stop high-speed, automated processes.

Annual Loads vs. Peak Design

Using TMY-2 records to examine loads on an annual basis is useful for evaluating configurations, components and controls, but average data does not yield the peak design loads needed for sizing equipment. By definition the TMY loads are typical rather than extreme. ASHRAE technical committees 4.2 (Engineering Weather Data) and 3.5 (Desiccant and Sorption Technologies) have recently collaborated on a joint research project which will address this problem.(11) The results of that project will be printed in Chapter 24 of the 1997 Handbook of FUNDAMENTALS. For the first time, the correct and separate peak values for temperature and moisture will be provided for the designer.

Summary

Examination of typical behavior of weather shows that latent loads usually exceed sensible loads in ventilation air by at least 3:1 and often as much as 8:1. A designer can use the engineering shorthand indexes presented in Table 1. to quickly assess the importance of this fact for a given system design. To size those components after they are selected, the designer can refer to Chapter 24 of the 1997 Handbook of Fundamentals, which, for the first time, includes separate values for peak moisture and peak temperature.

Acknowledgments

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