Effects of Dry Bulb and Humidity Design Setpoints on Theoretical Energy Used in Ventilation

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The purpose of this paper is to present the energy required to condition a constant volumetric airflow and determine the variability of this energy due to changes in the design dry bulb and humidity setpoints. Hourly weather data from a typical year from 32 European locations and long-term data from 11 American locations were analyzed to determine the coincident dry-bulb and dew-point temperatures. These data were then analyzed to determine the heating, cooling and moisture removal energy requirements for a constant mass of airflow per hour. It was found that significant amounts of energy were used to heat the air to the desired setpoint with smaller amounts being used for air-conditioning. In situations where air conditioning is used, a significant amount of this energy is used in dehumidifying the air. It was found that the energy used was highly sensitive to the heating, cooling and relative humidity setpoints. Empirical equation coefficients are presented for each location to predict the heating energy required as a function of the setpoint. The variation in energy requirements due to dry-bulb and humidity setpoints are also presented for those locations with significant air conditioning loads.

INTRODUCTION AND OBJECTIVES

The tradeoffs between bringing in outdoor air for indoor air pollution reduction and the energy required to condition this air to a specified setpoint are significant. However many times the amount of energy required to condition this air is not recognized when regulations and standards are being developed and implemented. Over the last several years structures have been built tighter to reduce air infiltration, increase thermal comfort and conserve energy used to heat the air coming into the building. Several standards and organizations around the world have been specifying minimum amounts of "fresh" outdoor air for indoor air quality purposes. While some of these allow natural ventilation and infiltration others are requiring mechanical ventilation. Questions remain however as to the overall energy impact and/or tradeoffs involved between bringing in outdoor air for pollution reduction and the energy required to condition this air to specified design conditions.

The objectives of this work are to determine the energy requirements per constant mass unit of outdoor air used for ventilation for a number of different climates and locations in North America and Europe; and secondly to determine the variation of this annual ventilation heating and cooling energy requirements due to the heating temperature setpoint and cooling setpoints for temperature and humidity.

PROCEDURE

Estimates were made of the theoretical amount of energy needed to condition (to a given dry-bulb temperature setpoint for heating and a dry-bulb temperature and relative humidity setpoint for cooling) a constant airflow rate of one kg of dry air per hour (kg-h) of outdoor air used for ventilation. These estimates were made using measured hourly weather data from a number of locations and the psychrometric processes needed to heat and/or cool the air as it enters the building.

The psychrometric chart may be divided into six regions where the air being described by that region undergoes the same psychrometric process to reach the desired condition of temperature and moisture content (see Figure 1). If the average condition (over all the hours the air is within that region) for the air within that region is known, then the energy and moisture which must be added or subtracted may then be determined.

The weather data for several locations were analyzed by initially determining the joint frequency of occurrence of dry-bulb and dew-point temperatures (an array of coincident dry-bulb versus dew-point temperatures) for each location. The number of hours the outdoor air conditions fell within each psychrometric process region and an average air statepoint which represented the hours within each region were determined from these joint frequency matrices. These values were determined on a monthly and an annual basis and are reported in [3].

The theoretical sensible and latent energies required in each of the psychrometric process regions were then determined using the average state-point air condition representing all the hours within that region. Energy requirements for each of the processes were then combined to determine the total energy per unit mass of ventilation.

It should be realized that there are different efficiencies based upon the type of heating and cooling equipment. In order to take out the effects of these efficiencies, the information given in this paper is based upon the theoretical heat and mass transfer. Using this technique, the results can also be used as a baseline upon which to compare different equipment and processes.

A further description of the procedure, the mathematical equations describing the processes and additional intermediate results can be found in [3] and [4].

WEATHER DATA SOURCES

Measured hourly weather data from 43 locations in North America and Europe were used to determine the average outdoor weather conditions. Representative North American locations were selected based upon their climate classification region [2, 5, 7] and availability of 30-year period-of-record hourly data [8] (see Figure 2a for locations).

European locations were selected based upon the availability of representative hourly weather data. Hourly weather data for 15 British locations were obtained from the CIBSE Example Weather Years (EWY) [6] (see Figure 2b). Weather data for other European locations and four additional UK locations were obtained from the CEC Test Reference Years [1] (see Figure 2c).

ANNUAL HEATING ENERGY REQUIREMENTS AND VARIATION DUE TO SETPOINT

The amount of sensible heating required for conditioning a constant airflow of one kg/hr of ventilating air to 18C for each of the locations is presented in Table 1 and Figure 3. This setpoint was used to closely correspond to a setpoint commonly used in American standards which relate to air infiltration and ventilation and comfort design (ASHRAE Stds 55, 119, and 136). Sometimes it is assumed that the entering air needs to be heated to a temperature less than the setpoint due to solar and internal heat gains. This is considered by determining the energy required to heat the air to 1,2, and 3 degrees less than the setpoint (17, 16, & 15C respectively). The lower setpoints' energy requirements and the percentage of energy required to heat to 18C are also presented in Table 1 and Figure 3.

There is a significant amount of energy used to heat the incoming air. For the 18C setpoint it varies from approximately 101 MJ-h/kg for Saint-Hubert, Belgium (cold climate) to 3.3 MJ-h/kg for Miami, USA (warm climate). These account for 99.6% and 2.3% of the total heating and cooling energy respectively.

The amount of sensible energy required to heat the air to the desired setpoint depends greatly upon the setpoint selected. The energy required at each location was determined over a range of heating setpoints from 5-40 C. The variation of energy required is given for several locations in Figure 4. It can be seen that this is an exponential curve of the form:

$$\text{Sensible energy} = a * \text{setpoint}^{b} \qquad (1)$$

The sensible energy required for each location in the range of setpoints from 10C to 25C was fit using a least-squares linear regression on the log transformation of Eq. 1 to determine the coefficients for each location. These coefficients are given in the Appendix.

It was also found that for the locations selected in this work which had a significant amount of heating required that there was approximately a 10% (7.2 MJ-h/kg) reduction in this energy for every degree C of reduction in the setpoint.

ANNUAL SENSIBLE AND LATENT COOLING ENERGY REQUIREMENTS

The sensible and latent energy exchange required for humidity control and cooling to the desired statepoint of 25.6C and 40% RH for psychrometric regions 3 through 6 and for regions 4 through 6 for each location are presented in [3].

The results indicate that conditioning of air to provide cooling and dehumidification can require significant amounts of energy for many locations in America and Southern France. The total sensible and latent energy exchange for psychrometric regions 4 through 6 are presented in Table 2 for those locations having greater than 5 MJ-h/kg cooling requirements. The greatest amount of sensible cooling was required in Phoenix, AZ (20.2 MJ-h/kg) and the greatest amount of latent cooling was required in Miami, FL (82.2 MJ-h/kg). The total cooling load (combined sensible and latent) is highest in Miami (92.1 MJ-h/kg) which has a hot humid climate.

When only those locations requiring more than 5 MJ/kg-hr are considered (i.e. consider only those locations typically requiring air conditioning), latent cooling averaged 79.7% of the total cooling load for each location.

Variation of Energy Required due to Cooling Setpoint

The effect of the cooling setpoint on the energy required was determined by changing the setpoint plus and minus two degrees C for those locations which had greater than 5 MJ-h/kg cooling load. The respective fractional increase and decrease of the total cooling energy required at 25.6C and 40% are presented in Table 2.

It was found that generally the greater the cooling energy required, the higher the potential for energy savings. This variation is an indication of the great sensitivity of the cooling energy requirements to the control setpoint selected. The greatest change in energy requirements was for Miami where the cooling energy required at 2C higher and lower setpoints was 151.4% and 49.5% of the energy required at 25.6C.

Variation of Energy Required due to Humidity Design Setpoint

The latent energy requirements in the previous table indicates that a significant amount of the energy used is for dehumidifying the air to the desired condition. Thus the design relative humidity greatly impacts the energy requirements. (The energy requirements were determined initially for a 40% relative humidity design.) In order to determine the sensitivity of the relative humidity setting, the energy required for relative humidity designs of 60% and 80% were also determined. These values and the fraction of the 40% RH energy requirements are presented in Table 3.

Increasing the relative humidity setpoint from 40% to 60% had a significant impact on the energy requirements for those locations with significant cooling requirements. The energy requirements at 60% relative humidity relative to that required at 40% RH ranged from 15.2% for Carpentras to 59.0% for Brownsville. When the setpoint was raised to 80% there was an even greater reduction in the energy requirements. The fraction of energy required at 80% RH ranged from 0.0% to 21.2% of that when the setpoint was 40% RH.

It should be remembered however that there are other important factors in humidity control design which may dictate the humidity setpoint. High humidity has the potential for creating IAQ problems with mold, fungi, etc. and thus tradeoffs must be carefully considered.

SUMMARY

The annual theoretical amount of energy required to condition a constant airflow rate of 1 kg/hr of air used for ventilation was determined for a number of American and European locations. In Europe most of the energy was used to heat the air to the desired setpoint. In America there were significant amounts of both heating and cooling required. In situations where air conditioning is used a significant amount of this energy is used in dehumidifying the air. The calculated values for a heating setpoint of 18C and a cooling setpoint of 25.6C, 40% RH are presented. The sensitivity of the theoretical energy requirements to these setpoints are also presented. Equations are presented for the reduction of heating requirements.

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Table 1. Average Annual Sensible Energy Required for Heating Air to the Setpoint, (MJ-h/kg)

		SETPOINT				Percentage of Energy Needed at 18C		
		18C	17C	16C	15C	17C	16C	15C
BEL	Bruxelles	73.4	65.8	58.1	51.2	89.6	79.2	69.7
BEL	Oostende	76.0	67.7	59.5	51.2	89.1	78.3	67.4
BEL	Saint-Hubert	101.1	92.8	84.5	76.2	91.8	83.6	75.4
DK	Copenhagen	89.6	81.6	73.6	65.7	91.1	82.2	73.4
FR	Carpentras	55.0	48.7	42.3	35.9	88.4	76.8	65.2
FR	Limoges	70.3	62.9	55.6	48.2	89.5	79.0	68.6
FR	Macon	72.4	65.2	58.1	51.0	90.1	80.3	70.4
FR	Nancy	78.7	71.1	63.5	55.9	90.4	80.7	71.1
FR	Nice	40.1	34.4	28.7	23.1	85.8	71.7	57.5
FR	Trappes	74.5	66.7	59.0	51.2	89.6	79.1	68.7
GB	Aberdeen	88.2	79.6	71.1	62.6	90.3	80.6	70.9
GB	Aberporth	72.7	64.2	55.8	47.4	88.4	76.8	65.2
GB	Aberporth,CEC	73.9	65.2	56.5	47.9	88.3	76.5	64.8
GB	Aldergrove	82.2	73.6	65.0	56.5	89.6	79.1	68.7
GB	Birmingham	77.0	69.0	61.0	53.0	89.6	79.2	68.9
GB	Bristol	82.1	73.8	65.4	57.1	89.8	79.7	69.5
GB	Camborne	67.0	58.6	50.2	41.8	87.5	74.9	62.4
GB	Dundee	84.6	76.2	67.7	59.2	90.0	80.0	70.0
GB	Eskdalemuir	95.1	86.6	78.0	69.4	91.0	81.9	72.9
GB	Eskdalemuir,CEC	96.1	87.4	78.8	70.2	91.0	82.0	73.1
GB	Glasgow	81.2	72.8	64.4	56.0	89.6	79.3	68.9
GB	Heathrow	67.6	59.8	52.1	44.4	88.6	77.2	65.7
GB	Kew	71.7	63.6	55.5	47.5	88.7	77.5	66.2
GB	Kew, CEC	70.4	62.5	54.5	46.6	88.7	77.4	66.2
GB	Lerwick, CEC	97.5	88.7	79.9	71.1	91.0	81.9	72.9
GB	Manchester	78.6	70.2	61.9	53.6	89.4	78.8	68.2
GB	Newcastle	88.0	79.4	70.7	62.1	90.2	80.3	70.5
GB	Norwich	79.5	71.6	63.8	55.9	90.1	80.2	70.4
GB	Sheffield	80.4	72.2	64.1	55.9	89.8	79.7	69.5
NL	DeBilt	77.5	69.7	62.0	54.2	90.0	79.9	69.9
NL	Eelde	83.2	75.2	67.3	59.3	90.4	80.9	71.3
NL	Vlissingen	69.8	61.8	53.8	45.8	88.5	77.1	65.6
USA	Boston, MA	77.3	70.9	64.6	58.3	91.8	83.6	75.4
USA	Brownsville, TX	10.7	8.9	7.1	5.3	83.3	66.6	49.9
USA	Cheyenne, WY	100.0	92.8	85.6	78.5	92.8	85.7	78.5
USA	Ft. Worth, TX	34.9	31.1	27.4	23.6	89.2	78.3	67.5
USA	Lexington, KY	64.9	59.5	54.1	48.7	91.7	83.4	75.0
USA	Los Angeles, CA	20.9	15.8	10.7	5.6	75.6	51.2	26.7
USA	Miami, FL	3.3	2.6	1.8	1.0	76.8	53.7	30.5
USA	Omaha, NE	84.7	78.9	73.2	67.5	93.2	86.4	79.7
USA	Phoenix, AZ	19.5	16.5	13.5	10.5	84.7	69.3	54.0
USA	Salt Lake City, UT	79.2	73.1	67.0	60.9	92.3	84.6	76.9
USA	Seattle, WA	67.2	59.7	52.1	44.6	88.8	77.5	66.3
	Average	**71.1**	**63.9**	**56.7**	**49.6**	**89.9**	**79.8**	**69.7**

Table 2. Variation in Cooling Energy Required Due to Temperature Setpoint

		Sensible (MJ-h/kg)	Latent (MJ-h/kg)	Total Cooling @ 25.6C (MJ-h/kg)	cooling @ 23.6C/ cooling @ 25.6C	cooling @ 27.6C/ cooling @ 25.6C
USA	Miami, FL	9.9	82.2	92.1	1.514	0.495
USA	Brownsville, TX	11.7	76.4	88.1	1.421	0.577
USA	Ft. Worth, TX	10.4	34.5	44.9	1.269	0.767
USA	Phoenix, AZ	20.1	8.7	28.8	1.258	0.772
USA	Omaha, NE	3.6	14.1	17.8	1.093	0.922
USA	Lexington, KY	2.5	12.0	14.5	1.128	0.906
USA	Boston, MA	1.4	5.8	7.2	1.068	0.954
FR	Nice	0.4	5.1	5.5	1.177	0.896
FR	Carpentras	1.8	3.5	5.3	1.077	0.950

Table 3. Variation in Cooling Energy Required Due to Humidity Setpoint (Dry-Bulb Setpoint = 25.6C)

		Total Cooling @ 25.6C (MJ-h/kg)			Energy Use Ratio	
		40% RH	60% RH	80% RH	60%/40%	80%/40%
USA	Miami, FL	92.1	51.4	16.0	0.558	0.174
USA	Brownsville, TX	88.1	52.0	18.7	0.590	0.212
USA	Ft. Worth, TX	44.9	21.8	4.4	0.486	0.098
USA	Phoenix, AZ	28.8	9.3	0.7	0.322	0.024
USA	Omaha, NE	17.8	8.0	1.8	0.450	0.101
USA	Lexington, KY	14.5	6.0	1.0	0.414	0.069
USA	Boston, MA	7.2	2.8	0.4	0.387	0.055
FR	Nice	5.5	2.6	0.5	0.474	0.091
FR	Carpentras	5.3	0.8	0.0	0.152	0.000

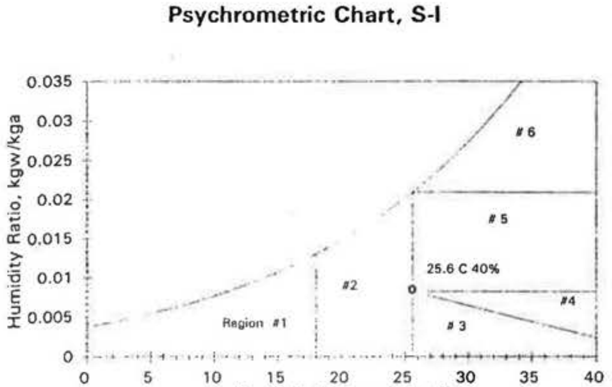

Figure 1. Psychrometric Chart with Regions of Processes Used to Reach Desired Statepoint

Figure 2a. American Locations Used in Analysis

Figure 2b. British CIBSE Example Weather Year Locations

Figure 2c. CEC Test Reference Year Locations Used in the Analysis

APPENDIX

A and B Coefficients used in Eq. 1 to Estimate Sensible Heating Energy Required

Coefficients for equation describing sensible energy required

Sensible energy = a * Temperature setting ^ b

	a	b
1 Bruxelles	302.8	1.8953
2 Oostende	253.7	1.9657
3 Saint-Hubert	1376.6	1.4840
4 Copenhagen	933.3	1.5784
5 Carpentras	113.6	2.1353
6 Limoges	260.0	1.9327
7 Macon	423.7	1.7781
8 Nancy	489.2	1.7550
9 Nice	10.6	2.8352
10 Trappes	292.0	1.9121
11 Aberdeen	459.0	1.8103
12 Aberporth	109.2	2.2327
13 Aberporth,CEC	95.2	2.2829
14 Aldergrove	279.0	1.9557
15 Birmingham	274.9	1.9417
16 Bristol	370.5	1.8611
17 Camborne	62.9	2.3938
18 Dundee	365.1	1.8747
19 Eskdalemuir	710.0	1.6871
20 Eskdalemuir,CEC	742.3	1.6751
21 Glasgow	293.3	1.9356
22 Heathrow	145.5	2.1168
23 Kew	175.1	2.0719
24 Kew, CEC	162.4	2.0917
25 Lerwick, CEC	545.5	1.7816
26 Manchester	276.1	1.9465
27 Newcastle	404.5	1.8518
28 Norwich	455.6	1.7827
29 Sheffield	352.5	1.8717
30 DeBilt	414.4	1.8070
31 Eelde	565.0	1.7240
32 Vlissingen	159.5	2.0963
33 Boston	1179.1	1.4522
34 Brownsville	1.03	3.2075
35 Cheyenne	2721.0	1.2506
36 Ft. Worth	118.4	1.9738
37 Lexington	947.3	1.4706
38 Los Angeles	0.0080	5.0596
39 Miami	0.0047	4.6803
40 Omaha	2823.6	1.1841
41 Phoenix	3.90	2.9383
42 Salt Lake City	1518.1	1.3721
43 Seattle	146.7	2.1104

Note: Limits of equation are for setpoint temperature from 10°C to 25°C.

R2 values for all regressions were >.99