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Energy Requirements for Conditioning of Ventilating Air

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Energy Requirements for Conditioning of Ventilating Air

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PREFACE

International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an International Energy Programme. A basic aim of the IEA is to foster co-operation among the twenty-one IEA Participating Countries to increase energy security through energy conservation, development of alternative energy sources and energy research development and demonstration (RD&D).

Energy Conservation in Buildings and Community Systems

The IEA sponsors research and development in a number of areas related to energy. In one of these areas, energy conservation in buildings, the IEA is sponsoring various exercises to predict more accurately the energy use of buildings, including comparison of existing computer programs, building monitoring, comparison of calculation methods, as well as air quality and studies of occupancy.

The Executive Committee

Overall control of the programme is maintained by an Executive Committee, which not only monitors existing projects but identifies new areas where collaborative effort may be beneficial.

To date the following have been initiated by the Executive Committee (completed projects are identified by *):

I	Load Energy Determination of Buildings*
II	Ekistics and Advanced Community Energy Systems*
III	Energy Conservation in Residential Buildings*
IV	Glasgow Commercial Building Monitoring*
V	Air Infiltration and Ventilation Centre
VI	Energy Systems and Design of Communities*
VII	Local Government Energy Planning*
VIII	Inhabitant Behaviour with Regard to Ventilation*
IX	Minimum Ventilation Rates*
X	Building HVAC Systems Simulation*
XI	Energy Auditing*
XII	Windows and Fenestration*
XIII	Energy Management in Hospitals*
XIV	Condensation*
XV	Energy Efficiency in Schools*
XVI	BEMS - 1: Energy Management Procedures*
XVII	BEMS - 2: Evaluation and Emulation Techniques
XVIII	Demand Controlled Ventilating Systems*
XIX	Low Slope Roof Systems
XX	Air Flow Patterns within Buildings*
XXI	Thermal Modelling*
XXII	Energy Efficient Communities
XXIII	Multizone Air Flow Modelling (COMIS)
XXIV	Heat Air and Moisture Transfer in Envelopes
XXV	Real Time HEVAC Simulation
XXVI	Energy Efficient Ventilation of Large Enclosures
XXVII	Evaluation and Demonstration of Domestic Ventilation Systems
XXVIII	Low Energy Cooling Systems
XXIX	Energy Efficiency in Educational Buildings
XXX	Bringing Simulation to Application

Annex V Air Infiltration and Ventilation Centre

The Air Infiltration and Ventlation Centre was established by the Executive Committee following unanimous agreement that more needed to be understood about the impact of air change on energy use and indoor air quality. The purpose of the Centre is to promote an understanding of the complex behaviour of air flow in buildings and to advance the effective application of associated energy saving measures in both the design of new buildings and the improvement of the existing building stock.

The Participants in this task are Belgium, Canada, Denmark, Germany, Finland, France, Netherlands, New Zealand, Norway, Sweden, Switzerland, United Kingdom and the United States of America.

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EXECUTIVE SUMMARY

The energy impact and/or trade-offs involved between bringing in outdoor air for indoor air pollution reduction and the energy required to condition this air are investigated in this report. Long-term hourly weather data from several European and American locations were analyzed to determine the average conditions of air over the period of record of the data. These data were then analyzed to determine the psychrometric process theoretical heating, cooling and moisture removal energy requirements for a constant mass of airflow per hour (MJ·h/kg). Summary weather data are also provided if it is desired to determine the additional effects of equipment and design.

It was found that a significant amount of energy is required to condition air which is used for ventilation. The annual energy required per kg/hr of airflow varied from 22.1 MJ·h/kg for Los Angeles to 102.5 MJ·h/kg for Omaha. In Europe the range was from 45.6 MJ·h/kg for Nice to 101.1 MJ·h/kg for Saint-Hubert. 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. Much of the variation was due to the amount of moisture in the air which had to be removed in air conditioning. In situations where air conditioning is used, a significant amount of this energy is used in dehumidifying the air. For example, in Miami 86% of the energy is used for moisture removal. It was found that the energy used was highly sensitive to the cooling and relative humidity setpoints.

1 INTRODUCTION

Outdoor air is brought into buildings for many different reasons such as free cooling, "fresh air" and pollution reduction. Over the last several years structures have been built tighter to reduce air infiltration and conserve energy used to heat the air coming into the building. Several standards and organizations have been specifying minimum amounts of "fresh" outdoor air for indoor air quality purposes. There are questions however as to the energy impact and/or trade-offs involved between bringing in outdoor air (for pollution reduction) and the energy required to condition this air.

1.1 Objectives

The objectives of this work are: first to determine the theoretical 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 setpoints for temperature and humidity.

1.2 Procedure

Estimates were made of the theoretical amount of energy needed to condition 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 change in the energy content of the air needed to heat and/or cool it, as it enters the building. The weather data for each location were analyzed to determine the number of hours the outdoor air conditions fell within each psychrometric process region and the weighted average air property for each region. The sensible and latent energies required in each of the psychrometric process regions were then determined by calculating the energy difference between the air statepoint representing the average condition for all the hours within that region and the air at the desired setpoint. Energy values from each of the processes were then combined to determine the total energy per unit mass of ventilation. The effects of equipment and different heating and/or cooling techniques are not included due to the wide variety and efficiencies of possible equipment. Summary weather data are provided to determine these effects if desired.

2 PSYCHROMETRIC PROCESSES ASSOCIATED WITH VENTILATION

A psychrometric chart is a visual presentation of the possible characteristics of an air-water vapor mixture and is often used to describe the possible conditions or statepoints which may be obtained by the air. The psychrometric chart is commonly used to determine the heat and moisture changes in the air as it goes from one condition (such as 32 °C, 65% relative humidity outdoor air) to another condition (26 °C, 40% relative humidity) such as inside a building.

The psychrometric chart can also be used to determine the heat and moisture which must be added or subtracted from the air. Therefore if the average conditions of the outdoor air are known, the theoretical energy which must be added or subtracted from the air to heat, cool and/or dehumidify it when the air enters the building may be determined.

Sensible heat is that energy which is used to increase the energy content of the dry air and the moisture vapor mixed with the dry air. The amount of sensible energy need to heat or cool air is based upon the dry-bulb temperature and is calculated as:

$$\text{Sensible} = (C_{pa} + W * C_{pw})(T_{db\text{-}setpt} - T_{db\text{-}outside}) \tag{1}$$

where:

C_{pa} = Specific heat of dry air (1.0056 kJ/{$kg_{dry\text{-}air}$°C})

W = Amount of moisture in the air (kg)

C_{pw} = Specific heat of water vapor (1.86 kJ/{kg_{water}°C})

$T_{db\text{-}setpt}$ = Setpoint dry-bulb temperature (°C)

$T_{db\text{-}outside}$ = Outside dry-bulb temperature (°C)

Latent heat is that energy which must be added or withdrawn when water is vaporized (in the case of humidification) or condensed (in the case of dehumidification) from the air. The latent heat transfer, or the energy which must be used for moisture control with humidification/dehumidification, can be determined from the amount of moisture which must be added or removed as:

$$\text{Latent} = L * \Delta W \tag{2}$$

where:

L = Latent heat of vaporization (2501.3 kJ/kg_{water})

The amount of water which must be subtracted from the air is:

$$\Delta W = H_{setpt} - H_{outside} \tag{3}$$

where:

H_{setpt} = Humidity ratio of the air at the setpoint ($kg_{water\ vapor}/kg_{dry\text{-}air}$)

$H_{outside}$ = Humidity ratio of the outside air ($kg_{water\ vapor}/kg_{dry\text{-}air}$)

If two independent measurements (such as dry-bulb temperature and relative humidity) and the air pressure are known, the others characteristics (such as humidity ratio, wet-bulb temperature, dew-point temperature, etc.) may be determined from the psychrometric chart or from equations which mathematically describing it. The computerized psychrometric routines used in this work were developed by Gates, et al. (1994).

The psychrometric chart may be divided into several regions where the air being described by that region undergoes the same psychrometric process to reach the desired condition of temperature and moisture content. 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 conditions of the outdoor air fall into six different regions on the chart with respect to the desired condition of the air in the building (see Figure 1).

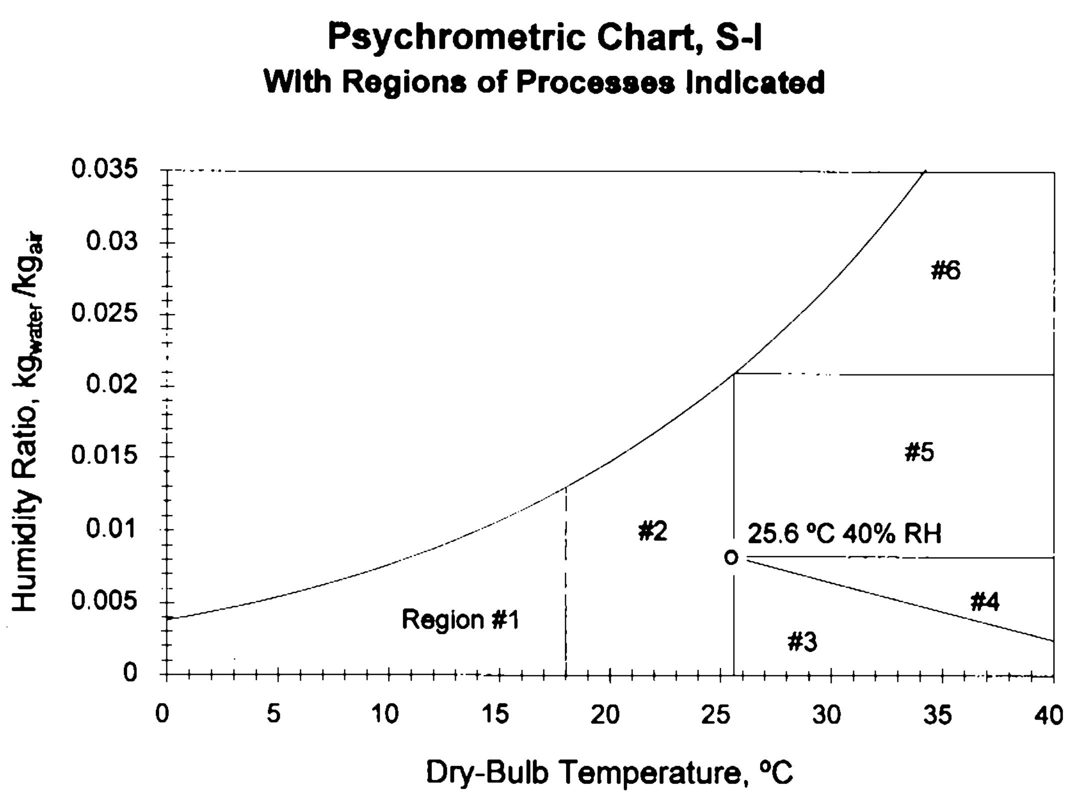


Figure 1. Psychrometric Chart with Regions of Processes Used to Reach Desired Statepoint

Region 1: Outdoor Dry-Bulb Temperature Less Than Heating Setpoint

($T_{db\text{-}outdoor} < T_{dbh\text{-}setpt}$)

(Heating Region)

This is the typical wintertime condition when heat is being added to the ventilation air. In this case only sensible heat is added to the air to reach the desired statepoint since typically moisture is not controlled in heating situations.

The sensible energy used (per unit mass of air) to condition the air in this region is calculated as:

$$\text{Sensible}_1 = C_p\,(T_{dbh\text{-}setpt} - T_{db\text{-}outdoor}) \qquad (4)$$

There is typically no moisture added in heating situations, therefore it will be assumed that there is no latent heat exchange in this region:

$$\text{Latent}_1 = 0$$

Region 2: Outdoor Dry-Bulb Temperature Greater Than Heating Setpoint but Less Than Cooling Setpoint

($T_{dbh\text{-}setpt} < T_{db\text{-}outdoor} < T_{dbc\text{-}setpt}$)

(No Heating nor Cooling Region)

This is the condition when the outdoor air does not need to be either heated or cooled. It represents the moderate weather conditions typically encountered during the spring and fall or at other times when neither heating or cooling are needed. This also represents the situation when the outdoor air is being introducing into the building for natural ventilation. In this case:

$$\text{Sensible}_2 = 0$$

Since the controls used to heat or cool ventilating air are primarily based upon dry-bulb control and the air in this region is below the dry-bulb cooling setpoint, the air conditioning would not be operating and therefore there would be no dehumidification from the air conditioning coils. Since moisture is not intentionally being added or withdrawn from the air the latent heat transfer is:

$$\text{Latent}_2 = 0$$

It should be recognized that a potential exists for moisture to be added to the building from the air represented by this statepoint. The amount of moisture added is determined by the moisture in the incoming air and the equilibrium moisture content of the materials of the building surfaces. However, condensation will occur only when the surface temperature is below the dew-point temperature of the incoming air. Moisture exchange between building materials and the incoming air is a very complex process and depends upon a number of building descriptors such as building contents, their sorption characteristics, etc. This has been the topic of several extensive research projects. It is not considered here because the time frame used in this study is much longer. (The moisture absorbed by the contents of the building during the high moisture conditions will be released later during lower moisture conditions and the building reaches the equilibrium moisture content.) In addition, it is assumed that this exchange does not directly impact the energy transfer in ventilation and thus is considered to be beyond the scope of this project. Therefore the energy impacts of moisture exchange is not considered in this region.

Region 3: Dry-Bulb Temperature Greater Than Cooling Setpoint Temperature and Wet-Bulb Less Than Desired Wet-Bulb

($T_{db\text{-}outdoor} > T_{dbc\text{-}setpt}$, $T_{wb\text{-}outdoor} < T_{wb\text{-}setpt}$)

(Evaporative Cooling Region)

The air in this region has a higher dry-bulb temperature than desired, however the outdoor wet-bulb temperature is less than the wet-bulb of the design setpoint. This condition is typically associated with hot, dry weather. Evaporative cooling (a process which approximately follows the wet-bulb line) can be used in this psychrometric region to provide the desired reduction in dry-bulb temperature. The sensible energy used to cool the air comes from the latent heat of evaporization of the water added to the air.

There is no external energy required for this cooling process other than that required for water pumping and/or spraying and air circulation. It is commonly assumed that these energy requirements are negligible compared to the sensible/latent energy exchange.

For the purposes of this work, it is assumed that humidities below the setpoint are acceptable. Otherwise energy would have to be used to vaporize water to raise the humidity. This energy-intensive humidification process is very rarely done in these situations. Therefore the amount of additional latent energy which would be required to evaporate water to raise the humidity to the desired condition is not determined.

The sensible heat exchange in this region, S_3, is defined by Eqn 1.

The latent heat in this region, L_3, is considered to be zero.

Since there is an exchange of sensible and latent heat in this region and in practice the energy required is for pumping/spraying, the sensible and latent energy requirements for this region will not be included in the total energy requirements.

Region 4: Outdoor Dry-Bulb and Wet-Bulb Temperatures Greater Than Cooling Setpoint Temperatures, Dew-Point Less Than Setpoint

($T_{db\text{-}outdoor} > T_{dbc\text{-}setpt}$, $T_{wb\text{-}outdoor} > T_{wbc\text{-}setpt}$, $T_{dp\text{-}outdoor} < T_{dpc\text{-}setpt}$)

(Refrigerative and Evaporative Cooling Region)

Air in this region may be partially cooled with evaporate cooling (up to the dew-point of the setpoint) and then external energy must be used to remove the remaining sensible heat if moisture conditioning is achieved.

In many cases, cooling is only controlled based upon dry-bulb temperature and moisture is controlled with the system design. However for the purposes of this study, the total energy required is the net of the sensible and latent heats.

The sensible and latent energy requirements in this region are defined by Eqns 1 and 2.

Region 5: Outdoor Dry-Bulb Temperature Greater Than Cooling Setpoint Temperature, Outdoor Dew-Point Greater than Setpoint and Less Than Saturation

($T_{db\text{-}outdoor} > T_{dbc\text{-}setpt}$, $T_{wb\text{-}outdoor} > T_{wbc\text{-}setpt}$, $T_{dpc\text{-}setpt} < T_{dp\text{-}outdoor} < T_{dpc\text{-}sat}$)

(Refrigerative Cooling Region, Dew-point less than Setpoint Saturation Temperature)

Air in this region must have both sensible heat and moisture (latent heat) removed to maintain the desired setpoint. The amount of moisture removed may be used to determine the amount of latent heat which is removed for humidity control.

The sensible and latent energy requirements in this region are defined by Eqns 1 and 2.

Region 6: Outdoor Dry-Bulb and Dew-Point Temperatures Greater Than Cooling Dry-Bulb Setpoint Temperature and Dewpoint at Saturation

($T_{db\text{-}outdoor} > T_{dbc\text{-}setpt}$, $T_{wb\text{-}outdoor} > T_{wbc\text{-}setpt}$, $T_{dp\text{-}outdoor} > T_{dpc\text{-}sat}$)

(Refrigerative Cooling Region, Dew-point greater than Setpoint Saturation Temperature)

Air in this region is hot and humid. The latent (moisture) heat removal is the significant energy requirement to maintain the desired conditions.

The sensible and latent energy requirements in this region are defined by Eqns 1 and 2.

It should be recognized that the energy values presented are for the minimum theoretical enthalpy changes of the air and the total amount of equipment energy used in Regions 4, 5, and 6 may be larger than the theoretical energies given due to the system design and equipment efficiencies.

2.1 Energy Transfer Summary

The sensible energy which must be used over all the psychrometric regions to heat to the desired heating setpoint and cool to the desired cooling setpoint is the sum of the heating and cooling energy requirements, or:

$$Sen_{total} = S_1 + | S_4 + S_5 + S_6 | \tag{5}$$

The total latent energy which must be removed to obtain the desired cooling humidity conditions is:

$$Lat_{total} = | L_4 + L_5 + L_6 | \tag{6}$$

The total energy which must be supplied to maintain the desired conditions is the sum of the sensible and latent heat transfers or:

$$Energy_{\,total} = Sen_{\,total} + Lat_{\,total} \tag{7}$$

3 WEATHER DATA SOURCES

Measured hourly weather data from a number of 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. European locations were selected based upon the availability of hourly weather data.

An overall climate indicator often used to describe the climatic conditions is the *climate region*. An indicator previously used to provide a reduced set of locations with a diverse weather when a large number of locations are available for larger data sets is the climate region. A climate region is an area of the earth's surface over which the combined effects of the processes in the earth's climate system result in an approximately homogeneous set of climatic conditions (Critchfield, 1983). The most widely used system of climatic classification is that of Köppen. It is based on vegetation zones, temperature, rainfall and their seasonal characteristics. A more comprehensive classification which considered vegetation, the daily and seasonal temperature differences as well as the proximity to maritime or continental weather patterns was introduced by Troll in 1980 (Müller, 1982). These two climate indicators have previously been used to select diverse data sites for weather data analysis (Colliver, 1993).

Long-term (30 years) hourly weather data for 238 US locations are available in the SAMSON data set (NCDC, 1993). A subset of these weather data sets was selected to be representative of the range of climates and weather conditions experienced in America. The selected United States locations and their Köppen and Troll climate classification are presented in Table 1 and Figure 2.

Table 1. US Locations and Climate Class

Location	WBAN #	Latitude (° 'N)	Longitude (° 'W)	Elevation (m)	Climate	
					Köppen	Troll
Atlanta, GA	13874	33 39	084 26	315	Cfa	IV7
Boston, MA	14739	42 22	071 02	5	Dfb	III8
Brownsville, TX	12919	25 54	097 26	6	Cfa	IV3
Cheyenne, WY	24018	41 09	104 49	1872	BSk	III4
Ft Worth, TX	03927	32 50	097 03	164	Cfa	IV4
Lexington, KY	93820	38 02	084 36	301	Cfa	III8
Los Angeles, CA	23174	33 56	118 24	32	Csa	IV2
Miami, FL	12839	25 48	080 16	2	Aw	V2
Omaha, NE	94918	41 22	096 31	404	Dfa	III9
Phoenix, AZ	23183	33 26	112 01	339	BWh	IV5
Salt Lake City, UT	24127	40 46	111 58	1288	Csa	III10
Seattle, WA	24233	47 27	122 18	122	Csb	III4

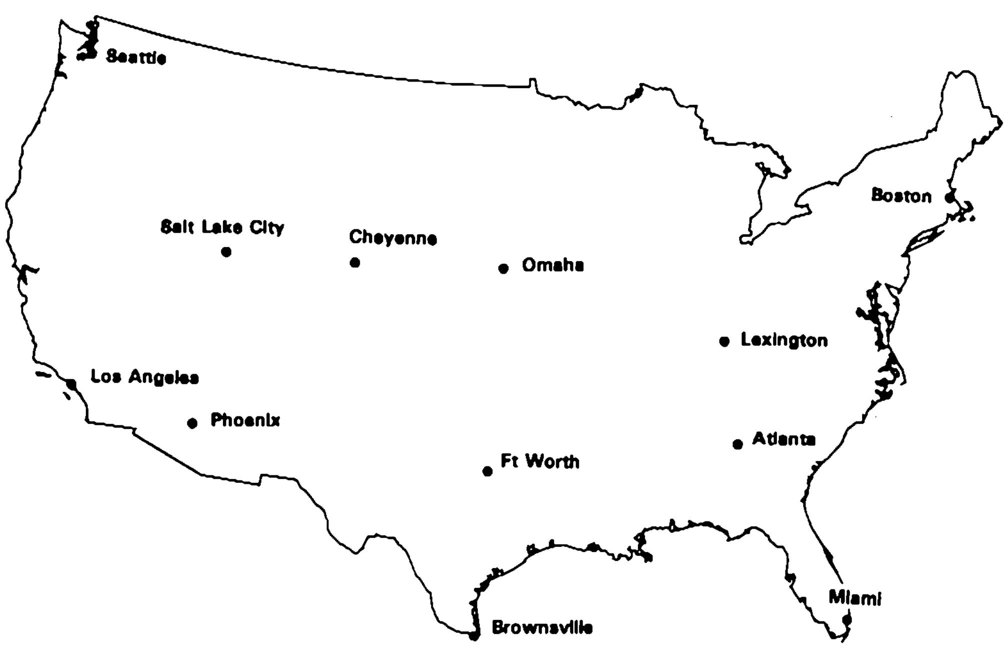


Figure 2. American Locations Selected for Analysis

Hourly weather data for most of the British locations were obtained from the CIBSE Example Weather Years (EWY). This data set was developed by the CIBSE Example Year Task Group to provide for weather data input into energy simulations to make comparisons of annual energy consumptions of different design options (Irving, 1988). It consists of a single year of representative weather data for 15 locations in Great Britain (see Figure 3). Their locations, standard air pressures used (determined from elevation) and climate classifications are presented in Table 2.

The EWY was derived by selection of a complete year of weather data out of the years of data available. A group of potential example weather years were selected in which each month had several parameters which were within two standard deviations of the long-term average monthly value for each of those parameters. The single year of data selected from these potential example years was the year which had the minimum total deviation of all the parameters from the long term means.

It should be recognized that this and other data sets of "average conditions" will not duplicate the extreme conditions which are needed for design purposes and it will also not contain the variation which will occur if several years of data are used. While it would be advantageous to use long term hourly data, example weather years are often used when the long term data are not available.

Weather data for other European locations and four additional UK locations were obtained from the CEC Test Reference Years (CEC, 1985). Their locations are presented in Figure 4 and Table 3. The CEC TRYs were compiled from 12 individual months of "average" measured weather data taken from different years. The data for the hours at the start and end of each month were adjusted to provide for a smooth transition between adjacent months when they were selected from different years. Comments about the applicability of the CIBSE data apply to the EC TRYs also. The month-year data selected to make up the TRY are presented in Appendix A. It should be noted that very few of the data months used in the TRYs come from the year of data used in the EWY.

Each TRY and EWY have been prepared for a specific location. The limits of its applicability should be restricted to a geographic region in which the deviations caused by the geographical distance from the original location do not exceed the standard deviation of the results caused by the stochastic variations of weather from year to year (CEC, 1985).

Table 2. British Locations Using CIBSE Example Weather Year

Location	WMO #	Lat (° ' N)	Long (° ' W)	Year Selected	Elevation (m)	Standard Pressure (mb)	Climate Classification	
							Köppen	Troll
Aberdeen	30910	57 12	02 13	80/81	65	1005.05	Cfb	III,2
Aberporth	35020	52 08	04 34	72/73	133	996.54	Cfb	III,2
Aldergrove (Belfast Airport)	39170	54 39	06 13	77/78	68	1004.67	Cfb	III,2
Birmingham	35340	52 27	01 44	72/73	96	1001.16	Cfb	III,2
Bristol	37260	51 28	02 36	84/85	11	1011.86	Cfb	III,2
Camborne	38080	50 13	05 19	81/82	88	1002.17	Cfb	III,2
Dundee	31634	56 27	03 01	80/81	4	1012.74	Cfb	III,2
Eskdalemuir	31620	55 19	03 12	70/71	242	983.06	Cfb	III,2
Glasgow	31400	55 52	04 26	72/73	5	1012.62	Cfb	III,2
Heathrow	37720	51 29	00 27	79/80	25	1010.09	Cfb	III,2
Kew		51 28	00 19	64/65	77	1003.54	Cfb	III,2
Manchester	33340	53 21	02 16	84/85	75	1003.80	Cfb	III,2
Newcastle	32433	55 02	01 42	86/87	81	1003.04	Cfb	III,2
Norwich	34920	52 38	01 19 (E)	81/82	18	1010.97	Cfb	III,2
Sheffield	33600	53 29	01 00	86/87	17	1011.10	Cfb	III,2

Figure 3. British CIBSE Example Weather Year Locations

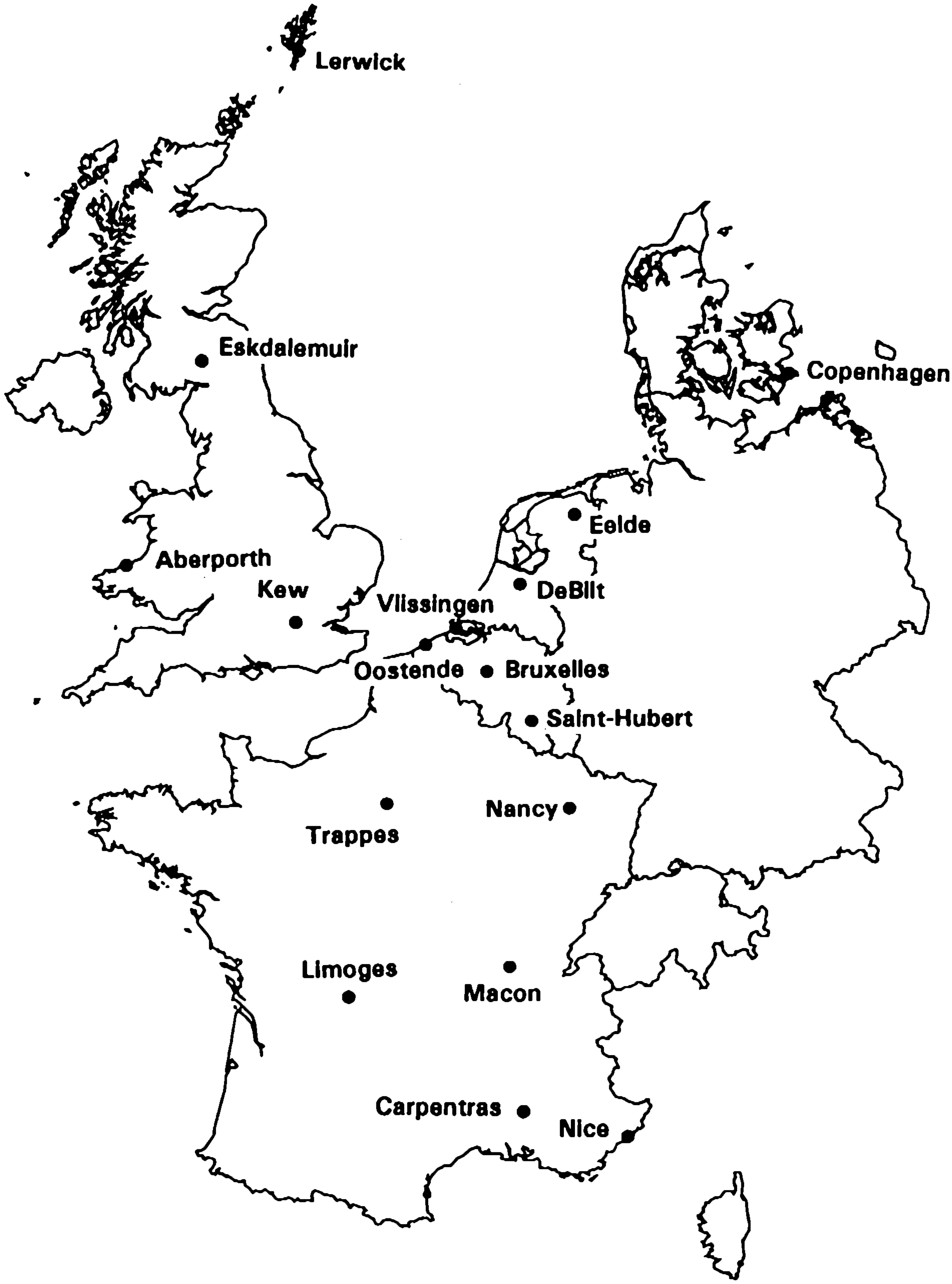


Figure 4. CEC Test Reference Year Locations Used in the Analysis

Table 3. Locations Using the CEC Test Reference Year

Location	Latitude (° ' N)	Longitude (° ' W)	Elevation (m)	Climate Classification	
				Köppen	Troll
Belgium					
Oostende	51 12	02 52	4	Cfb	III,2
Saint-Hubert	50 02	05 24	563	Cfb	III,3
Uccle (Bruxelles)	50 48	04 21	105	Cfb	III,3
Denmark					
Copenhagen	55 46	12 19	19	Cfb	III,3
France					
Carpentras	44 05	05 03	105	Csa	IV,1
Limoges	45 49	01 17	284	Cfb	III,2
Macon	46 18	04 48	217	Cfb	III,3
Nancy	48 41	06 13	204	Cfb	III,3
Nice	43 39	07 12	10	Csa	IV,1
Trappes	48 46	02 01	168	Cfb	III,2
Netherlands					
De Bilt	52 06	05 11	40	Cfb	III,3
Eelde	53 08	06 35	5	Cfb	III,3
Vlissingen	51 27	03 36	22	Cfb	III,2
United Kingdom					
Aberporth	52 08	04 34	133	Cfb	III,2
Eskdalemuir	55 19	03 12	242	Cfb	III,2
Kew	51 28	00 19	77	Cfb	III,2
Lerwick	60 08	01 11	82	Cfb	III,2

4 DETERMINATION OF THE AVERAGE WEATHER CONDITION FOR EACH PSYCHROMETRIC REGION

The "average air" in each psychrometric region for each location was determined by analyzing the long-term, measured weather data. Coincident matrices or arrays were made which contained the number of hours each dew-point temperature occurred coincidentally with each dry-bulb temperature. These X-Y arrays (X dry-bulb temperature vs. Y dew-point temperature) contained the number of occurrences of Y dew-point temperature which had occurred at X dry-bulb temperature. Thirteen (12 monthly and one yearly total) matrices were determined from the long-term weather data for each location. One degree Celsius bins were used for both dry-bulb and dew-point temperatures.

The "average air" statepoint for each region was then determined from the matrices by assuming that it was a mixing process of all the occurrences of conditions within a psychrometric region. In a mixing process of two air streams, each air stream is weighted by the mass of air flowing in that stream. In this situation each dry-bulb/dew-point combination was weighted by the number of hours of occurrence of that condition in the historical data set. Dry-bulb and absolute humidity for the given dew-point were the psychrometric parameters used in the mixing routines. The psychrometric properties were calculated using the routines of Zhang and Gates (1992). Standard air pressure based upon station elevation was used for all the mixing calculations.

The average percentage of the annual hours in each psychrometric region and the corresponding average dry-bulb temperature and humidity ratio are given in Table 4 for each of the locations investigated. This is given for a heating setpoint of 18 °C and a cooling setpoint of 25.6 °C, 40% relative humidity. Examples of the data contained in this table are given in Figure 5 for four locations. The percentage of the total number of hours in each region is given for the sample locations in the pie charts in Figure 6.

Table 4:Average Conditions for the Air within Each Psychrometric Region and Percentage of Annual Occurrence

(Note: The average condition is computed from all the period-of-record hours the hourly air statepoint is bounded by the region.)

			REGION 1			REGION 2			REGION 3			REGION 4			REGION 5			REGION 6		
			DB	HR	%	DB	HR	%	DB	HR	%	DB	HR	%	DB	HR	%	DB	HR	%
1	BEL	Bruxelles	8.4	6.3	0.868	20.3	10.1	0.123							27.3	13.5	0.009			
2	BEL	Oostende	8.8	6.2	0.936	19.4	10.3	0.063							28.5	10	0.001			
3	BEL	Saint-Hubert	5.8	5.6	0.941	20.2	9.8	0.059							28	10.7				
4	DK	Copenhagen	6.7	5.5	0.903	20	8.3	0.095				27	7.6	0.000	27.2	10.4	0.002			
5	FR	Carpentras	9.4	5.8	0.724	20.8	9.4	0.204	27.3	6.8	0.006	29.4	7.4	0.003	28.6	10.8	0.063			
6	FR	Limoges	8.5	6.1	0.836	20.5	9.3	0.148	28	7.4	0.001	28.3	7.9	0.000	27.9	10.3	0.016			
7	FR	Macon	7.9	6	0.811	20.5	10.1	0.164	28.2	7.1	0.001	27.3	7.8	0.001	28.2	11.7	0.024			
8	FR	Nancy	7.6	5.8	0.862	20.4	9.6	0.126							27.3	11.7	0.012			
9	FR	Nice	10.9	5.9	0.645	21	11.3	0.321	27.2	6.7	0.001	29	7.1	0.000	28.8	15.3	0.033			
10	FR	Trappes	8.4	6.1	0.884	20.2	9.4	0.112							28.6	11.7	0.004			
11	GB	Aberdeen	7.7	5.8	0.969	19.3	9.3	0.03							28	12.2	0.000			
12	GB	Aberporth	9.4	6.5	0.958	19.7	10.1	0.041							28.5	12.3	0.001			
13	GB	Aberporth,CEC	9.5	6.5	0.984	19.4	9.4	0.016							28	10.8	0.000			
14	GB	Aldergrove	8.4	6.1	0.973	19.4	9.3	0.027												
15	GB	Birmingham	8.4	6	0.907	20.1	9.5	0.091	28	7.2	0.000				28.8	10.8	0.002			
16	GB	Bristol	8.2	6.1	0.948	19.8	9.1	0.051							28.4	10.6	0.001			
17	GB	Camborne	10	7	0.953	19.1	10.6	0.047												
18	GB	Dundee	8	5.7	0.961	19.5	8.6	0.039												
19	GB	Eskdalemuir	6.9	5.9	0.976	19.6	9.9	0.024												
20	GB	Eskdalemuir,CEC	6.9	5.7	0.979	19	8.6	0.021												
21	GB	Glasgow	8.3	5.9	0.954	19.6	9.2	0.045							28	12.6	0.001			
22	GB	Heathrow	9.2	6.3	0.876	19.8	9.2	0.122	28	6.7	0.000				28.9	11.8	0.002			
23	GB	Kew	9.1	6	0.915	19.7	8.9	0.084							28.4	9.7	0.001			
24	GB	Kew, CEC	9.1	5.9	0.902	20	8.2	0.097							28.8	9.4	0.001			
25	GB	Lerwick, CEC	6.9	5.6	1															
26	GB	Manchester	8.6	6	0.946	19.5	9.2	0.053							28.6	11.7	0.001			
27	GB	Newcastle	7.8	5.8	0.982	18.9	9.7	0.018												
28	GB	Norwich	7.9	5.9	0.891	20.1	10	0.105							28.8	12.4	0.004			
29	GB	Sheffield	8.2	5.8	0.929	19.7	9.7	0.07							28	11.6	0.001			
30	NL	DeBilt	8	6	0.883	20	9	0.111							27.6	10.2	0.006			
31	NL	Eelde	7.5	6	0.902	20.1	9.5	0.096							28.1	10.5	0.001			
32	NL	NL	9.3	6.3	0.908	19.5	10.2	0.091							28.3	11.4	0.000			
33	USA	Boston, MA	5.8	4.3	0.718	21	10.6	0.222	28.8	6.3	0.004	29.4	7.4	0.001	28.4	13	0.055			
34	USA	Brownsville, TX	12	7.2	0.202	22.1	13.7	0.396	27.4	5.6	0.002	30.5	7	0.001	28.8	16.9	0.393	28.4	21.4	0.006
35	USA	Cheyenne, WY	4	3.3	0.812	20.9	6.2	0.141	27.9	5.2	0.04	30.5	7.4	0.002	27.1	9.6	0.004			
36	USA	Ft. Worth, TX	8.8	5.2	0.429	21.7	11.6	0.3	27.1	5.9	0.007	30.7	7.2	0.003	30	14.3	0.26	30.3	21.5	0.000
37	USA	Lexington, KY	6	4.7	0.613	21.2	11.5	0.282	28.8	6.6	0.003	29.5	7.4	0.001	28.3	13.7	0.1	30.4	21.7	0.000
38	USA	Los Angeles, CA	13.9	7.4	0.579	20.2	10	0.399	28.1	4.3	0.008	32.3	6.6	0.001	27.3	11.6	0.013			
39	USA	Miami, FL	13.7	7.3	0.088	22.5	13.3	0.459	28.7	6.5	0.001	28.6	7.5	0.000	28	18.4	0.447	28.4	21.4	0.005
40	USA	Omaha, NE	3.2	4	0.652	21.2	10.9	0.227	27.2	6.2	0.006	29.7	7.4	0.002	29.1	13.9	0.113	31.8	21.9	0.001
41	USA	Phoenix, AZ	11.5	4.4	0.339	21.3	5.3	0.24	30	4.2	0.154	36.2	6.2	0.081	33.1	11.3	0.186	29	21.7	0.000
42	USA	Salt Lake City, UT	5	3.8	0.693	21.1	6.4	0.182	29	5.2	0.077	32.7	6.8	0.028	28.9	9.6	0.02			
43	USA	Seattle, WA	9.1	5.7	0.857	20.4	8.1	0.122	27.1	6.4	0.004	29.7	7.3	0.002	27.9	9.4	0.015			

Notes:
DB - Average dry-bulb temperature (°C)
HR - Average humidity ratio (g/kg)
% - Percentage of the annual hours in this psychrometric region (decimal)

Heating Setpoint = 18 °C
Cooling Setpoint = 25.6 °C, 40% RH

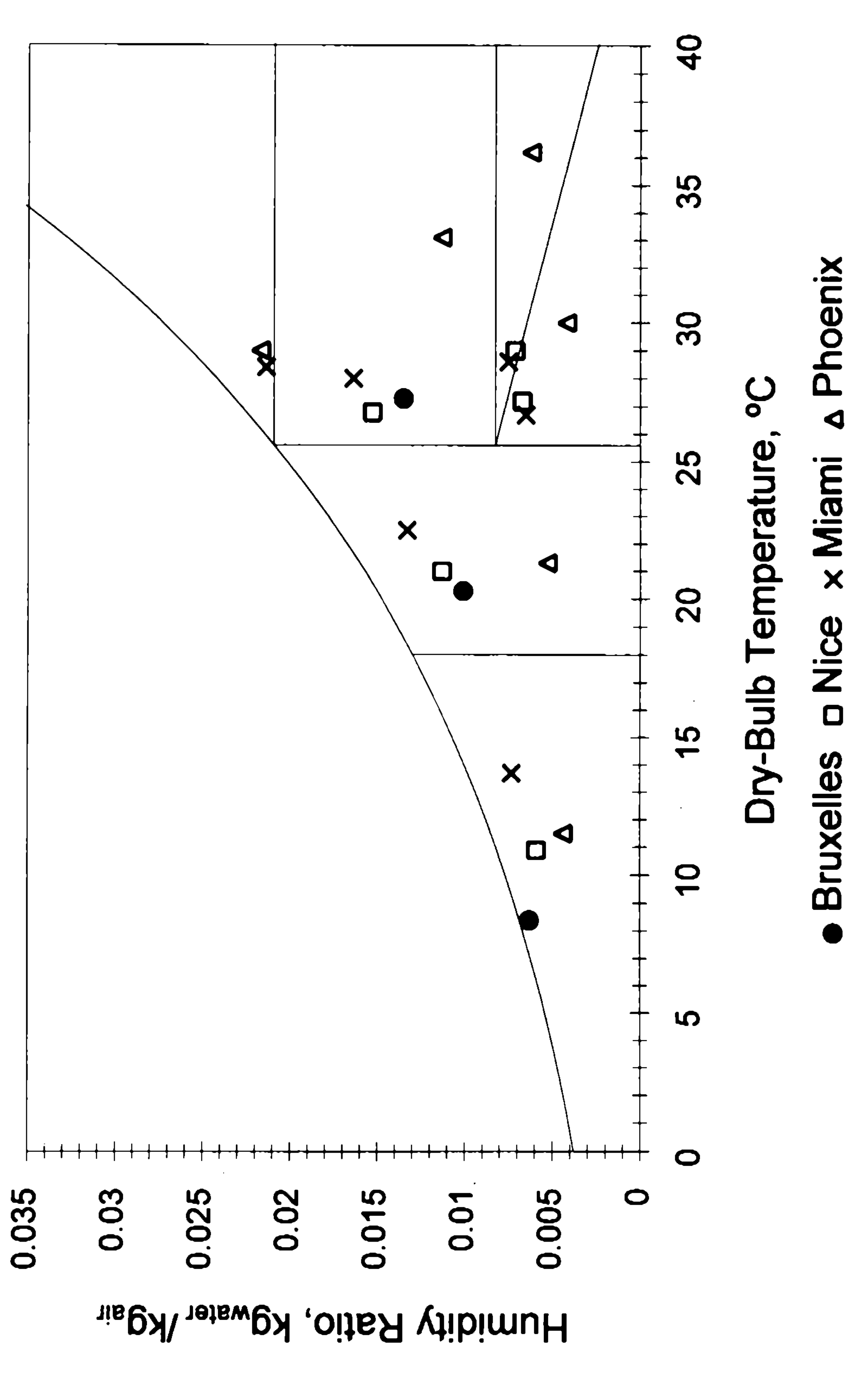


Figure 5. Psychrometric Chart with Average Conditions for Sample Locations

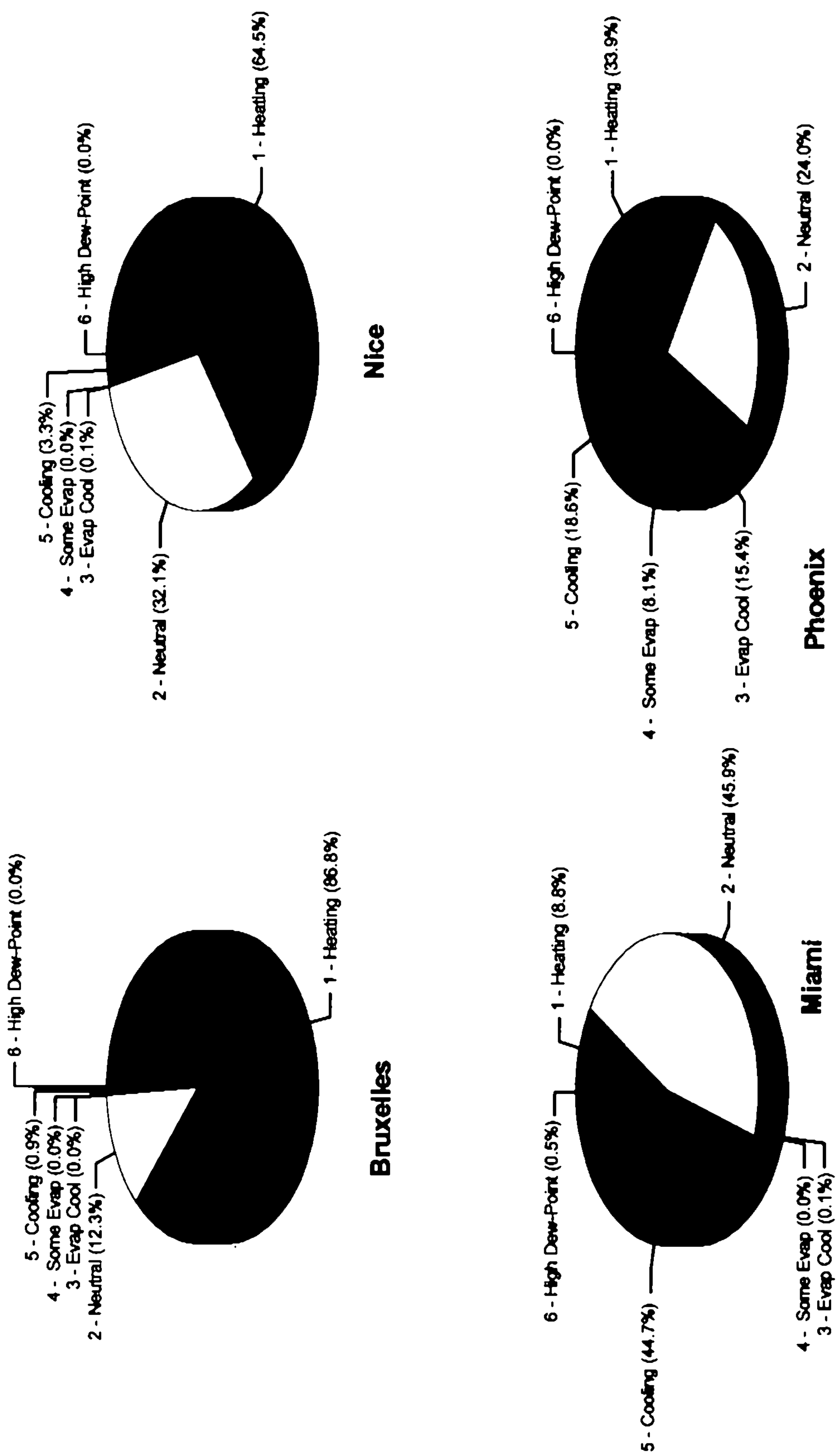


Figure 6. Pie Chart with Percentage of Hours in Each Psychrometric Region

5 ANNUAL HEATING ENERGY REQUIREMENTS

The amount of sensible heating required for conditioning a constant airflow of one kg/h of ventilating air to 18 °C for each of the locations is presented in Table 5 and in Figure 7. This setpoint was used to closely correspond to a setpoint commonly used in some American standards which relate to air infiltration and ventilation (ASHRAE Stds. 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 °C, 16 °C, & 15 °C respectively). The lower setpoints' percentage of energy required to heat to 18 °C are also presented in Table 5 and the amount of energy in Figure 7.

There is a significant amount of energy used to heat the incoming air. For the 18 °C 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 energy respectively.

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 Celsius of reduction in the setpoint.

Table 5. Average Annual Sensible Energy Required for Heating Air to the Setpoint (MJ·h/kg)

			Setpoint				Percentage of Energy Needed at 18 °C		
			18 °C	17 °C	16 °C	15 °C	17 °C	16 °C	15 °C
1	BEL	Bruxelles	73.4	65.8	58.1	51.2	89.6	79.2	69.7
2	BEL	Oostende	76.0	67.7	59.5	51.2	89.1	78.3	67.4
3	BEL	Saint-Hubert	101.1	92.8	84.5	76.2	91.8	83.6	75.4
4	DK	Copenhagen	89.6	81.6	73.6	65.7	91.1	82.2	73.4
5	FR	Carpentras	55.0	48.7	42.3	35.9	88.4	76.8	65.2
6	FR	Limoges	70.3	62.9	55.6	48.2	89.5	79.0	68.6
7	FR	Macon	72.4	65.2	58.1	51.0	90.1	80.3	70.4
8	FR	Nancy	78.7	71.1	63.5	55.9	90.4	80.7	71.1
9	FR	Nice	40.1	34.4	28.7	23.1	85.8	71.7	57.6
10	FR	Trappes	74.5	66.7	59.0	51.2	89.6	79.1	68.7
11	GB	Aberdeen	88.2	79.6	71.1	62.6	90.3	80.6	70.9
12	GB	Aberporth	72.7	64.2	55.8	47.4	88.4	76.8	65.2
13	GB	Aberporth,CEC	73.9	65.2	56.5	47.9	88.3	76.5	64.8
14	GB	Aldergrove	82.2	73.6	65.0	56.5	89.6	79.1	68.7
15	GB	Birmingham	77.0	69.0	61.0	53.0	89.6	79.2	68.9
16	GB	Bristol	82.1	73.8	65.4	57.1	89.8	79.7	69.5
17	GB	Camborne	67.0	58.6	50.2	41.8	87.5	74.9	62.4
18	GB	Dundee	84.6	76.2	67.7	59.2	90.0	80.0	70.0
19	GB	Eskdalemuir	95.1	86.6	78.0	69.4	91.0	81.9	72.9
20	GB	Eskdalemuir,CEC	96.1	87.4	78.8	70.2	91.0	82.0	73.1
21	GB	Glasgow	81.2	72.8	64.4	56.0	89.6	79.3	68.9
22	GB	Heathrow	67.6	59.8	52.1	44.4	88.6	77.2	65.7
23	GB	Kew	71.7	63.6	55.5	47.5	88.7	77.5	66.2
24	GB	Kew, CEC	70.4	62.5	54.5	46.6	88.7	77.4	66.2
25	GB	Lerwick, CEC	97.5	88.7	79.9	71.1	91.0	81.9	72.9
26	GB	Manchester	78.6	70.2	61.9	53.6	89.4	78.6	68.2
27	GB	Newcastle	88.0	79.4	70.7	62.1	90.2	80.3	70.5
28	GB	Norwich	79.5	71.6	63.8	55.9	90.1	80.2	70.4
29	GB	Sheffield	80.4	72.2	64.1	55.9	89.8	79.7	69.5
30	NL	DeBilt	77.5	69.7	62.0	54.2	90.0	79.9	69.9
31	NL	Eelde	83.2	75.2	67.3	59.3	90.4	80.9	71.3
32	NL	Vlissingen	69.8	61.8	53.8	45.8	88.5	77.1	65.6
33	USA	Boston, MA	77.3	70.9	64.6	58.3	91.8	83.6	75.4
34	USA	Brownsville, TX	10.7	8.9	7.1	5.3	83.3	66.6	49.9
35	USA	Cheyenne, WY	100.0	92.8	85.6	78.5	92.8	85.7	78.5
36	USA	Ft. Worth, TX	34.9	31.1	27.4	23.6	89.2	78.3	67.5
37	USA	Lexington, KY	64.9	59.5	54.1	48.7	91.7	83.4	75.0
38	USA	Los Angeles, CA	20.9	15.8	10.7	5.6	75.6	51.2	26.7
39	USA	Miami, FL	3.3	2.6	1.8	1.0	76.8	53.7	30.5
40	USA	Omaha, NE	84.7	78.9	73.2	67.5	93.2	86.4	79.7
41	USA	Phoenix, AZ	19.5	16.5	13.6	10.5	84.7	69.3	54.0
42	USA	Salt Lake City, UT	79.2	73.1	67.0	60.9	92.3	84.6	76.9
43	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

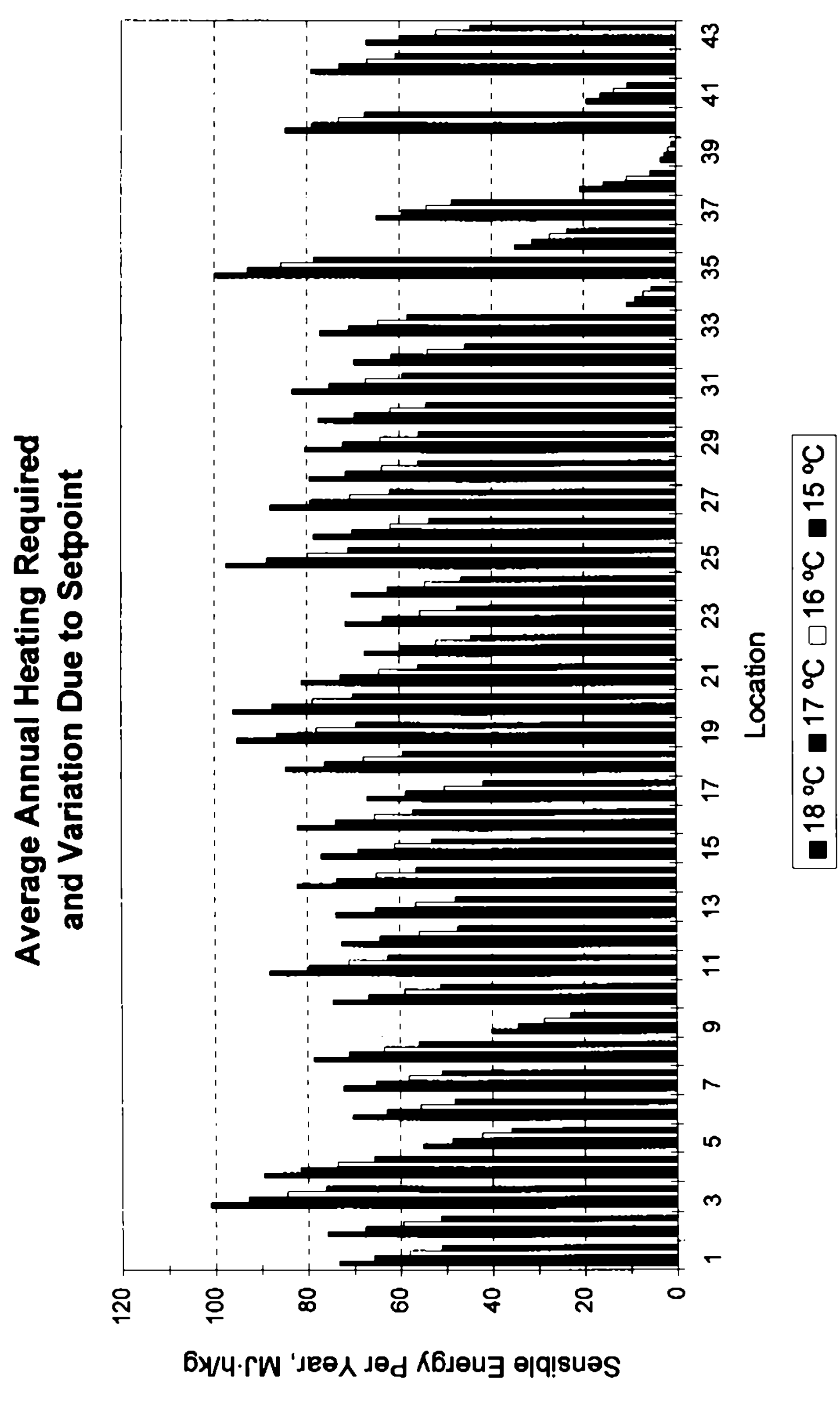


Figure 7. Average Annual Sensible Energy Required for Heating Air (MJ·h/kg)

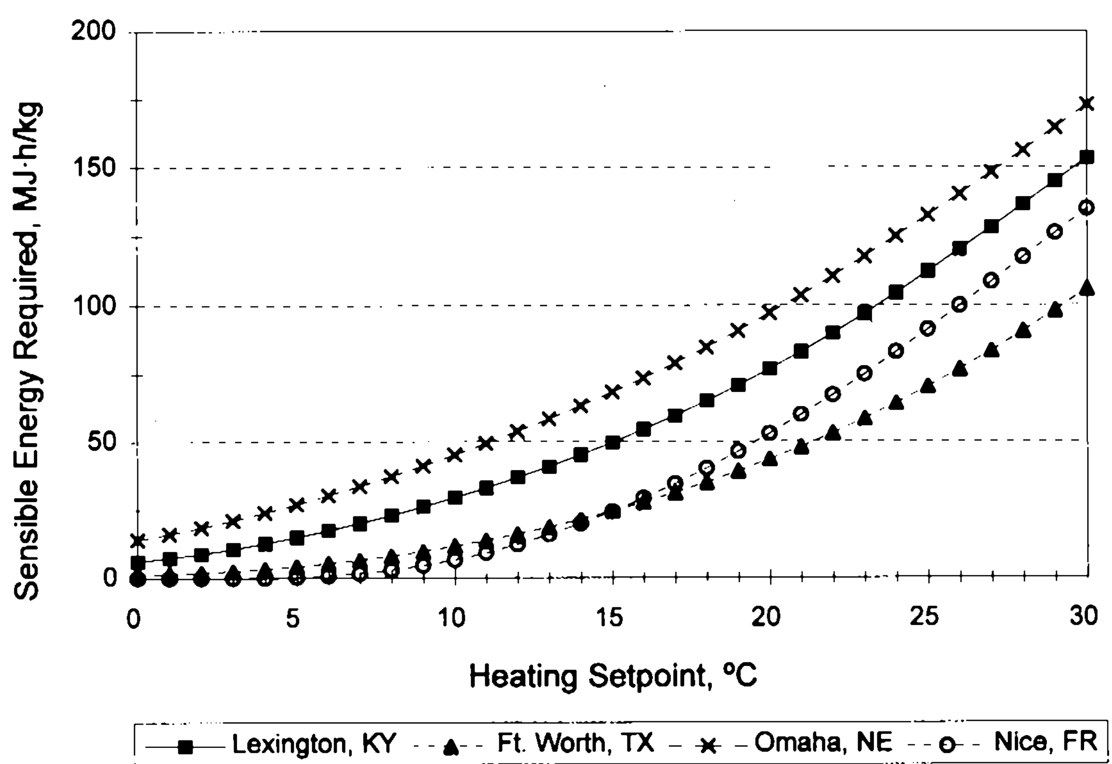
5.1 Variation of the Heating Requirements due to Setpoint Temperature

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 setpoints from 5 °C to 40 °C. This variation of energy required is given for several locations in Figure 8. It can be seen that this is an exponential curve of the form:

$$\text{Sensible energy} = a * \text{setpoint}^{b} \qquad (8)$$

The sensible energy required for each location in the range of setpoints from 10 °C to 25 °C was fit using a least-squares linear regression on the log transformation of Eqn 8 to determine the coefficients for each location. These coefficients are given in Appendix B. The coefficients to use for a 1,2 and 3 degree reduction in setpoint are also presented.

Figure 8. Variation of Heating Energy Required Due to Setpoint Temperature



6 ANNUAL SENSIBLE AND LATENT COOLING ENERGY REQUIREMENTS

The sensible and latent energy exchange required for humidity control and cooling to the desired statepoint of 25.6 °C and 40% RH for psychrometric Regions 3 through 6 for each location is presented in Table 6.

The total sensible and latent energy exchange for psychrometric Regions 4 through 6 are presented in Table 7 and Figure 9. (Evaporative cooling humidity control is not commonly done for Region 3 therefore it is not included in the totals.)

These results indicate that conditioning of air to provide cooling and dehumidification can require significant amounts of energy. The greatest amount of sensible cooling was required in Phoenix, AZ (20.2 MJ·h/kg dry air) 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. The percentage of total cooling for sensible and latent cooling is also presented in Table 7.

On the average (each station weighted evenly), latent cooling required 65.3% of the total cooling load for all the locations investigated. When only those locations requiring more than 5 MJ·h/kg are considered (i.e. consider only those locations typically requiring air conditioning) latent cooling required 79.7% of the total cooling load.

Table 6. Sensible and Latent Energy Transfer for Temperature and Humidity Control to 25.6 °C and 40% RH (kJ·h/kg)

			Region 3		Region 4		Region 5		Region 6	
			Sensible	Latent	Sensible	Latent	Sensible	Latent	Sensible	Latent
1	BEL	Bruxelles	0	0	0	0	-133	-989	0	0
2	BEL	Oostende	0	0	0	0	-7	-36	0	0
3	BEL	Saint-Hubert	0	0	0	0	0	-5	0	0
4	DK	Copenhagen	0	0	-1	1	-29	-102	0	0
5	FR	Carpentras	-83	183	-108	56	-1698	-3519	0	0
6	FR	Limoges	-4	28	-8	4	-328	-657	0	0
7	FR	Macon	-3	20	-11	8	-565	-1754	0	0
8	FR	Nancy	0	0	0	0	-183	-881	0	0
9	FR	Nice	-19	46	-7	5	-357	-5125	0	0
10	FR	Trappes	0	0	0	0	-33	-284	0	0
11	GB	Aberdeen	0	0	0	0	-1	-20	0	0
12	GB	Aberporth	0	0	0	0	-7	-79	0	0
13	GB	Aberporth,CEC	0	0	0	0	0	-6	0	0
14	GB	Aldergrove	0	0	0	0	0	0	0	0
15	GB	Birmingham	-2	3	0	0	-21	-107	0	0
16	GB	Bristol	0	0	0	0	-6	-48	0	0
17	GB	Camborne	0	0	0	0	0	0	0	0
18	GB	Dundee	0	0	0	0	0	0	0	0
19	GB	Eskdalemuir	0	0	0	0	0	0	0	0
20	GB	Eskdalemuir,CEC	0	0	0	0	0	0	0	0
21	GB	Glasgow	0	0	0	0	-2	-56	0	0
22	GB	Heathrow	0	4	0	0	-25	-170	0	0
23	GB	Kew	0	0	0	0	-4	-18	0	0
24	GB	Kew, CEC	0	0	0	0	-29	-25	0	0
25	GB	Lerwick, CEC	0	0	0	0	0	0	0	0
26	GB	Manchester	0	0	0	0	-34	-95	0	0
27	GB	Newcastle	0	0	0	0	0	0	0	0
28	GB	Norwich	0	0	0	0	-38	-323	0	0
29	GB	Sheffield	0	0	0	0	-4	-86	0	0
30	NL	DeBilt	0	0	0	0	-10	-247	0	0
31	NL	Eelde	0	0	0	0	-6	-70	0	0
32	NL	Vlissingen	0	0	0	0	-2	-24	0	0
33	USA	Boston	-38	147	-33	17	-1403	-5820	0	0
34	USA	Brownsville	-40	140	-23	13	-11512	-74729	-149	-1667
35	USA	Cheyenne	-828	3219	-93	68	-55	-63	0	0
36	USA	Ft. Worth	-101	378	-114	57	-10307	-34480	-6	-39
37	USA	Lexington	-37	128	-38	20	-2482	-11965	-3	-19
38	USA	Los Angeles	-168	650	-58	34	-205	-996	0	0
39	USA	Miami	-10	41	-7	4	-9747	-80826	-120	-1360
40	USA	Omaha	-81	265	-67	39	-3533	-13940	-43	-223
41	USA	Phoenix	-6031	13919	-7605	3731	-12578	-12392	0	-2
42	USA	Salt Lake City	-2327	5910	-1788	1156	-579	-407	0	0
43	USA	Seattle	-56	165	-57	30	-314	-387	0	0

Note: Negative energy indicates heat extraction (cooling).

Table 7. Average Sensible and Latent Energy Required for Conditioning Air to the 25.6 °C, 40% RH Setpoint (MJ·h/$kg_{dry-air}$)

		COOLING	Sensible (MJ·h/kg)	Latent (MJ·h/kg)	Total (MJ·h/kg)	% Sensible	% Latent
1	BEL	Bruxelles	0.1	1.0	1.1	0.119	0.881
2	BEL	Oostende	0.0	0.0	0.0	0.163	0.837
3	BEL	Saint-Hubert	0.0	0.0	0.0	0.000	1.000
4	DK	Copenhagen	0.0	0.1	0.1	0.229	0.771
5	FR	Carpentras	1.8	3.5	5.3	0.343	0.657
6	FR	Limoges	0.3	0.7	1.0	0.340	0.660
7	FR	Macon	0.6	1.7	2.3	0.248	0.752
8	FR	Nancy	0.2	0.9	1.1	0.172	0.828
9	FR	Nice	0.4	5.1	5.6	0.066	0.934
10	FR	Trappes	0.0	0.3	0.3	0.104	0.896
11	GB	Aberdeen	0.0	0.0	0.0	0.048	0.952
12	GB	Aberporth	0.0	0.1	0.1	0.081	0.919
13	GB	Aberporth,CEC	0.0	0.0	0.0	0.000	1.000
14	GB	Aldergrove	0.0	0.0	0.0		
15	GB	Birmingham	0.0	0.1	0.1	0.164	0.836
16	GB	Bristol	0.0	0.0	0.1	0.111	0.889
17	GB	Camborne	0.0	0.0	0.0		
18	GB	Dundee	0.0	0.0	0.0		
19	GB	Eskdalemuir	0.0	0.0	0.0		
20	GB	Eskdalemuir,CEC	0.0	0.0	0.0		
21	GB	Glasgow	0.0	0.1	0.1	0.034	0.966
22	GB	Heathrow	0.0	0.2	0.2	0.128	0.872
23	GB	Kew	0.0	0.0	0.0	0.182	0.818
24	GB	Kew, CEC	0.0	0.0	0.1	0.537	0.463
25	GB	Lerwick, CEC	0.0	0.0	0.0		
26	GB	Manchester	0.0	0.1	0.1	0.264	0.736
27	GB	Newcastle	0.0	0.0	0.0		
28	GB	Norwich	0.0	0.3	0.4	0.105	0.895
29	GB	Sheffield	0.0	0.1	0.1	0.044	0.956
30	NL	DeBilt	0.1	0.2	0.3	0.290	0.710
31	NL	Eelde	0.0	0.1	0.1	0.079	0.921
32	NL	Vlissingen	0.0	0.0	0.0	0.077	0.923
33	USA	Boston, MA	1.4	5.8	7.2	0.198	0.802
34	USA	Brownsville, TX	11.7	76.4	88.1	0.133	0.867
35	USA	Cheyenne, WY	0.1	0.0	0.1	1.035	0.035
36	USA	Ft. Worth, TX	10.4	34.5	44.9	0.232	0.768
37	USA	Lexington, KY	2.5	12.0	14.5	0.174	0.826
38	USA	Los Angeles, CA	0.3	1.0	1.2	0.215	0.785
39	USA	Miami, FL	9.9	82.2	92.1	0.107	0.893
40	USA	Omaha, NE	3.6	14.1	17.8	0.205	0.795
41	USA	Phoenix, AZ	20.2	8.7	28.8	0.700	0.300
42	USA	Salt Lake City, UT	2.4	0.7	1.6	1.463	0.463
43	USA	Seattle, WA	0.4	0.4	0.7	0.510	0.490
	Average for all locations		1.6	5.8	7.4	0.216	0.784
	Average for cooling locations		6.9	26.9	33.8	0.204	0.796

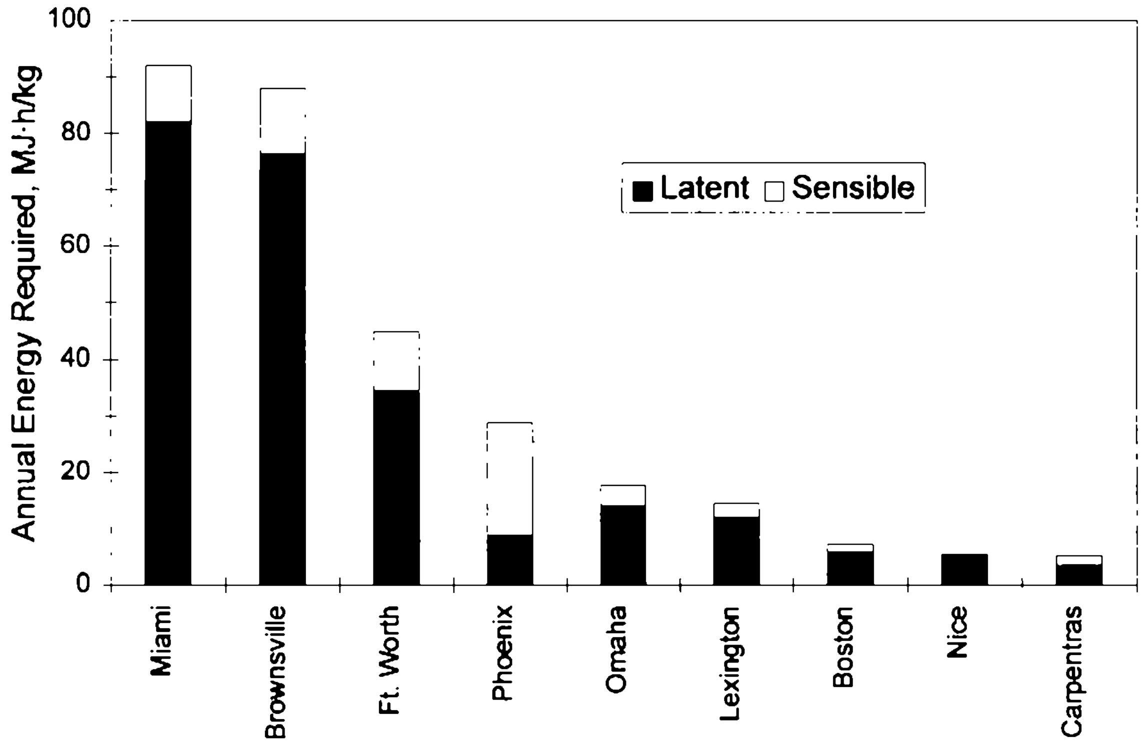


Figure 9. Latent and Sensible Cooling for Conditioning to 25.6 °C and 40% RH (kJ·h/kg$_{dry-air}$)

6.1 Variation of Energy Required due to Setpoint

The effect of the cooling setpoint on the energy required was determined by changing the setpoint plus and minus two degrees Celsius for those locations which had greater than 5 MJ·h/kg cooling load. The respective percentage increase and decrease of the total cooling energy required at 25.6 °C and 40% are presented in Table 8.

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 2 °C higher and lower setpoints was 151.4% and 49.5% of the energy required at 25.6 °C.

Table 8. Variation in Cooling Energy Required Due to Temperature Setpoint

		Total Cooling @ 25.6 °C (MJ·h/kg)	cooling @ 23.6 °C/ cooling @ 25.6 °C	cooling @ 27.6 °C/ cooling @ 25.6 °C
USA	Miami, FL	92.1	1.514	0.495
USA	Brownsville, TX	88.1	1.421	0.577
USA	Ft. Worth, TX	44.9	1.269	0.767
USA	Phoenix, AZ	28.8	1.258	0.772
USA	Omaha, NE	17.8	1.093	0.922
USA	Lexington, KY	14.5	1.128	0.906
USA	Boston, MA	7.2	1.068	0.954
FR	Nice	5.5	1.177	0.896
FR	Carpentras	5.3	1.077	0.950

6.2 Variation of Energy Required due to Humidity Design Setpoint

The latent energy requirements in the previous tables indicate 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 percentage of the 40% RH energy requirements are presented in Table 9.

Increasing the relative humidity setpoint from 40% to 60% had a significant impact of 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.

Table 9. Variation in Cooling Energy Required Due to Humidity Setpoint (Dry-Bulb Setpoint = 25.6 °C)

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

7 COMBINED ANNUAL SENSIBLE, LATENT AND TOTAL ENERGY REQUIREMENTS PER UNITARY AIRFLOW RATE

The combined heating and cooling sensible, latent and total energy requirements (based on the 18 °C heating, and 25.6 °C, 40% cooling setpoints) are presented for each of the locations in Table 10 and Figure 10. This is the total energy required over the entire year which must be supplied to condition the ventilation air to the desired conditions. The total energy required ranged from 22.1 to 102.5 MJ·h/kg in America (Los Angeles and Omaha) and from 45.6 to 101.1 MJ·h/kg in Europe (Nice and Saint-Hubert). Heating accounted for almost all the energy used for conditioning ventilating air in Europe with the maximum air conditioning load being 5.5 MJ·h/kg (12.1% of total) in Nice. In America the fraction of the total energy used for cooling varied from 96.5% to 0.1% (92.1 to 0.1 MJ·h/kg for Miami and Cheyenne respectively). The latent load was larger than the sensible load for air conditioning in all the locations with a significant cooling load except Phoenix which has a hot dry climate.

Table 10. Annual Sensible, Latent and Total Energy Requirements (MJ·h/kg$_{dry-air}$)

			Total Heating (MJ·h/kg)	Cooling Sensible (MJ·h/kg)	Cooling Latent (MJ·h/kg)	Total Cooling (MJ·h/kg)	TOTAL HEATING & COOLING (MJ·h/kg)
1	BEL	Bruxelles	73.4	-0.1	-1.0	-1.1	74.5
2	BEL	Oostende	76.0	0.0	0.0	0.0	76.0
3	BEL	Saint-Hubert	101.1	0.0	0.0	0.0	101.1
4	DK	Copenhagen	89.6	0.0	-0.1	-0.1	89.7
5	FR	Carpentras	55.0	-1.8	-3.5	-5.3	60.3
6	FR	Limoges	70.3	-0.3	-0.7	-1.0	71.3
7	FR	Macon	72.4	-0.6	-1.7	-2.3	74.7
8	FR	Nancy	78.7	-0.2	-0.9	-1.1	79.7
9	FR	Nice	40.1	-0.4	-5.1	-5.5	45.6
10	FR	Trappes	74.5	0.0	-0.3	-0.3	74.8
11	GB	Aberdeen	88.2	0.0	0.0	0.0	88.2
12	GB	Aberporth	72.7	0.0	-0.1	-0.1	72.8
13	GB	Aberporth,CEC	73.9	0.0	0.0	0.0	73.9
14	GB	Aldergrove	82.2	0.0	0.0	0.0	82.2
15	GB	Birmingham	77.0	0.0	-0.1	-0.1	77.1
16	GB	Bristol	82.1	0.0	0.0	-0.1	82.2
17	GB	Camborne	67.0	0.0	0.0	0.0	67.0
18	GB	Dundee	84.6	0.0	0.0	0.0	84.6
19	GB	Eskdalemuir	95.1	0.0	0.0	0.0	95.1
20	GB	Eskdalemuir,CEC	96.1	0.0	0.0	0.0	96.1
21	GB	Glasgow	81.2	0.0	-0.1	-0.1	81.2
22	GB	Heathrow	67.6	0.0	-0.2	-0.2	67.8
23	GB	Kew	71.7	0.0	0.0	0.0	71.7
24	GB	Kew, CEC	70.4	0.0	0.0	-0.1	70.5
25	GB	Lerwick, CEC	97.5	0.0	0.0	0.0	97.5
26	GB	Manchester	78.6	0.0	-0.1	-0.1	78.7
27	GB	Newcastle	88.0	0.0	0.0	0.0	88.0
28	GB	Norwich	79.5	0.0	-0.3	-0.4	79.8
29	GB	Sheffield	80.4	0.0	-0.1	-0.1	80.5
30	NL	DeBilt	77.5	-0.1	-0.2	-0.3	77.9
31	NL	Eelde	83.2	0.0	-0.1	-0.1	83.2
32	NL	Vlissingen	69.8	0.0	0.0	0.0	69.9
33	USA	Boston, MA	77.3	-1.4	-5.8	-7.2	84.5
34	USA	Brownsville, TX	10.7	-11.7	-76.4	-88.1	98.7
35	USA	Cheyenne, WY	100.0	-0.1	0.0	-0.1	100.1
36	USA	Ft. Worth, TX	34.9	-10.4	-34.5	-44.9	79.8
37	USA	Lexington, KY	64.9	-2.5	-12.0	-14.5	79.4
38	USA	Los Angeles, CA	20.9	-0.3	-1.0	-1.2	22.1
39	USA	Miami, FL	3.3	-9.9	-82.2	-92.1	95.4
40	USA	Omaha, NE	84.7	-3.8	-14.1	-17.8	102.5
41	USA	Phoenix, AZ	19.5	-20.2	-8.7	-28.8	48.3
42	USA	Salt Lake City, UT	79.2	-2.4	0.7	-1.6	80.8
43	USA	Seattle, WA	67.2	-0.4	-0.4	-0.7	67.9

Note: Negative energy represents energy extracted in cooling.
The total is the sum of the absolute values of heating and cooling.

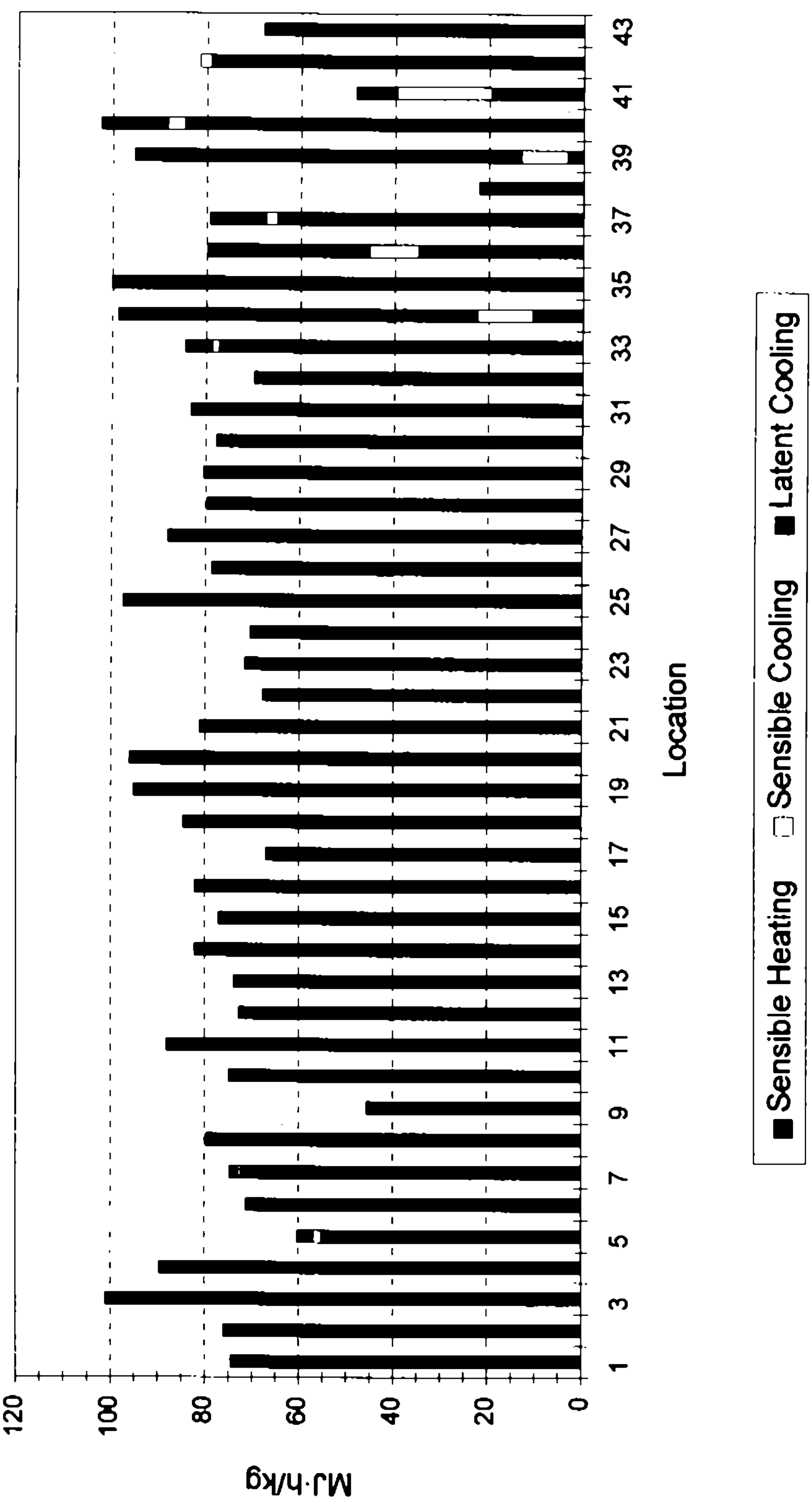


Figure 10. Total Energy Required for Ventilation Based Upon Constant Airflow Rate (Setpoints: Heating = 18 °C, Cooling 25.6 °C, 40% RH)

8 SUMMARY

A significant amount of energy is required to condition air which is used for ventilation. The annual energy required per kg/hr of airflow varied from 22.1 MJ·h/kg for Los Angeles to 102.5 MJ·h/kg for Omaha. In Europe the range was from 45.6 MJ·h/kg for Nice to 101.1 MJ·h/kg for Saint-Hubert. 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. Much of the variation was due to the amount of moisture in the air which had to be removed in air conditioning. In situations where air conditioning is used a significant amount of this energy is used in dehumidifying the air. For example in Miami 86.1% of the energy is used for moisture removal.

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APPENDIX A

Years Used in the CEC Test Reference Year - 19XX

LOCATION	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
DeBilt	65	76	74	80	73	69	73	74	66	76	72	67
Eelde	73	76	75	80	73	69	77	70	66	77	72	73
Vlissingen	71	71	74	80	73	80	77	80	77	80	72	71
Aberporth	68	62	68	64	66	68	61	61	67	61	60	67
Eskdalemuir	62	64	63	63	61	59	63	60	68	65	61	63
Kew	65	64	63	64	63	63	61	65	60	61	59	68
Lerwick	65	64	68	67	61	61	67	68	63	60	61	62
Carpentras	69	70	78	74	75	75	71	76	71	71	73	76
Limogens	77	68	69	77	69	73	75	74	69	73	73	76
Macon	76	76	70	74	69	71	70	74	70	69	72	76
Nancy	77	68	72	69	75	68	77	71	77	78	75	71
Nice	69	74	70	72	74	78	68	70	69	71	71	76
Trappes	68	71	69	69	73	74	72	77	68	75	72	73
Oostende	70	74	70	77	74	78	77	70	78	80	79	80
Saint-Hubert	80	74	69	79	69	71	77	70	77	76	72	73
Uccle	67	62	63	62	68	64	62	61	70	58	72	67

APPENDIX B

A and B Coefficients used in Eqn 8 to Estimate Sensible Heating Energy Required

Sensible = a * (temperature setting) ^ b

		Temperature Setting			Temp Setting minus 1 °C			Temp Setting minus 2 °C			Temp Setting minus 3 °C		
		a	b	R^2	a	b	R^2	a	b	R^2	a	b	R^2
1	Bruxelles	302.8	1.8953	0.9996	179.8	2.0372	0.9996	92.0	2.2251	0.9993	36.9	2.4895	0.9983
2	Oostende	253.7	1.9657	0.9990	141.6	2.1277	0.9989	66.0	2.3461	0.9983	22.5	2.6631	0.9965
3	Saint-Hubert	1376.6	1.4840	0.9998	944.2	1.5844	0.9998	599.8	1.7082	0.9997	342.0	1.8654	0.9995
4	Copenhagen	933.3	1.5784	0.9998	644.7	1.6745	0.9998	411.8	1.7941	0.9999	235.2	1.9478	0.9999
5	Carpentras	113.6	2.1353	0.9997	63.5	2.2932	0.9996	29.2	2.5110	0.9992	9.55	2.8371	0.9980
6	Limoges	260.0	1.9327	0.9995	152.2	2.0787	0.9994	76.2	2.2734	0.9990	29.4	2.5498	0.9981
7	Macon	423.7	1.7781	0.9999	274.1	1.8926	1.0000	158.9	2.0405	0.9999	77.9	2.2403	0.9997
8	Nancy	489.2	1.7550	0.9998	306.5	1.8811	0.9997	170.2	2.0444	0.9995	78.3	2.2663	0.9988
9	Nice	10.6	2.8352	0.9964	3.85	3.1289	0.9946	0.741	3.6244	0.9891	0.0128	4.9148	0.9483
10	Trappes	292.0	1.9121	0.9994	170.2	2.0601	0.9993	84.7	2.2571	0.9990	32.5	2.5367	0.9978
11	Aberdeen	459.0	1.8103	0.9980	262.0	1.9676	0.9978	127.6	2.1750	0.9972	48.0	2.4646	0.9956
12	Aberporth	109.2	2.2327	0.9949	47.4	2.4758	0.9937	14.4	2.8342	0.9901	1.90	3.4631	0.9760
13	Aberporth,CEC	95.2	2.2829	0.9934	40.3	2.5340	0.9928	11.7	2.9047	0.9901	1.46	3.5544	0.9792
14	Aldergrove	279.0	1.9557	0.9974	149.9	2.1312	0.9974	66.3	2.3681	0.9968	20.9	2.7129	0.9948
15	Birmingham	274.9	1.9417	0.9985	151.9	2.1076	0.9982	69.8	2.3312	0.9975	23.4	2.6564	0.9954
16	Bristol	370.5	1.8611	0.9989	221.3	2.0022	0.9990	116.0	2.1863	0.9990	47.9	2.4395	0.9987
17	Camborne	62.9	2.3938	0.9948	25.7	2.6554	0.9937	6.84	3.0534	0.9900	0.617	3.8061	0.9730
18	Dundee	365.1	1.8747	0.9978	202.3	2.0411	0.9976	94.0	2.2628	0.9968	32.5	2.5793	0.9948
19	Eskdalemuir	710.0	1.6871	0.9983	420.6	1.8339	0.9980	217.1	2.0240	0.9972	90.2	2.2833	0.9953
20	Eskdalemuir,CEC	742.3	1.6751	0.9984	446.5	1.8171	0.9982	235.9	1.9996	0.9976	101.9	2.2461	0.9963
21	Glasgow	293.3	1.9356	0.9978	158.2	2.1100	0.9975	70.3	2.3455	0.9966	22.3	2.6893	0.9940
22	Heathrow	145.5	2.1168	0.9989	77.7	2.2910	0.9987	33.6	2.5317	0.9982	9.88	2.8941	0.9964
23	Kew	175.1	2.0719	0.9987	95.2	2.2410	0.9987	42.5	2.4718	0.9984	13.4	2.8123	0.9972
24	Kew, CEC	162.4	2.0917	0.9985	87.0	2.2653	0.9985	38.0	2.5034	0.9981	11.5	2.8580	0.9966
25	Lerwick, CEC	545.5	1.7816	0.9938	276.9	1.9772	0.9924	115.1	2.2415	0.9894	32.4	2.6300	0.9825
26	Manchester	276.1	1.9465	0.9987	156.7	2.1034	0.9988	76.2	2.3124	0.9986	27.3	2.6098	0.9978
27	Newcastle	404.5	1.8518	0.9973	223.9	2.0191	0.9971	104.1	2.2412	0.9965	36.2	2.5582	0.9946
28	Norwich	455.6	1.7827	0.9998	285.2	1.9087	0.9998	158.2	2.0718	0.9997	72.7	2.2935	0.9993
29	Sheffield	352.5	1.8717	0.9990	206.4	2.0192	0.9990	103.9	2.2136	0.9988	41.0	2.4852	0.9980
30	DeBilt	414.4	1.8070	0.9998	258.1	1.9342	0.9998	141.9	2.0997	0.9997	64.2	2.3260	0.9992
31	Eelde	565.0	1.7240	0.9998	360.6	1.8445	0.9998	205.9	1.9990	0.9997	99.3	2.2061	0.9994
32	Vlissingen	159.5	2.0963	0.9989	83.1	2.2793	0.9985	34.4	2.5346	0.9972	9.24	2.9287	0.9927
33	Boston	1179.1	1.4522	0.9984	895.7	1.5176	0.9987	647.2	1.5972	0.9990	436.9	1.6968	0.9994
34	Brownsville	1.03	3.2075	0.9992	0.525	3.3753	0.9997	0.184	3.6543	0.9999	0.0243	4.2365	0.9968
35	Cheyenne	2721.0	1.2506	0.9985	2152.9	1.3061	0.9986	1644.4	1.3716	0.9987	1200.1	1.4504	0.9989
36	Ft. Worth	118.4	1.9738	0.9988	80.2	2.0680	0.9992	48.9	2.1928	0.9996	25.2	2.3674	0.9999
37	Lexington	947.3	1.4706	0.9967	744.8	1.5234	0.9972	561.3	1.5879	0.9978	399.3	1.6685	0.9984
38	Los Angeles	0.0080	5.0596	0.9905	0.00113	5.6355	0.9914	2.30E-07	8.3739	0.8954	3.63E-06	7.3038	0.9846
39	Miami	0.0047	4.6803	0.9982	0.00186	4.9019	0.9994	2.76E-04	5.4165	0.9989	9.96E-07	7.0949	0.9852
40	Omaha	2823.6	1.1841	0.9957	2364.7	1.2210	0.9961	1934.2	1.2642	0.9966	1535.6	1.3154	0.9972
41	Phoenix	3.90	2.9383	0.9994	1.69	3.1682	0.9991	0.469	3.5372	0.9981	0.0393	4.2914	0.9905
42	Salt Lake City	1518.1	1.3721	0.9989	1163.8	1.4389	0.9992	835.8	1.5196	0.9995	567.8	1.6194	0.9998
43	Seattle	146.7	2.1104	0.9983	75.6	2.2970	0.9979	30.8	2.5574	0.9968	8.09	2.9587	0.9929

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

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