INNOVATIONS IN VENTILATION TECHNOLOGY

21ST ANNUAL AIVC CONFERENCE
THE HAGUE, NETHERLANDS, 26-29 SEPTEMBER 2000

THE INFLUENCE OF VARIATIONS IN BASE TEMPERATURE OVER THE CALCULATED VENTILATION ENERGY DEMAND

Augustino Binamu and Prof. Ralf Lindberg

Tampere University of Technology
Department of Civil Engineering
Institute of Structural Engineering
P.O. Box 600, FN-33101
Tampere, FINLAND

THE INFLUENCE OF VARIATIONS IN BASE TEMPERATURE OVER THE CALCULATED VENTILATION ENERGY DEMAND

SYNOPSIS

The heating degree-days method is widely used for calculation of the air change heating energy demand. However, different countries perceive different values for base temperatures due to different insulation levels and internal loads, decreased infiltration rates through tighter construction practices, and low temperature settings in efforts to reduce energy consumption. This has always made it difficult to make accurate comparisons for heating energy demand between different countries. In this study, the influence of variations in base temperature over the calculated heating energy demand was investigated. The heating degree-days for three test buildings were calculated by using different base temperatures i.e. 15, 16, 17, 18, and 20 ^{o}C as perceived in different countries. The air change heating energy demand was computed by using the obtained heating degree-days. The results were analysed and an equation that can be used for recalculation of the air change heating energy demand for alternative base temperatures was derived. The results have clearly confirmed that even a difference of 1 ^{o}C in base temperature can lead to a substantial difference in the calculated ventilation energy demand. The derived equation makes it possible to recalculate the air change energy consumption to alternative base temperatures and hence make comparisons among different countries.

1. INTRODUCTION

Buildings' heating energy losses are composed of transmission and ventilation (air change) heat losses. Several methods are available for evaluating the air change energy demand of a building. These methods can be grouped into steady-state methods (based on degree-days or temperature bins) and dynamic methods (based on transfer functions). The degree-day procedures are most popular for estimating heating energy requirements in residential buildings, where the envelope transmission and air change are the dominating factors contributing to the heating energy losses. They are based on the assumption that on a long term average, for a given average internal temperature, solar and internal heat gains will offset transmission heat losses when the daily mean temperature is equal to the heating base temperature.

The degree-day method assumes that the base temperature, T_b, is constant which is actually not the case in practice. The values of T_b varies widely from one country to another [1] and even from one building to another because of different building characteristics and widely differing personal preferences for the settings of thermostat and thermostat setbacks. Also, solar gains are zero at night while the internal gains tend to be highest during the day. The closer the outdoor temperature, T_o, is to T_b the greater the uncertainty. If the occupants keep the windows closed during milder weather, T_i will rise above the set point. If they open the windows, the potential benefit of heat gains is reduced. In either case the true values of T_b become uncertain. In fact, the energy consumption becomes most sensitive to occupants' behavior and cannot be estimated with accuracy.

Despite these uncertainties, the degree-day method (using an appropriate base temperature) can give remarkably accurate results for the annual heating of single-zone buildings dominated by losses within the wall, roof, and air change (ventilation and infiltration). It has been observed [2], that provided the requirement is a prediction of the energy use during a heating/cooling season, simple methods may be as accurate and of greater value to the designer, if only because the importance of necessary assumptions is clearly evident. The degree-day and its generalisations can provide simple estimate of annual loads, which can be accurate if the indoor temperature and the internal gains are relatively constant and if the heating or cooling systems are to operate efficiently for a complete season [3,4]. The applicability of this procedure is however limited to residential buildings, where the envelope transmission and infiltration are the dominating factors contributing to the building loads. In commercial buildings with highly varying internal loads, sophisticated control systems, and complex air systems or plant arrangements, the degree-days method is totally inadequate [5]. Also, the degree-day method, like any steady-state method, is unreliable for estimating the heating energy consumption during mild weather.

This study examines the influence variations in base temperatures over the calculated air change heating energy demand.

2. BASIC THEORY

2.1 Heating base temperature

The heating base temperature, T_b, of a building is defined as that value of the outdoor temperature T_o, at which for the specified value of the internal temperature T_i, the total transmission heat loss through the envelope is equal to the incidental heat gain, $\dot{Q}_{gain}$, from the sun, occupants, equipment, lights, etc. Thus, the incidental heat gain is given by the expression:

$$\dot{Q}_{gain} = K_{tot}\left(T_i - T_b\right) \tag{1}$$

Where, K_{tot} (W/^{o}C) is the total heat-loss of the building. The heating base temperature is therefore obtained through the expression:

$$T_b = T_i - \frac{\dot{Q}_{gain}}{K_{tot}} \tag{2}$$

Heating is needed only when the outdoor temperature drops below the base temperature. If the outdoor temperature equals the base temperature, the transmission losses will equal the free heat gain, hence no additional heating is needed.

2.2 Heating degree-days

Heating degree-days (degree-hours) is a function of the base temperature, reflecting the role of indoor temperature, heat gain, and the heat loss coefficient of the envelope. It is based on the period during which the outdoor temperature is less than a specified base temperature. It is given by sum of the differences between the base temperature and each hourly average outdoor temperature throughout the heating season for which T_o is less than T_b. The obtained sum is then known as the heating degree-hours. To determine the number of heating degree-days, the sum obtained is divided by 24. Summing up the differences between the base temperature and the hourly average outdoor temperature, one obtains the heating degree-hours as

$$D_h = \sum_{i=1}^{n} \left(T_b - T_o\right), \text{ for } T_b > T_o \text{ ; } \;➢\; D_d = \tfrac{1}{24} D_h \qquad (3)$$

Where D_h is the heating degree-hours (^oC), and n is the total number of hours over the whole heating and ventilating period. (See appendix for an alternative heating degree-days formula)

3. METHODS

3.1 Test buildings

The tests were carried in three of six test buildings constructed in a parking area within the compound of Tampere University of Technology, western part of Finland. The buildings' external walls are made of different materials, which include polyurethane insulated wooden frame wall (Bldg. No. 1), insulated log wall (Bldg. No. 3), and autoclaved aerated concrete block wall (Bldg. No. 5). The floor area of each test building is 2,4 x 2,4 m^2 and the free floor to ceiling height is 2,6 m. Both the ceiling and the floor consists of two layers of foamed polyurethane elements with overall thickness of 200 mm. All the buildings have two well-insulated outer doors fixed one after another. The buildings have no windows. The colours on the façade of the buildings are greyish white (building no. 1), light green (building no.3), and old rose (building no. 5). The calculated U-value of the roofs and the floors for all the buildings is 0,19 $Wm^{-2}K^{-1}$. The U-values of the building walls are 0.17 $Wm^{-2}K^{-1}$, 0,29 $Wm^{-2}K^{-1}$, and 0,35 $Wm^{-2}K^{-1}$ for building no. 1, 3, and 5 respectively.

The buildings were heated by using electric radiators. Additional heat in the indoor air was obtained from the control and monitoring equipment such as computer etc. During the heating season the indoor air temperature was maintained constant at 20 ± 1^oC. Balanced mechanical ventilation systems with air-to-air heat recovery, (PARMAIR IIWARI Ex S) were installed into the three test buildings. Full details of the ventilation system can be obtained from the manufacturer and supplier*.

*LVI-PARMAIR Oy, Yrittäjänkaari 23, 30420 FORSSA, FINLAND. Tel +538 3 422 699

The air change rate in the buildings was adjusted to 0,5 l/h. Water kept in a container inside every building was continuously heated to provide additional moisture content in the indoor air of 2 g/m^3 in order to simulate the indoor conditions as in a living house. The indoor RH varied between 25.27 and 45.21 % depending on the moisture content in the outdoor air.

3.2 **Measurements**

Measurements carried out included indoor and outdoor air temperatures, relative humidity, wind speed and direction, solar radiation, building air tightness, infiltration/exfiltration, heat energy used for heating the buildings, and energy used by the ventilation system. The indoor air temperature was monitored at three levels and the average value was taken as the indoor temperature. Exterior temperatures were monitored over the roof, under the floor, and on the exterior wall surfaces. The supply air temperature was monitored at two points before entering the heat exchanger and at one point when it leaves the heat exchanger before being supplied into the room. Similarly, the extract air temperature was monitored at two points just as it leaves the heat exchanger and before being dispatched outside the buildings. The temperatures were measured by using calibrated semiconductor sensors (T-type) and cooper-constantan thermocouples (Cu-Ko, Cu-CuNi). Humidity sensors were used to measure the RH inside and outside the buildings. The wind speed and direction was measured at a 10-m height from the earth surface by using a wind speed meter that was fixed on a steel mast at building no. 2. For the wind speed measurements, a 3-cup anemometer was used whilst the wind direction was defined by using a wind streamer. Solar radiation intensity was measured by using a solar meter, which was fixed on the eaves of the building no. 1. The air tightness of the buildings was determined by using fan pressurisation method at a 50 Pa pressure difference as described by [6]. Uncontrolled air infiltration and exfiltration rates were determined by using tracer gas technique (concentration decay method). In this technique, tracer gas (CO_2) was injected into the buildings until a concentration level of 4 g/m^3 was achieved. Concentration decay of the gas was then automatically monitored over a period of 3 to 4 days until it reached 0 g/m^3.

3.3 **Computation**

Based on the tracer gas measurements, the average air infiltration flow rates $\overline{Q}$ (h^{-1}), for the three test buildings were calculated by using equation (4), [7].

$$\overline{Q} = V\,\frac{\ln\frac{C(t_1)}{C(t_2)}}{t_2 - t_1} \tag{4}$$

Where, V is the volume of the room in m^3, $C(t_1)$ and $C(t_2)$ are the percentage concentrations of the gas at time t_1 and t_2 in hours respectively. The heating degree-hours were computed by using equation (3). Neglecting the dehumidification (humidification) and cooling energies, the heating degree-days method was used to estimate the air change heating energy consumption in the three test buildings by using equation (5).

$$E^{h}_{airchange} = (24.D_d.\dot{Q}_{ach}.V.\rho.c_p)/3600 \qquad (5)$$

Where, $E^{h}_{airchange}$ is the air change heating energy (kWh), V is the volume of the building (m^3), ρ is the air density (1.2 kg/m^3), and c_p is the specific heat capacity of air (1.0 kJ/kg.K)

For recalculation of a given value of $E^{h}_{airchange}$ that is calculated by using one base temperature T_{b1}, to an equivalent value for another base temperature T_{b2}, equation (6) can be used. This equation was derived and validated by using the gathered data from the three test buildings.

$$E^{h}_{ach(eqv)} = 24.\left[\{D_{h1} + 29.5(T_{b2} - T_{b1})\}.Q_{ach}.V.\rho.c_p\right]/3600 \qquad (6)$$

Where, $E^{h}_{ach(eqv)}$ is the equivalent air change energy for another base temperature, D_{h1} is the heating degree-days used in the calculation for the known $E^{h}_{airchange}$, T_{b1} is the base temperature used in the former air change energy calculations. T_{b2} is the other desired base temperature to which the air change heating energy is recalculated. 29.5 is a constant, which represents the monthly average heating degree-days difference between two consecutive base temperatures. The Q_{ach} and V values used in the later calculations have to be accordingly correlated to those used in the former calculations.

4. RESULTS

Tables 4.1(a-c) present the heating degree-days for the three test buildings calculated by using equation (3). The influence of variations in the base temperatures on these results is clearly evidenced.

Figure 4.1. Illustrates the air change heating energy consumption for different base temperatures. This was observed in the three different test buildings. If the base temperature points were to represent different countries' base temperatures, it can be seen from Figure 4.1 that the variation in base temperatures will render comparison among the obtained air change energy values impossible. It can be inferred from the same figure that comparison, if required, must be based on same base temperatures. Nevertheless the fact remains that, the total absolute energy expended (measured) in the test buildings remain the same regardless of the base temperature used in the calculated values. Comparison of calculated air change energy values by using the heating degree-days method, if required, must therefore 'factor-in' the influence of the base temperatures.

Table 4.1: Calculated heating degree-days for three test buildings at different base temperatures (weather conditions for Tampere, Finland)

MONTH	HEATING DEGREE-DAYS Base Temperature, °C				
	15	**16**	**17**	**18**	**20**
Nov ´99	357	388	418	448	508
Dec ´99	570	600	630	659	719
Jan ´00	547	575	600	631	687
Feb ´00	540	568	596	624	680
Mar ´00	480	508	536	564	620
Apr ´00	302	330	358	386	442
May ´00	147	175	203	231	287
Sum	**2944**	**3144**	**3341**	**3544**	**3944**

(a) Polyurethane insulated wooden frame wall building

MONTH	HEATING DEGREE-DAYS Base Temperature, °C				
	15	**16**	**17**	**18**	**20**
Nov ´99	409	439	468	500	560
Dec ´99	578	607	641	667	727
Jan ´00	545	571	599	627	683
Feb ´00	538	566	594	622	678
Mar ´00	481	509	536	565	621
Apr ´00	302	330	357	386	442
May ´00	142	170	198	226	282
Sum	**2995**	**3193**	**3392**	**3593**	**3994**

(b) Insulated log wall building

MONTH	HEATING DEGREE-DAYS, Base Temperature, °C				
	15	**16**	**17**	**18**	**20**
Nov ´99	326	356	386	417	477
Dec ´99	559	589	623	649	708
Jan ´00	550	579	608	635	691
Feb ´00	544	572	600	628	684
Mar ´00	485	513	541	569	625
Apr ´00	330	358	386	414	470
May ´00	181	209	237	265	321
Sum	**2976**	**3176**	**3382**	**3577**	**3977**

(c) Autoclaved aerated concrete block wall building

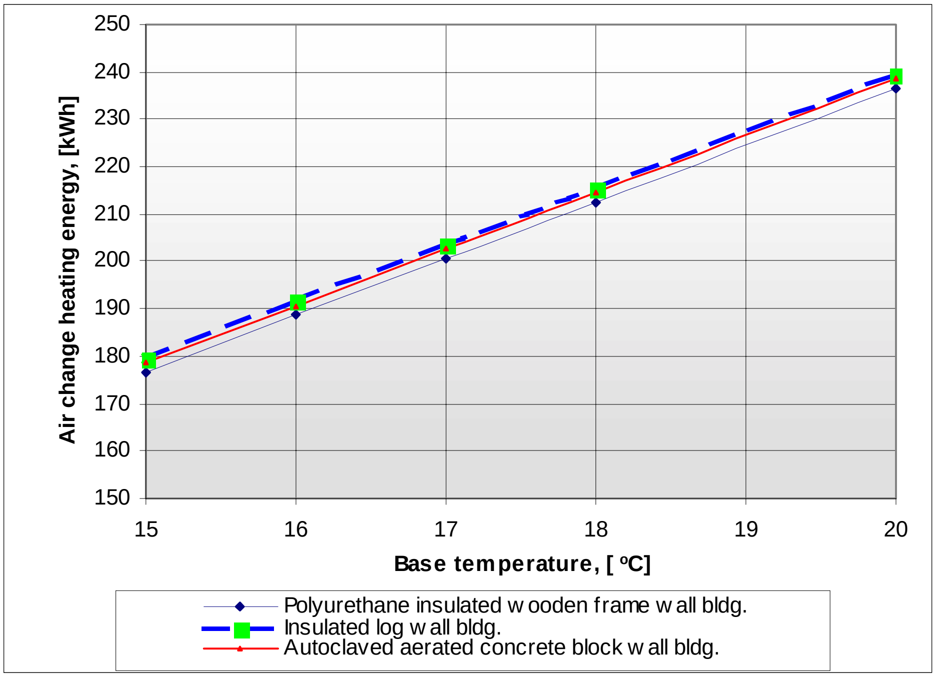

Figure 4.1: Air change heating-energy versus base temperatures

5. DISCUSIONS

Heating degree-days can make a good comparison for heating energies expended among different countries if all countries used the same base temperatures in the their calculations. However, since different countries uses different base temperatures, it would be of great significance to have an average base temperature that can be used in all countries. Such an average base temperature could be the basis for calculating the air change heating energies spent in different countries that can be compared. In reality however, heating demand for each country is based on their individual base temperatures, which are determined by their buildings' characteristics, internal heat gains, and the climate. Heating systems in each of these countries are triggered automatically to start operating at the countries' own base temperatures. So the true heating energy dispensed is inextricably linked to the base temperature. The issue of whether to use a uniform base temperature so as to be able to compare heating energies expended goes against the fact that different heating systems in different countries start operating at different base temperatures. The closest base temperature that can be used for recalculation so as to be able to compare the energy results in different countries would be an average base temperature.

6. CONCLUSIONS

I. The air change heating energy results is greatly influenced by the base temperature

II. The base temperature does not influence measured air change heating energy results
III. Calculated values for air change heating energy for different countries cannot be compared unless same base temperatures are used in the calculations. However, there is no real meaning of such comparison since using a base temperature that a country does not actually use in its heating energy calculations does not represent the reality
IV. Comparisons should only take place where it can reasonably be assumed that the external temperatures are the only factors considered in the calculations ignoring the building based factors (i.e. the level of insulation, materials used for construction, internal heat gains, etc.)
V. If these building based variables are considered then the basis for comparison ceases to exist even within the same country

7. APPENDIX

When data for hourly average outdoor temperature is not available, other formulas proposed by several authors can be used for estimating the degree-days relative to an arbitrary base temperature. The idea is based on assumption of a typical probability distribution of temperature data, characterised by its monthly mean outdoor temperature, $\bar{T}_o$, and by its standard deviation, σ. If the monthly mean outdoor temperature is known, the standard deviation for each month, σ_m, can be estimated from the correlation [5].

$$\sigma_m = 1.45 - 0.029\bar{T}_o + 0.0664\sigma_{yr} \text{ (dimensional eqn., } T \text{ and } \sigma \text{ in } ^oC) \tag{7}$$

Where σ_{yr} is the standard deviation of the monthly mean temperatures, given by:

$$\sigma_{yr} = \sqrt{\frac{1}{12}\sum_{n=1}^{12}\left(\bar{T}_o - \bar{T}_{o,yr}\right)^2} \tag{8}$$

about the annual average $\bar{T}_{o,yr}$. To obtain a simple expression for the degree-days, a normalised temperature variable θ is defined as

$$\theta = \frac{T_{bal} - \bar{T}_o}{\sigma_m\sqrt{N}} \tag{9}$$

Where N is the number of days in a month (N and θ are dimensionless). The mean monthly temperature $\bar{T}_o$ and its standard deviation account for the difference in temperature distribution from month to month and location to location. Being centred around $\bar{T}_o$ and scaled by σ_m, the quantity θ eliminates these effects. In terms of θ, the monthly heating degree-days for any location are very well approximated by the following expression:

$$D_d\,(T_{bal}) = \sigma_m N^{3/2}\left\{\frac{\theta}{2} + \frac{\ln\left[\exp(-a\theta) + \exp(a\theta)\right]}{2a}\right\} \quad (10)$$

Where a = 1.698. If one uses this equation for each month, the annual heating degree-days can be estimated with a maximum error of 175 ^{o}C [5].

8. AKNOWLEGDEMENT

The Finnish Technology Development Centre (TEKES), SPU-Systems Oy, H+H Siporex Oy, and LVI-PARMAIR Oy financially supported this research.

9. REFERENCES

1. *ORME M. "Energy Impact of Ventilation: Estimates for the Service and Residential Sectors". Air Infiltration and Ventilation Centre, Great Britain, 1998*

2. *COLDICUTT A.B. "A Simple Method for Predicting Annual Energy Requirements for Heating Buildings", CIB Proceedings of the Second International CIB Symposium on Energy Conservation in Built environment, Danish Building research Institute, Copenhagen, 1979.*

3. *ASHRAE. "ASHRAE Handbook of Fundamentals", American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, 1997.*

4. *KREIDER J.F. and RABL A. "Heating and Cooling of Buildings: Design for Efficiency", McGraw-Hill, Inc., Singapore, 1994.*

5. *KNEBEL D.E. "Simplified Energy Analysis Using the Modified Bin Method", American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc., Atlanta, 1983.*

6. *FASANO G., GIROGIANTONI G., and GUILI G. "Air Tightness Measurements in Three Dwellings in Rome", Proceedings of the 19th AIVC Conference - Ventilation Technologies in Urban Areas, pp. 85-92. 1998.*

7. *ETHERIDGE D. and SANDBERG M. "Building Ventilation: Theory and Measurements", John Wiley & Sons Ltd., West Sussex PO19 1UD, England, 1996.*