ESTIMATION OF ENERGY PERFORMANCE OF BUILDINGS BY USING THE FREE-RUNNING TEMPERATURE

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Abstract

This paper demonstrates that the time series values obtained from measurements or dynamic simulation can be used to estimate the energy load curve, that this curve may be applied to calculate the energy consumption and that the free-running temperature is an equivalent form of the load curve. The main advantages of using the concept of free-running temperature are that 1) the dynamic behavior may be described by steady-state concepts, 2) the whole range of building operation (heating, ventilation and cooling) is described by a single concept, and 3) the thermal behavior of the building, the comfort and the climate are decoupled. The mathematical formalism uses matrix notation.

Key words: energy performance, bin methods, degree-day, on-line measurements, BEMS

1 Introduction

Currently, energy performance of buildings is assessed by using two types of methods: steady-state and dynamic. Steady-state approach is appropriate if the building operation and the efficiency of HVAC systems are constant, at least on intervals of time and/or outdoor temperature [1]. Dynamic analysis, which uses building thermal simulation, requires exhaustive information about the building construction and operation. The results are usually given in the form of time series. The current dynamic approach needs two important improvements in order to become a current practice: to reduce the amount of input data [2] and to give more condensed information as results.

A new paradigm for estimating the energy performance in the initial stages of design is based on frequency distribution [3] which may be combined with qualitative reasoning [4]. The advantage of the frequency distribution over the time series is that the information contained is much richer.

Nomenclature

q	heat flux, energy rate (W)
s	complex variable, $s = \sigma + j\omega$ ($\mathrm{rad} \cdot \mathrm{s}^{-1}$)
F	frequency occurrences (-)
K	thermal conductance (W/K)
Q	energy (J or kWh)
R	thermal resistance (K/W)
T	temperature (K or °C)

Vectors

$\mathbf{F}$	frequency occurrences (-)
$\mathbf{K}$	conductance (W/K)
$\mathbf{Q}$	energy (J or kWh)
$\mathbf{T}$	temperature (K or °C)

Symbols

$\times$	matrix product
$*$	element by element array multiplication

Superscript

T	transpose

Subscripts

b	base
c	cooling
cd	conduction
cl	lower comfort limit
cu	upper comfort limit
fc	free-cooling
fr	free-running
g	gains
h	heat
i	indoor
l	total loss
o	outdoor
s	sun
v	ventilation

Diacritical marks

~	transfer function
–	mean value

Greek symbol

δ	condition, $\delta \in \{0;\ \ 1\}$

For example, the designer would be more interested in the frequency of occurrences and in the duration of the indoor temperature values larger than the upper comfort limit in a period of, lets say, 10 years, than in the time variation of the temperature during each day of a standard weather year. With this information, the design decisions become a choice of accepted risk with important economic and social benefits.

Steady-state methods based on temperatures [5, 6] or on load (i.e. heating / cooling) curve [7] can be adapted to characterized the dynamic behavior by considering their frequency of occurrence or probability distributions [3]. The load curve and the temperatures were used separately in analyzing the building performance [8, 9]. This paper demonstrates the equivalence between the load curve and the free-running temperature, which allows us to analyze the building in heating, ventilation, and cooling regimes by using a single concept. The advantage of this method consists in decoupling the three main factors that influence the energy consumption of the building: the thermal behavior of the building, the thermal comfort range and the climate.

2 Energy calculation from load curve

The heating load for a bin (i.e. an interval) of the outdoor temperature for a given operating mode of the HVAC system is

$$\overline{q}_h = \overline{K}(T_o - \overline{T}_b)\,, \qquad (1)$$

where $\overline{K}$, $\overline{K} = \overline{K}_{cd} + \overline{K}_v$, is the mean value of the thermal conductance and T_b is the outdoor temperature for which the heating load is zero, called the base temperature

$$T_b \equiv T_o \big|_{q_h = 0}\,. \qquad (2)$$

By using the equation (1), the sum of energy rate for heating in a bin around T_o is:

$$\sum \lfloor q_h \rfloor = F \cdot \overline{q}_h = F \cdot \overline{K}(T_o - \overline{T}_b)\,, \qquad (3)$$

where and the brackets $\lfloor \ \rfloor$ indicate the operation:

$$\lfloor f \rfloor = \begin{cases} f \text{ if } f < 0 \\ 0 \text{ otherwise} \end{cases}. \qquad (4)$$

$F \equiv F(T_o \big| \, q_h < 0)$ is the frequency of occurrences of the outdoor temperature in the considered bin, with the condition that the heating is needed. The energy consumption on the whole range of variation of the outdoor temperature is:

$$\sum_{T_o} \lfloor q_h \rfloor = \mathbf{F}^T \times \overline{\mathbf{K}} * (\mathbf{T}_o - \overline{T}_b)\,, \qquad (5)$$

$\mathbf{T}_o = [T_{o1} \quad T_{o2} \quad ... \quad T_{ok}]^T$ is the vector which represents the centers of the bins of outdoor temperature, $\mathbf{F} = [F(T_{o1}) \quad F(T_{o2}) \quad ... \quad F(T_{ok})]^T$ is the vector of frequencies of occurrences of outdoor temperature in the bins $\mathbf{T}_o$, and $\overline{\mathbf{K}} = [\overline{K}(T_{o1}) \quad \overline{K}(T_{o2}) \quad ... \quad \overline{K}(T_{ok})]^T$ is the vector of mean global conductance values corresponding to the bins $\mathbf{T}_o$. The operator $\times$ represents the matrix multiplication and the operator $*$ represents the array multiplication, i.e. the element-by-element product of arrays:

$$\overline{\mathbf{K}} * \mathbf{T}_o = [\overline{K}(T_{o1}) \cdot T_{o1} \quad \overline{K}(T_{o2}) \cdot T_{o2} \quad \ldots \quad \overline{K}(T_{ok}) \cdot T_{ok}]^T . \qquad (6)$$

If the values of the vector $\overline{\mathbf{K}}$ are constant, then:

$$\overline{\mathbf{K}} * \mathbf{T}_o = \overline{K}\mathbf{T}_o , \qquad (7)$$

and equation (5) becomes:

$$\sum_{T_o} \lfloor q_h \rfloor = \mathbf{F}^T \times \overline{K}(\mathbf{T}_o - \overline{T}_b) . \qquad (8)$$

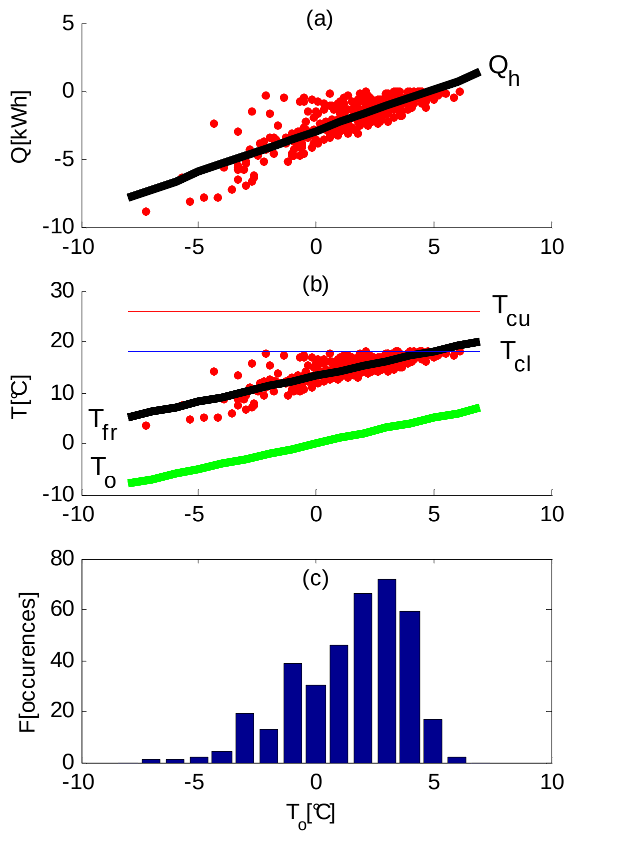

Fig. 1 Energy load and free-running temperature for heating: a) Heating load; b) Free-running temperature obtained from heating load; c) Frequency of occurrences distribution of outdoor temperature.

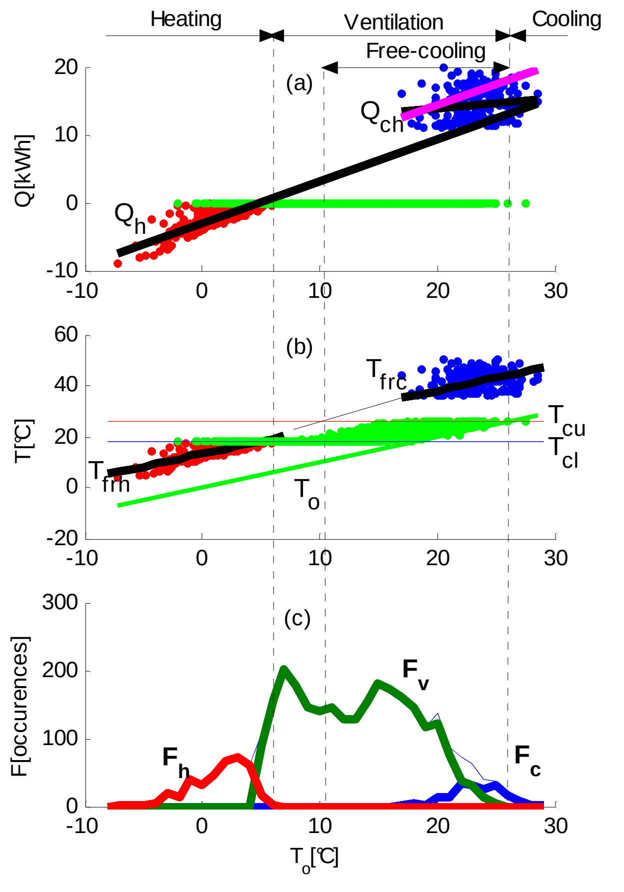

Fig. 2 Energy load and free-running temperature for heating and cooling: a) Heating load; b) Free-running temperature obtained from heating load; c) Frequency of occurrences distribution of outdoor temperature.

Commonly, energy simulation software and energy meters in real buildings give energy consumption for heating over a sample time, Δt, e.g. $\Delta t = 1\text{h}$. Integrating the energy rate expressed by the equation (1), the energy consumption during the period Δt is

$$\overline{Q} = \overline{K}(T_o - \overline{T}_b)\Delta t \,, \quad (9)$$

where $\overline{Q}$, $\overline{K}$, and $\overline{T}_b$ are the mean values of the hourly energy consumption, overall thermal conductance and base temperature for the bin of the outdoor temperature T_o. The energy consumption for heating is then

$$\sum_{T_o} \lfloor Q \rfloor = \mathbf{F}^T \times \overline{K}(\mathbf{T}_o - \overline{T}_b)\Delta t \,. \quad (10)$$

If the values of the vector $\overline{\mathbf{K}}$ are constant, i.e. the mean values of the total thermal conductance are constant for a bin of outdoor temperature and an operating mode of the HVAC system, then the global thermal conductance $\overline{K}$ may be found from experimental data by regression.

3 Experimental estimation of the load curve

Representing the energy losses for heating, Q, as a function of the outdoor temperature will result in a cloud of data. Fig. 1 presents the results of a thermal simulation of a full air-conditioned building. The linear regression model for this data cloud is:

$$\mathbf{Q} = [\mathbf{1}_n \quad \mathbf{T}_o] \times \mathbf{b} + \mathbf{E} \,, \quad (11)$$

where $\mathbf{1}_n = [1,...,1]^T \in R^n$, the hourly energy consumption $\mathbf{Q} = [Q_1 \quad Q_2 \quad ... \quad Q_n]^T$ and the hourly mean outdoor temperature $\mathbf{T} = [T_1 \quad T_2 \quad ... \quad T_n]^T$ are the observations, and $\mathbf{b} = [b_0 \quad b_1]^T$ is the unknown parameter vector. The vector $\mathbf{E} = [E_1 \quad E_2 \quad ... \quad E_n]^T$ models the scatter of data and the variation of K_v and K_{cd}. The vector $\mathbf{b}$ is found by ordinary or robust regression [13],

$$\mathbf{b} = [\mathbf{1}_n \quad \mathbf{T}_o] \backslash \mathbf{Q} \quad (12)$$

where \ is the regression operator.

From equation (11) we obtain the global heat loss coefficient of the building,

$$\overline{K} = b_1 / \Delta t \quad (13)$$

and the base temperature, i.e. the outdoor temperature for which the heat load is zero:

$$\overline{T}_b = -b_0 / b_1 \,. \quad (14)$$

3.1 Conditions of application and limits of ordinary regression

The assumptions made for linear regression are that the outdoor temperature, T_o, has a normal distribution and that the heat load, Q, is a random variable of mean $\mu_Q = \beta_0 + \beta_1 T_o$ and homogeneous variance σ^2. These conditions may be synthesized in [34]:

The random variables Q are independent
of mean $\mu_Q = \beta_0 + \beta_1 T_o$ (15)
and variance σ^2

The conditions (15) imply that the residuals of the regressions should have a normal distribution of zero mean.

Over a long period of time, the statistical distribution of the outdoor temperature, $T_o(t)$, is normal (or Gaussian). If the building if fully air conditioned, if the internal gains (occupation) and the ventilation rates are independent random variables having a normal distribution, and if the indoor temperature is controlled within a narrow range, then the energy load (heating and cooling) has also a normal distribution. These conditions are not satisfied in real situations; for example, the building is not air-conditioned at a constant temperature for the whole range of the outdoor temperature. Consequently, the outdoor temperature which correspond to the heating period does not have a normal distribution.

The heating load is, in a first approximation, a linear function of the random variable outdoor temperature, as indicated by the equation (11). The linear transformation will change the mean and the variance but not the form of the distribution. When $\mathbf{x}$ is vector of random values,

if $\mathbf{y} = [\mathbf{1} \quad \mathbf{x}] \times [a \quad b]^T$
then $\mu_y = a + b\mu_x$ (16)
and $\sigma_y = |b|\sigma_x$

where μ and σ represent the mean and the standard deviation of the indices variables. If we want to find the answer to the question what is the expected value of Q as a function of T_o, then we use the least mean square to estimate the coefficients of the equation:

$$\mathbf{Q} = [\mathbf{1} \quad \mathbf{T}_o] \times [a_T \quad b_T]^T \tag{17}$$

as

$$b_T = \frac{(\mathbf{T} - \mu_T)^T \times (\mathbf{Q} - \mu_Q)}{(\mathbf{T} - \mu_T)^T \times (\mathbf{T} - \mu_T)} \tag{18}$$

and

$$a_T = \mu_Q - b_Q \mu_T \,. \tag{19}$$

An example of estimation of $\mathbf{Q} = [\mathbf{1} \quad \mathbf{T}_o] \times [a_T \quad b_T]^T$ for a real building is given in Fig. 4 (a):

$$Q = -22.43 + 1.47 T_o \,. \tag{20}$$

On the other hand, if we want to answer the question what is the outdoor temperature T_o for which the building is in thermal balance for a given energy flow rate, Q, then we find out by regression the coefficients of the equation:

$$\mathbf{T}_o = [\mathbf{1} \quad \mathbf{Q}] \times [a_Q \quad b_Q]^T \tag{21}$$

as

$$b_Q = \frac{(\mathbf{Q} - \mu_Q)^T \times (\mathbf{T} - \mu_T)}{(\mathbf{Q} - \mu_Q)^T \times (\mathbf{Q} - \mu_Q)} \tag{22}$$

and

$$a_Q = \mu_T - b_Q \mu_Q \,. \tag{23}$$

An example of estimation of $\mathbf{T}_o = [\mathbf{1} \quad \mathbf{Q}] \times [a_Q \quad b_Q]^T$ for a real building is given in Fig. 4 (a):

$$T_o = 9.99 + 0.28 Q \,. \tag{24}$$

The correlation coefficient of the regressions (17) and (21) is

$$r_{T_o Q}^2 = b_{T_o} \cdot b_Q \,. \tag{25}$$

For the example shown in Fig. 4 (a), by using the values from (20) and (24), it results $r_{T_o Q}^2 = 0.41$. This value shows a small correlation between data indicating low confidence in the model. Note that the model (17) will give good results for the estimation of energy consumption by using equation (10) for the data set on which it was calculated but the results will be much less precise when used with other sets of outdoor temperature.

3.2 *Robust regression of heating load curve based on q-q plot*

A robust regression based on quantile – quantile plot is proposed to mitigate this problem. The discussion of this method is done on real data collected in a school building in La Rochelle, France, for a month during the heating season. The school is heated intermittently, with the daytime set-point of 20°C and the nighttime set-point of 15°C. The data set considered in this example is selected for daytime, from 10:00H to 17:00H.

The points in a q-q plot represent quantiles of the data. Quantiles indicate the number of elements of a random variable that are in a given range. The *k*-th quantile, P_k, is that value of the random variable *x* having *N* values, say x_k, which corresponds to a cumulative frequency of Nk/n. The quantile is called percentile for $n = 100$ [35]. The 25th and the 75th percentiles are called the first and the third quartiles, respectively, and the 50th percentile is called the median [34]. If the points in a q-q plot lie roughly on a line, then the distributions are the same, whether normal or not.

A robust estimation of the linear relation between the outdoor temperature and the heat load may be done based on the central region of the q-q plot by considering data between the 1st and the 3rd quartile. If the two distributions are the same for this quantile range, then the coefficients of the model

$$\mathbf{Q} = a + b\mathbf{T}_o \qquad (26)$$

are:

$$b = \sigma_Q / \sigma_{T_o} \qquad (27)$$

and

$$a = \mu_{T_o} - b\mu_Q \qquad (28)$$

which represents the principal component axis in Fig. 4.

Equation (28) is a direct result of the fact that Q is a function of the random variable T_o and it is in accordance with the set of equations (16). In Fig. 4, the principal component axis (28) is located between the regression models (17) and (21). Fig. 4 (b) shows that the model (28) approximates the q-q plot in the central zone.

It is known from physical considerations that the relation $Q = f(T_o)$ is non linear for hot water heating systems equipped with radiators due to the nonlinearity of the heat transfer by convention and radiation:

$$P_i = kS(T_m - T_a)^n,\ 1 \le n \le 1.5 \qquad (29)$$

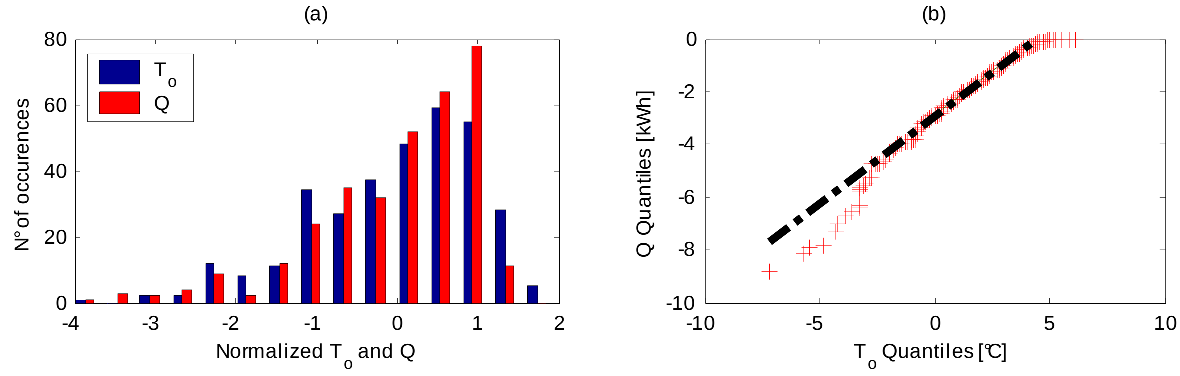

Fig. 3 Outdoor temperature and the heating load have partially the same statistical distribution. a) histogram b) quantile-quantile plot

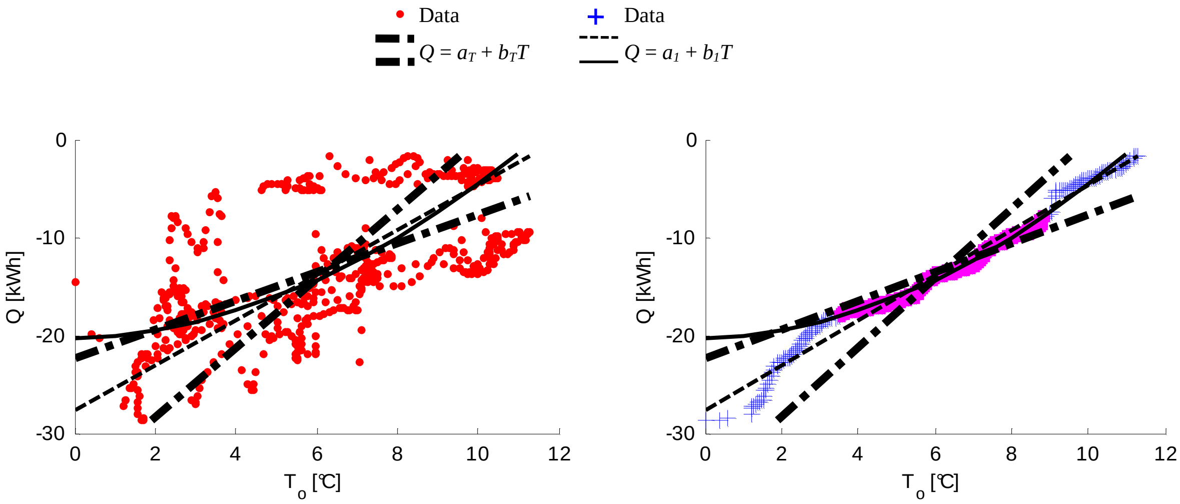

Fig. 4. Regression models on a) scatter plot b) quantile-quantile plot

where P is the heat flux of the radiators, k is the global transfer coefficient, S is the total surface, T_a is the ambient temperature and T_m is the mean temperature of the hot water:

$$T_m = (T_s + T_r)/2 \tag{30}$$

where T_s and T_r are the supply and the return hot water temperature, respectively. The nonlinearity of the relation $Q = f(T_o)$ may be modeled by considering a quadratic function of the type:

$$Q = a_2 + b_2 T_o + c_2 T_o^2 . \tag{31}$$

For the same reasons as above, a robust estimation of the parameters of equation (31) can be done by using the data from the q-q plot between the 1st and the 3rd quartile. For the data set shown in Fig. 4, the model obtained is:

$$Q = -20.35 + 0.12T_o + 0.15T_o^2 . \quad (32)$$

This model has a small slope for $T_o = -5°C$ which is the design temperature for heating in La Rochelle, France, and a higher slope for the base temperature of 12°C.

When energy consumption is estimated by using equation (10), the ordinary regression, equations (17) - (19), gives relative errors of 0.5% for the data on which it was obtained and of about 5-10 % for different set of data. The q-q regressions, equations (26) and (31), give the same relative error of 2-4% for the data set on which it was obtained as well as on new data set.

4 Relation between the free-running temperature and the load curve

The heat gains from sun, occupants, lights, and so forth, $\overline{q}_g$, are equal to the total energy loss when the outdoor temperature is equal to the balance point, T_b, for a given lower limit of the indoor comfort temperature, T_{cl} [1]:

$$\overline{\mathbf{g}}_g = \overline{\mathbf{K}} * (T_{cl} - \overline{\mathbf{T}}_b) . \quad (33)$$

The free-running temperature, T_{fr}, is the indoor temperature when no energy is supplied by the heating or cooling system and the air permeability of the building is kept at the winter value, i.e. the windows are closed [3]. In this case, the heat gains are:

$$\overline{\mathbf{g}}_g = \overline{\mathbf{K}} * (\overline{\mathbf{T}}_{fr} - \overline{\mathbf{T}}_o) . \quad (34)$$

From equations (33) and (34) it results that:

$$\overline{\mathbf{T}}_{fr} - T_{cl} = \overline{\mathbf{T}}_o - \overline{\mathbf{T}}_b . \quad (35)$$

Expressed as a function of the free-running temperature, the heating load equation (1) becomes:

$$\overline{q}_h = \overline{K}(\overline{T}_{fr} - T_{cl}) . \quad (36)$$

From equation (36) we obtain the free-running temperature:

$$\overline{\mathbf{T}}_{fr} = T_{cl} + \overline{\mathbf{R}} * \overline{\mathbf{q}} . \quad (37)$$

With the notations used, the energy rate for heating, $\overline{\mathbf{q}}_h$, is negative. For practical purposes, equation (37) may be expressed as a function of the energy consumption, $\overline{\mathbf{Q}}_h$, during a time interval, Δt:

$$\overline{\mathbf{T}}_{fr} = T_{cl} + \overline{\mathbf{R}} * \overline{\mathbf{Q}}_h / \Delta t . \quad (38)$$

Equation (38) provides the means of representing the free-running temperature as a function of the energy load. Fig. 1 (a) shows the scattered data of the energy consumption and the load curve obtained by regression, Q_h. Fig. 1 (b) shows the equivalent of the panel (a) obtained by using the free-running temperatures calculated with equation (38). The last panel, Fig. 1 (c), shows the frequency distribution of the outdoor temperature.

5 Energy performance evaluation by using the free-running temperature

The free-running temperature may replace the load curve to estimate the energy performance of buildings. In addition, it may be used in energy estimating methods such as degree-day and bin methods or to assess the climatic suitability of HVAC solutions and the potential for cooling by ventilation [3, 4, 14].

The load curves for heating and air conditioning are shown in Fig. 2 (a). The regression line Q_h represents the heating load. The regression line for cooling is more difficult to obtain due to data scattering produced mainly by the variable ventilation rates used for free-cooling [15]. Since the building is the same, it may be assumed that the cooling load is similar to the heating load with a difference introduced by the change of the base temperature equal to $T_{cu} - T_{cl}$. Consequently, the cooling load obtained from heating load Q_{ch} is parallel to the heating load, Q_h, and biased so that it passes through the center (mean) of the data cloud.

The free-running temperatures, obtained by using equation (38) for the regression line, are shown in Fig. 2 (b). Although mathematically equivalent to Fig. 2 (a), this is a condensed representation of the building performance during heating, ventilation and cooling. The conditions for heating, ventilation and cooling can be expressed as:

$$\delta_h = \begin{cases} 1, \text{if } T_{fr} < T_{cl} \\ 0, \text{if } T_{fr} \geq T_{cl} \end{cases}, \tag{39}$$

$$\delta_v = \begin{cases} 1, \text{if } T_{fr} > T_{cl} \text{ and } T_o < T_{cu} \\ 0, \text{if not.} \end{cases}, \tag{40}$$

and

$$\delta_c = \begin{cases} 1, \text{if } T_{fr} > T_{cu} \\ 0, \text{if not.} \end{cases}. \tag{41}$$

The condition for free-cooling (cooling by ventilation) is a sub-domain of ventilation,

$$\delta_{fc} = \begin{cases} 1, \text{ if } T_{fr} > T_{cu} \text{ and } T_o < T_{cu} \\ 0, \text{ if not.} \end{cases} \quad (42)$$

These domains are shown in Fig. 5. The example data shown in Fig. 2 (b) reveals that the free-cooling potential is not fully used since there are many points plotted for mechanical cooling in the free-cooling domain.

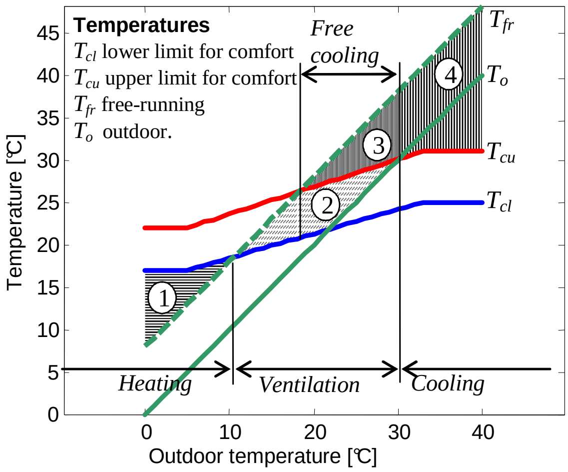

Fig. 5 HVAC operating zones: 1) heating, 2) ventilation 3) free-cooling, 4) mechanical cooling.

The frequency distributions of heating, $\mathbf{F}_h$, ventilation, $\mathbf{F}_v$, and cooling, $\mathbf{F}_c$, are shown in Fig. 2 (c). They represent the number of occurrences of outdoor temperature that satisfy the conditions (39), (40), and (41). The free-running temperature, $\mathbf{T}_{fr}$, the comfort range, $\mathbf{T}_{cl}$ and $\mathbf{T}_{cu}$, and the frequency distributions, $\mathbf{F}_h$, $\mathbf{F}_v$, and $\mathbf{F}_c$, can be used in energy performance estimation methods such as the bin method [3, 14]. The frequency distribution of degree-hour in bins of outdoor temperature for heating is:

$$\mathbf{F}_{DHh} = \mathbf{F}_h * (\mathbf{T}_{cl} - \mathbf{T}_{fr}), \quad (43)$$

for cooling is:

$$\mathbf{F}_{DHc} = \mathbf{F}_c * (\mathbf{T}_{fr} - \mathbf{T}_{cu}), \quad (44)$$

and for free-cooling is:

$$\mathbf{F}_{DHfc} = \mathbf{F}_{fc} * (\mathbf{T}_{fr} - \mathbf{T}_{cu}). \quad (45)$$

Multiplying the equations (43), (44), and (45) by $\overline{K}$ we obtain the frequency distribution of energy consumption for heating and cooling and of the energy savings for cooling by using free-cooling.

The total energy for heating is:

$$Q_h = \mathbf{F}_h \times \overline{K}(\mathbf{T}_{cl} - \mathbf{T}_{fr}), \tag{46}$$

and for cooling is:

$$Q_c = \mathbf{F}_c \times \overline{K}(\mathbf{T}_{fr} - \mathbf{T}_{cu}). \tag{47}$$

The total energy saved for cooling by using ventilation is:

$$Q_{fc} = \mathbf{F}_{fc} \times \overline{K}(\mathbf{T}_{fr} - \mathbf{T}_{cu}). \tag{48}$$

6 Conclusions

The load curve may be used in conjunction with the frequency distribution of the outdoor temperature to estimate the energy consumption of a building in different locations or in the same location but in different years. The errors introduced by using the energy load curve instead of using the measured energy are, generally, less than 5 %. These properties make the load curve useful in three applications: 1) to specify and check the building energy performance, 2) to estimate the energy consumption of a given building in another climate, and 3) to compare energy performance for different periods of time. Since the load curve is a characteristic of the building, which is independent of the climate, it can be used as a performance requirement for the design that may be easily checked during the operation of the building. The load curve obtained experimentally may be used to estimate the energy consumption of a building in another climate. This may be helpful for a first estimate of the feasibility of an exemplary building in a new climatic context. The same experimental load curve may be applied to assess the building performance in different years; consequently, it may be used in service contracts that offer comfort as a product. The energy consumption will vary from year to year not only due to the weather but also to the operation of the building; these variations are partially shown by the load curve.

The main disadvantage of the load curve is that it characterizes only the operation modes for heating and cooling but not for ventilation and it does not show explicitly the influence of the temperature comfort range on energy consumption. The information given by the load curve may be conveyed by the free-running temperature. The advantages of using the free-running temperature are that it describes the thermal behavior of the building that is decoupled from the temperature comfort domain and the weather data. By using the thermal characteristic of the building, the comfort range and the climate, we may obtain the distribution of degree-hour, which is mathematically equivalent to the bin method employed in energy estimating methods. The total thermal conductance, which makes the link between the energy load curve and the free-running temperature, may be helpful in estimating the energy consumption from the frequency distribution of degree-hours.

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References

1. ASHRAE, *Energy Estimating and Modeling Methods*, in *ASHRAE Fundamentals*. 2001.
2. Ellis, M.W. and E.H. Mathews, *A new simplified thermal design tool for architects.* Building and Environment, 2001. **36**(9): p. 1009-1021.
3. Ghiaus, C., *Free-running building temperature and HVAC climatic suitability.* Energy and Buildings, 2003. **35**(4): p. 405-411.
4. Germano, M., et al., *Natural ventilation potential of urban buildings:.* International Journal of Ventilation, 2005. **4**: p. 49-56.
5. Shaviv, E., A. Yezioro, I. G. Capeluto, *Thermal mass and night ventilation as passive cooling design strategy.* Renewable Energy, 2001. **24**: p. 445-452.
6. Heras, M.R., et al., *Energetic analysis of a passive solar design, incorporated in a courtyard after refurbishment, using an innovative cover component based in a sawtooth roof concept.* Solar Energy, 2004. **78**(1): p. 85-96.
7. Elkhuizen, P.A., H.C. Peitsman, and W. W.J., *A new design guideline for the heating and cooling curve in AHU units of HVAC systems.* Building Services Engineering Research and Technology, 2003. **24**(3): p. 191-202.
8. Pfafferott, J., S. Herkel, and J. Wapler, *Thermal building behaviour in summer: long-term data evaluation using simplified models.* Energy and Buildings, 2005. **37**(8): p. 844-852.
9. Pfafferott, J., S. Herkel, and M. Jäschke, *Design of passive cooling by night ventilation: evaluation of a parametric model and building simulation with measurements.* Energy and Buildings, 2003. **35**(11): p. 1129-1143.
10. ASHRAE, *Nonresidential cooling and heating load calculation procedures*, in *ASHRAE Fundamentals*. 2001.
11. Laub, A.J., et al., *Computation of system balancing transformations and other applications of simultaneous diagonalization algorithms.* IEEE Trans. Automatic Control, 1987. **32**: p. 115-122.
12. Moore, B., *Principal component analysis in linear systems: sontrollability, observability, and model reduction.* IEEE Transactions on Automatic Control, 1981. **26**: p. 17-31.
13. Ghiaus, C., *Experimental estimation of building energy performance by robust regression.* Energy and buildings, 2005. **in press**.
14. Ghiaus, C. and F. Allard, *Potential for free-cooling by ventilation.* Solar Energy, 2005. **in press**.
15. Yik, F.W.H. and K.S.Y. Wan, *An evaluation of the appropriateness of using overall thermal transfer value (OTTV) to regulate envelope energy performance of air-conditioned buildings.* Energy, 2005. **30**: p. 41-71.