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Incorporation of latent loads into the cooling degree days concept

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ABSTRACT

The cooling degree days concept is a tool to estimate and analyze weather related energy consumption in buildings, i.e. the cooling system electric energy consumption. The main problem with applying this method is that it disregards latent cooling loads. This paper deals with an approach for monitoring electric energy consumption due to cooling in buildings based on cooling degree days, which allows an estimation of latent loads. In addition to applying methods for determining base temperature to base humidity, a new technique is introduced, which is based on a significance test of the enthalpy latent days partial regression coefficient. Analogous to the performance line concept, the influence of latent loads can be presented in the form of a "performance surface" graph. The performance surface is a plot of electric energy consumption as a function of cooling degree days and latent enthalpy days. The above methods are tested on data sets consisting of electric energy consumption data obtained from two buildings and hourly meteorological data.

1. Introduction

In times when energy prices are continuously reaching new heights and rising electric energy consumption due to air conditioning in buildings as a consequence of global warming, an analysis of electric energy consumption in buildings is crucial, because the energy savings potential of HVAC systems is estimated to be up to 25%. While computer simulations are becoming more and more accurate, other simpler methods for energy estimation are still important as is shown by Day et al. [1]. One of these simple methods is the cooling degree day method. Cooling degree days (*CDD*) are the summation of temperature differences between the outside θ_0 and a reference temperature θ_b:

$$CDD = \sum \left(\theta_0 - \theta_b\right) \tag{1}$$

The reference temperature is known as the base temperature, which is a balance point temperature at which the cooling system does not need to run to maintain comfortable conditions. It represents the set indoor temperature, lowered due to internal and external heat gains and is, as such, specific for each building. Therefore, base temperature should be determined for each building individually instead of using degree days calculated to a standard reference temperature as is given in [2] and described by Ali et al. [3].

The main disadvantage of the degree day method is that it neglects the influence of latent loads, which become more significant at higher outdoor temperatures. Huang et al. [4] and Sailor [5,6] introduced the use of enthalpy latent days (*ELD*) to incorporate the influence of humidity on energy consumption. Enthalpy latent days are the summation of enthalpy differences between the outdoor air enthalpy h_0 and enthalpy at the outdoor air temperature θ_b and a reference absolute humidity x_b:

$$ELD = \frac{1}{24} \times \sum_{i=1}^{24} \left[h_0(\theta_0, x_0) - h_b(\theta_0, x_b)\right] \tag{2}$$

Ihara et al. [7] used a similar concept to determine the sensitivity of electricity consumption to air temperature and air humidity in selected business districts of Tokyo, but with reference humidity determined for each district separately and with momentary temperature/humidity differences instead of summations of temperature/humidity differences over time (i.e. *CDD* and *ELD*). Principal component analysis (PCA) was used in a study carried out by Lam et al. [8] to investigate seasonal variations in electricity use in 20 air-conditioned office buildings in Hong Kong as a function of dry-bulb temperature, wet-bulb temperature, global solar radiation, wind speed and clearness index. Since the new variables derived by PCA (i.e. principal components) are linear combinations of original ones, their physical meaning is obscure and one cannot determine the sensible/latent portion of the buildings cooling load or even a threshold temperature/humidity at which the cooling system starts to operate.

In this paper a new approach for monitoring electric energy consumption based on the concept of degree and latent enthalpy

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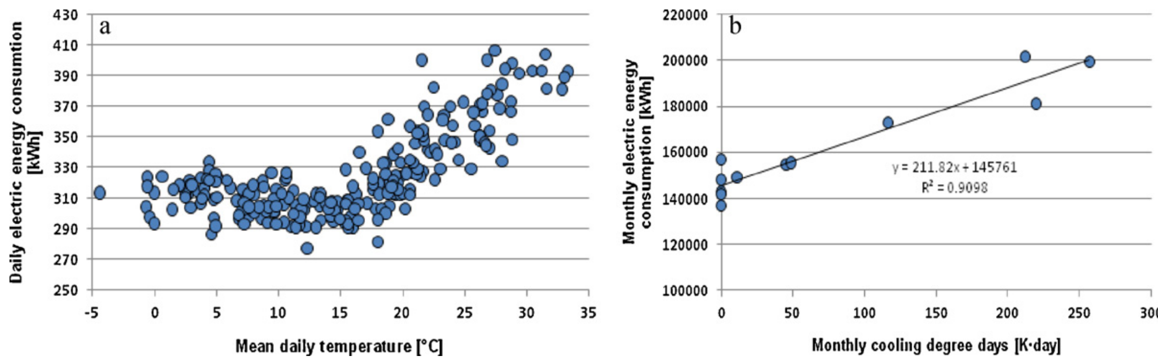

Fig. 1. (a) Energy signature; (b) performance line.

days is presented and tested on real building performance data.

2. Theory

In this section approaches for monitoring electric energy consumption in existing buildings and statistical methods for determining base temperatures are described. In addition, a new technique for determining base humidity is presented.

2.1. Monitoring electric energy consumption

There are two common approaches for monitoring electric energy consumption in existing buildings by means of outdoor temperature. One approach is to plot an energy signature for a building, which is a plot of daily energy consumption against mean daily temperature as shown in Fig. 1a. Since cooling degree days capture both the extremity and duration of outdoor temperatures, a better way to analyze electric energy consumption for building cooling is to use performance lines. A building performance line is a plot of monthly energy consumption against monthly degree days (Fig. 1b). The main advantage of performance lines, apart from using cooling degree days instead of outdoor temperatures, is that they, because of using monthly values, require significantly smaller data sets than equivalent daily energy signatures and so exhibit much less scatter [2].

To include the influence of latent loads on energy consumption we defined the performance surface analogously to the performance line concept. The performance surface is a plot of monthly electric energy against monthly cooling degree and latent enthalpy days as shown in Fig. 2. In contrast to the building power line, the performance surface $\bar{E}$ makes it possible to observe building's electric energy consumption regarding both sensible and latent loads in the form of *CDD* and *ELD*:

$$\bar{E} = E_0 + \left(\frac{\Delta E}{\Delta CDD}\right) \times CDD + \left(\frac{\Delta E}{\Delta ELD}\right) \times ELD \tag{3}$$

E_0 the intercept with the *z*-axis represents the building base load, while the cooling degree day's partial regression coefficient ($\Delta E/\Delta CDD$) is lower compared to the regression coefficient of the performance line obtained from the same data because latent loads are included in the regression model.

2.2. Determination of base temperature

Because analytical determination of base temperatures is complex and time-consuming mainly statistical methods are used [9]. We can obtain a building's base temperature from energy signatures by using piecewise linear regression to determine the intercept of weather dependent and independent electric energy consumption. Another statistical method for determining base temperature of a building is based on the performance line. Instead of using linear regression we use second order polynomial regression and determine the base value by a variation of

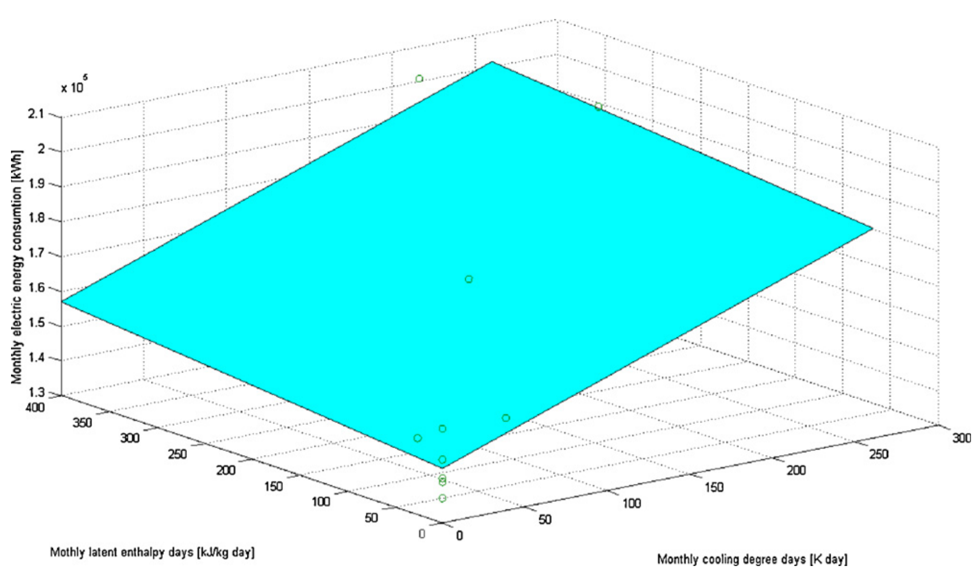

Fig. 2. Performance surface.