References and Sensitivity Analysis

Proportioning the total number of points obtained in the product analysis to the total expenditure given as a result of cost analysis will show how the different alternatives differ in terms of economic viability:

$$\text{reference of alternative} = \frac{\text{number of points in product analysis}}{\text{total units}} \qquad (3)$$

Sensitivity analysis can be applied if the effect of any given property on the total costs is known. In this case:

$$\text{reference of alternative} = \frac{\text{points in product analysis} \pm \text{points of additional property}}{\text{total costs} \pm \text{cost of additional property}} \qquad (4)$$

In the reference obtained in this way is greater, the inclusion or not of the additional property will be profitable, provided that the costs remain below the maximum set. Sensitivity analysis is relevant if the reference values of two or more systems are almost the same, or the inclusion of additional properties is considered profitable. The latter alternative will have to be considered if, for instance, there is room for extra points in the data gathering panels.

Simplified Models for Monthly HVAC System Performance in Large Buildings

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KEY WORDS

Cooling, HVAC, Building, Energy Analysis.

ABSTRACT

Heating and cooling load relations are formulated for a variety of HVAC systems in common use today. These equations are integrated over operating temperature ranges. The resulting expressions can be interpreted in terms of degree-days. This allows the use of previously generated weather statistics to determine monthly and annual heating and cooling energy requirements. The results of this approach are compared to those using actual weather records. It is shown that the simplified approach yields results within 5% of more exact methods. The techniques developed are suitable for use on microcomputers.

Modèle simplifié de calcul des performances mensuelles du système de chauffage-air conditionné dans les grands bâtiments

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Mots Clés:

Refroidissement, Chauffage Ventilation et Conditionnement d'air Analyse énergétique.

Résumé:

Les valeures des charges de chauffage et de refroidissement sont explicitées pour tout une série de systèmes de Chauffage et Conditionnement d'air actuellement utilisés. Ces équations sont intégrées sur la plage des températures d'utilisation. Les relations résultantes peuvent être interprétées en termes de Degré-Jour, ceci permettant l'utilisation des statistiques météorologiques pour obtenir les couts énergétiques mensuels et annuels des systèmes de chauffage et conditionnement d'air.
La comparaison de cette approche avec les méthodes traditionelles montre que cette simplification s'écarte de moins de 5% des modèles plus précis. Les techniques appliquées sont adaptables à un usage micro-informatique.

INTRODUCTION

Many different types of HVAC systems are in common use today. It is often of interest to estimate the seasonal energy use of these systems. In this paper, simplified techniques for the evaluation of the major HVAC systems in common use today are presented. The operation of terminal reheat, variable air volume, dual duct, three-deck, and dual fan/dual duct HVAC systems are studied. The relations are evaluated using an equivalent degree day approach, and the results are compared against detailed weather records. Reference 1 provides more detail on the approach and the results.

ANALYSIS

The zone loads may be calculated in a variety of ways, depending on the level of detail required. In order to develop simple relationships which give insight into system operations, the load will be representing as a conductance-area product times the overall temperature difference. This formulation neglects storage efforts in the walls and interior spaces. More complicated formulations for the load could be chosen, but the development of the relations for the equipment would be the same. For this paper, the cooling load for the zones is represented by

$$q_z = UA(T_a - T_{bal})^+ \qquad (1)$$

where the balance temperature includes the internal and solar gains in the zone. The + superscript denotes that only positive values of the term in parenthesis contribute to the cooling load.

Equation (1) represents an hourly load, and may be integrated over time to yield a weekly, monthly, or annual load. For any time period, τ_f, Eq. (1) may be integrated as

$$Q_z = UA \int_0^{\tau_f} (T_z - T_{bal})^+ d\tau \qquad (2)$$

The integral is commonly referred to as the degree-days based on the balance temperature. The value of the integral may be rewritten in terms of the density distribution function for ambient temperatures, P(T). This function is the frequency of occurrence of ambient temperature at any temperature level. The integration of the function PCT over a finite temperature interval yields the number of hours in a given temperature interval (bin information). The expression for the zone load, Eq. 2, can be rewritten as

$$Q_z = UA \int_{T_{low}}^{T_{high}} (T_a - T_{bal})^+ P(T)\, dT \qquad (3)$$

where T_{low} and T_{high} are the temperature extremes for the time period. The integral is termed the "degree-days" based on the balance temperature.

The development of the overall energy relations will be illustrated for the case of a terminal reheat system serving one zone. As shown in Figure 1, a constant flow rate of fresh air $k\dot{m}$ enters the system. The mixed air T_m passes through a central cooling coil which cools it to a set temperature T_c, usually on the order of 55°F. The air is delivered at a constant rate to each of a number of zones. A reheat coil at the entrance to each zone responds to a thermostat signal and adds heat to raise the entering cold stream temperature as needed to meet the zone cooling load. The return is mixed with all other zone return streams. The flow rate for each zone is fixed by the design cooling load which is met by airflow at the cold duct temperature. The required sensible cooling coil load becomes

$$\dot{q}_{cs} = k\dot{m}c_p \left[T_A - \frac{T_c - T_R(1-k)}{k}\right]^+ \tag{4}$$

The + superscript again indicates that only positive values of the term in brackets contribute to the load on the cooling coil.

The air stream then passes through the reheat coil. Air enters at T_c and heat is added to bring it to T_i, the supply air temperature. An energy balance on the zone and reheat coil together yields

$$\dot{q}_h = UA \left[\frac{(\dot{m}c_p + UA)T_R - \dot{m}c_p T_c - \dot{q}_G}{UA} - T_A\right]^+ \tag{5}$$

Where again only positive values of the term in brackets contributes to the reheat loads.

The moisture present after the return and outside air streams are mixed is determined by a mass balance on the mixing box. The internal moisture generation and flow rate are combined as $\omega_L = \dot{q}_L/\dot{m}h_{fg}$. The resulting latent load on the cooling coil, $\dot{q}_{cL}$ is given by

$$q_{c\ell} = k\dot{m}h_{fg}\left[\omega_A - \left(\omega_c - \frac{1-k}{k}\,\omega_L\right)\right]^+ \tag{6}$$

The expressions for the sensible, latent and reheat coil loads can be interpreted similar to the expressions for zone load. For example, for the sensible coil load, the term $(k\dot{m}c_p)$ is analogous to the conductance-area product UA, and the term $(T_c - T_R(1-k))/K$ is analogous to the balance temperature T_{bal}.

The total coil sensible cooling load is given by integrating Eq. (4) over all times. Using the density distribution function for ambient temperature, the integral becomes

$$Q_{cs} = k\dot{m}c_p \int_{T_{low}}^{T_{high}} \left[T_A - \frac{T_c - T_R(1-k)}{k}\right]^+ P(T)dT \tag{7}$$

This expression is similar in form to that for the zone load. The coefficient in front of the integral, $k\dot{m}c_p$, is an equivalent conductance, and the integral the "degree days" based on a balance temperature. In this case, the equivalent UA and balance temperature are

$$UA_{eq} = k\dot{m}c_p \quad \text{and} \quad T_{eq} = \frac{T_c - T_R(1-k)}{k} \tag{8}$$

A similar interpretation holds for the reheat coil. The coil latent load produces an expression with humidity that has been termed "gallon-days".

In a terminal reheat system, it is often common to use the outside air at low temperatures to provide "free" cooling. In terms of the development of the equivalent degree-day relations, this requires that the coil load be integrated only over the ambient temperatures for which coil cooling is supplied. For the coil sensible cooling load given by Eq. (7), this means that the lower limit of the integral is the highest temperature at which the outside air is used, T_E. Equation (7) for a terminal reheat system with the use of outside air becomes

$$Q_{cs} = k\dot{m}c_p \int_{T_E}^{T_{high}} \left[T_A - \frac{T_c - T_R(1-k)}{k}\right]^+ P(T)dT \tag{9}$$

The same interpretation in terms of an equivalent conductance-area product and balance temperature hold. The limits of integration for the reheat coil and coil latent load are similarly changed.

The advantage of formulating the loads in terms of equivalent degree days is that existing weather statistics may be used to evaluate the integrals. As discussed in the section on weather data, ambient temperature and humidity distributions may be readily described by relatively simple expressions. The integrals may be evaluated in closed form, and "degree days" obtained directly. When the difference between the ambient and balance temperatures is greater than about 10°F, the distribution of temperatures is not significant, and the integral reduces to the product of the temperature difference times the hours of occurrence. The relations that have been developed for weather description allow the hours of occurrence to be determined over any temperature level. All of these techniques reduce computational time significantly and provide increased generality of application.

Four other common HVAC systems were evaluated in a similar manner. These were the variable air volume dual duct, three deck, and dual fan/dual duct systems. The use of the economizer cycle was included. For all of these, the total energy was written in terms of equivalent conductance-area products and balance temperatures. The details are given in Reference 4.

Weather Data

The integrals in the energy relations require detailed weather records for the number of hours in each temperature bin. Bin data are available in, for example, Air Force Manual 88-29 [2], which lists 5°F dry bulb temperature bins each with a coincident wet bulb temperature for three eight hour periods of a day for a number of locations in the US. A year of bin data entails as many as 120 or more pieces of data.

A method developed by Erbs et al. [3] describes a set of relations for temperature and humidity distributions which may be used either to generate bin data of any bin size or, through integration, to yield degree-day totals for any month-long time period. The monthly weather data needed to generate a set of ambient temperature bins for a month is the long term monthly average temperature, $\bar{T}_m$, and the standard deviation of that month's average temperature over the long term σ_m. These relations are relatively simple expressions. Their accuracy in producing bin information will be assessed. The total system coil and equipment loads calculated with bin data derived from Erbs relations were compared to those calculated with hourly data for temperature and specific humidity.

System Performance

The use of generated weather data in determining system performance was compared to that using actual weather records. A building zone similar to a perimeter zone was chosen as a base case model for all calculations, and the parameters were varied to show the effects of different building types. Calculation of average monthly total loads over a year using bin data and TMY data were made for sensible cooling, latent cooling, total cooling and chiller energy, as shown in Figs. 2-4 for Madison. All thirteen building sets are plotted for each system, which is represented by a different symbol. The line with a slope of one represents a perfect fit.

The sensible cooling loads (Fig. 2) fall very close to the agreement line for all systems and all configurations. The latent cooling loads (Fig. 3), however, show noticeable deviations. However, the total cooling load (Fig. 4) is unaffected because latent loads are much smaller than sensible loads for Madison. The energy use for the economizer cycles are underpredicted. The reason lies in the link between temperature and humidity distributions. The generated bin temperatures have only one average humidity associated with them, whereas humidity is distributed over any temperature.

In Seattle, the latent loads are smaller than sensible cooling loads and, as for Madison, total cooling and chiller loads show good agreement between TMY and bin methods. The economizer cycles tend to overpredict chiller use because the differences in the ratio of latent to sensible totals for the two data sets.

The latent load totals for Miami are of the same order of magnitude as sensible cooling totals. Agreement between bin and TMY totals is good for systems with smaller latent loads. The generated distributions underpredict

slightly for large latent loads. The chiller totals show good agreement between bin and TMY summations.

The results show that the equivalent degree-day calculations for purchased energy requirements using bin data generated using Erbs' correlations give good results when compared to the same calculations using actual hourly data. Differences are less than 5% for all system types and all locations.

CONCLUSIONS

The heating, cooling, and zone load expressions were formulated on an instantaneous basis, and then integrated over time periods to obtain totals. The resulting expressions were cast as the product of equivalent conductance-area products and degree-days. This allows use of existing degree day statistics and relationships.

Both hourly and bin weather data were used in degree day summations. The use of bin data obtained from the correlation of Erbs for calculating total heating and cooling coil energy compares well to that using actual hourly data for a wide range of systems and locations. This is useful because the correlations require only monthly average temperature and humidity values for input data, and may than be used to generate bins of any size for any time period of the day.

REFERENCES

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3. Erbs, D.G., Klein, S.A. and Beckman, W.A., "Estimation of Degree-Days and Ambient Temperature Bin Data From Monthly-Average Temperatures", ASHRAE Journal, 25, 6, (1983).

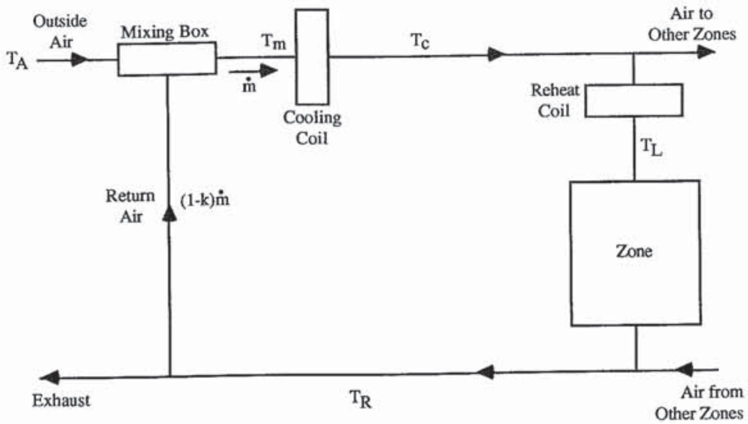

FIGURE 1: Schematic of a Terminal Reheat System.

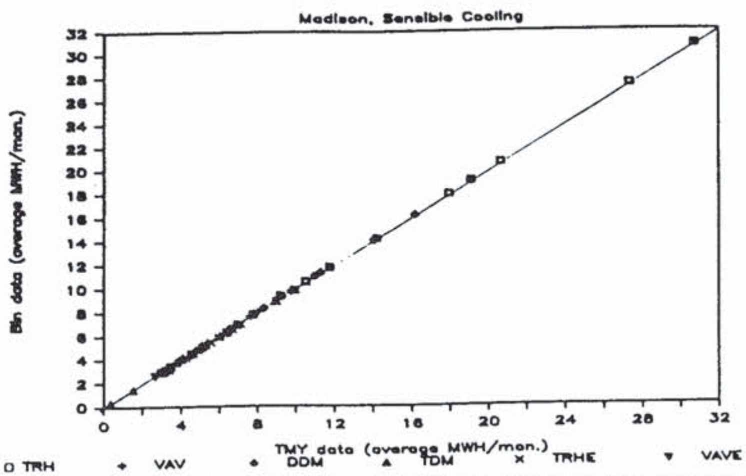

FIGURE 2: Comparison of TMY and Generated Bin Data for Sensible Cooling Energy.

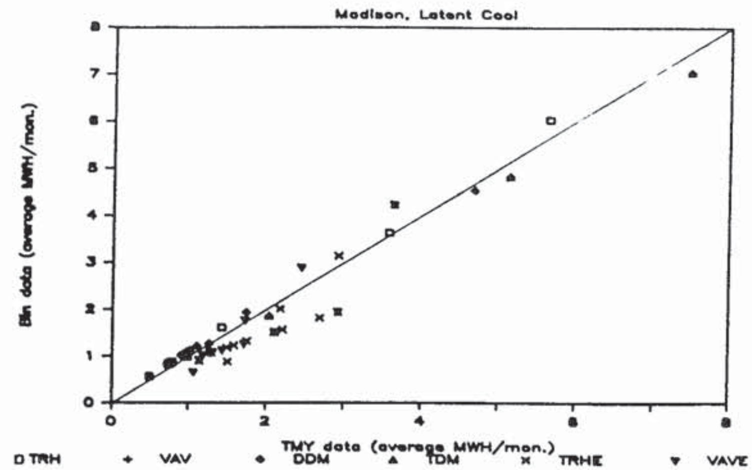

FIGURE 3: Comparison of TMY and Generated Bin Data for Latent Cooling Energy.

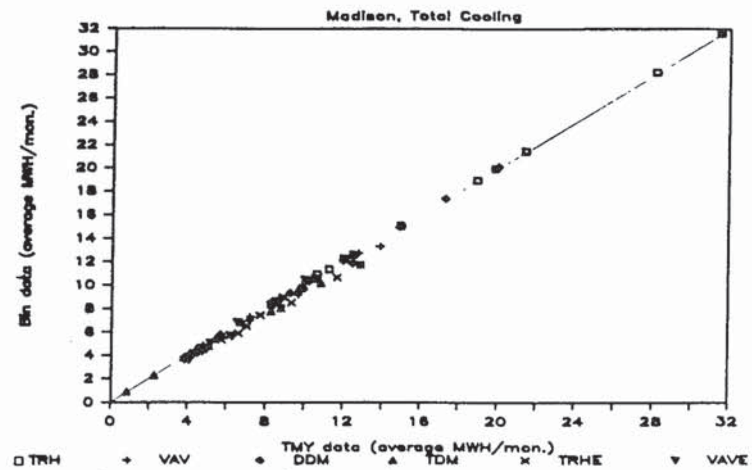

FIGURE 4: Comparison of TMY and Generated Bin Data for Total Cooling Energy.