Disaggregating Cooling Energy Use of Commercial Buildings Into Sensible and Latent Fractions From Whole-Building Monitored Data: Methodology and Advantages

S. Katipamula, Ph.D., T.A. Reddy, Ph.D. and D.E. Claridge, P.E., Ph.D.
Energy Systems Laboratory, Dept. of Mechanical Engineering,
Texas A&M University, College Station, TX 77843.

ABSTRACT

In hot and humid climates, where summers are both warm and humid, the latent cooling can be a significant portion of the total cooling load (as much as 40%). Typically the monitored data only includes whole-building heating and cooling energy use and total electric consumption. A method to disaggregate the latent cooling energy use from the measured whole-building heating and cooling energy use would be of particular interest. This paper presents such a method and discusses its benefits.

It is shown that the overall heat transfer coefficient, including the conduction, infiltration, and ventilation effects of a building, can be evaluated. Subsequently this enables the disaggregation of the total cooling energy use into sensible and latent cooling fractions. The benefits of such a method include: (i) better understanding of the sensible and latent fractions in the total cooling energy use of a building, and (ii) better regression models for energy analysis.

In addition to the whole-building cooling and heating energy use and the ambient conditions, the required system parameters include: (i) cold deck supply temperature, (ii) hot deck supply temperature, (iii) mixed air temperature or ventilation rate, (iv) internal gains, and (v) total mass flow rate of the dual duct constant volume system. If continuous measurements of the system parameters are not available, then one-time measurements may be used to disaggregate the latent cooling energy use.

INTRODUCTION

Several state-owned buildings are being retrofitted with energy efficient heating ventilating and air-conditioning (HVAC) systems as part of the Texas LoanSTAR (Loan for Saving Taxes And Resources) Program (Verdict et al., 1990). A state-wide Monitoring and Analysis Program (MAP) has been established, at the Energy System Laboratory (ESL), at Texas A&M University to monitor the pre- and the post-retrofit energy use. The program is currently collecting hourly data from over fifty buildings in Texas (Claridge et al., 1991).

The monitoring provides (pre- and post-retrofit) data to support building energy analysis and to verify the energy savings due to energy conservation retrofits implemented in the buildings. The installed equipment typically includes whole-building thermal metering (chilled water and hot water/steam condensate (Btu)), whole-building electric load metering (kW), air handler load (fans, motors, pumps, etc (kW)) and weather (outdoor dry-bulb temperature, outdoor relative humidity/dew point temperature, solar radiation and wind speed) (O'Neal et al., 1992).

The instrumentation that measures cooling energy use does not measure the sensible and latent cooling energy use individually. In hot and humid climates, where summers are both warm and humid, the latent cooling can be a significant portion of the total cooling load (as much as 40%). The sensible and latent energy use can be monitored individually, but this is expensive. Also, even state of the art moisture measuring devices need frequent calibration (Bryant and O'Neal 1992). On the other hand measurement of the whole-building heating and cooling energy use is relatively simple and inexpensive. Therefore, to improve the building energy analysis a method is needed whereby the latent cooling can be disaggregated from the measured whole-building heating and cooling energy use. The benefits of such a method include: (i) better understanding of the sensible and latent fractions in the total cooling energy use of a building, and (ii) better regression models for energy analysis. Such a method is presented in this paper.

The methodology to disaggregate sensible and latent cooling from total cooling is presented. The methodology is based on first evaluating the overall heat transfer coefficient (U_o which includes conduction, infiltration, ventilation and solar gain effects) of a building. U_o which has units of Btu/h/F is analogous to the inverse of the heat resistance. It was evaluated by performing an energy balance on the building in the heating mode, with the use of mixed air, cold deck, hot deck, and ambient dry-bulb temperatures, internal gains and whole-building heating energy use. The sensible cooling energy use is then estimated by performing an energy balance on the building in the cooling mode with the

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use of system temperatures, internal gains and U_o. The latent cooling energy use of the building is the difference between the measured whole-building cooling energy use and the estimated sensible cooling energy. This methodology was applied to two large buildings located in Central Texas.

METHODOLOGY

The methodology will be illustrated for dual-duct constant volume (DDCV) systems (Figure 1). It can be easily adapted to other systems as well, with minor changes. In addition to the whole-building cooling and heating energy use, total internal gains, and the ambient conditions, several system parameters are needed. These include: (i) cold deck supply temperature (T_c), (ii) hot deck supply temperature (T_h), (iii) mixed air temperature (T_m) or ventilation rate, (iv) internal gains ($\dot{q}_{i,s}$) and (v) total mass flow rate [illegible]a-surements of the system parameters are not available then one time measurement may be used in the analysis.

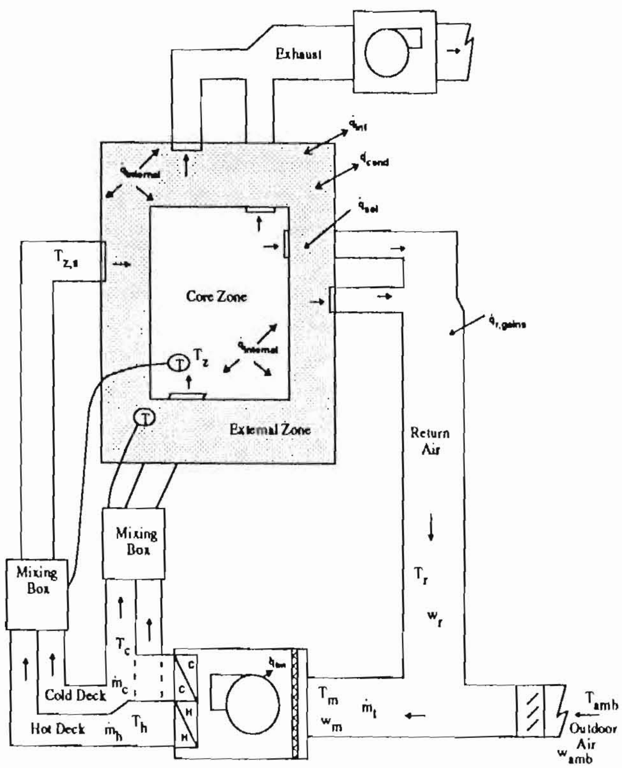

Figure 1 – Schematic of a Typical Two-Zone Building With Dual-Duct System.

* Not required for variable volume system (VAV)

The sensible heating/cooling is, in general, a function of the outdoor (T_{amb}) and indoor (T_z) dry-bulb temperatures and the latent cooling is a function of the amount of moisture in the mixed air and of the surface temperature of the cooling coil. The whole-building cooling energy use is made up of sensible and latent effects, whereas the whole-building heating energy use consists of sensible heating only. Therefore, by performing an energy balance on the building in heating mode, U_o can be evaluated. The measured total heating energy use, $\dot{q}_h$, is given by:

$$\dot{q}_h = \dot{m}_h c_p (T_h - T_m). \tag{1}$$

The hot deck mass flow rate, $\dot{m}_h$, is an unknown, but for a DDCV system (Knebel 1983) it can be expressed in terms of the total mass flow rate $\dot{m}_t$ as:

$$\dot{m}_h = \frac{T_{z,s} - T_c}{T_h - T_c} \dot{m}_t. \tag{2}$$

The zone supply air temperature, $T_{z,s}$, which is a function of zone sensible load is also an unknown and is given by:

$$T_{z,s} = T_z - \frac{\dot{q}_{z,s}}{\dot{m}_t c_p} \tag{3}$$

where $\dot{q}_{z,s}$ is the zone sensible load and T_z the mean zone temperature.

$T_{z,s}$ is controlled by zone thermostat which only responds to changes in sensible loads. The sensible loads, $\dot{q}_{z,s}$, on a building include: (i) envelope loads (conduction losses/gains, and solar heat gains), (ii) internal loads (gains from lights, equipment and people) and (iii) infiltration losses/gains. However, $\dot{q}_{z,s}$ does not account for ventilation load, whereas $\dot{q}_h$ does. The sensible portion of the ventilation load is:

$$\dot{q}_{ven,s} = \dot{m}_t c_p (T_m - T_z). \tag{4}$$

If the return air temperature, T_r, is known, it should be used in place of T_z in the above equation. Failure to do so essentially implies that the heat losses/gains in the return air ducts have been implicitly lumped into the ventilation load. However, using T_z instead of T_r is a reasonable assumption because (i) the losses/gains in the return air duct are a small fraction of the total load, (ii) both the duct losses/gains and ventilation losses/gains are a function of the outdoor dry-bulb temperature, and (iii) T_r is, very often, more difficult to measure or estimate than T_z. In this analysis T_z will be used in instead of T_r. Eliminating T_z from Eq. (3) and Eq (4) yields:

$$T_{z,s} = T_m - \frac{\dot{q}_z}{\dot{m}_t c_p} \qquad (5)$$

where $\dot{q}_z = \dot{q}_{z,s} + \dot{q}_{ven,s}$. Now substituting for $T_{z,s}$ in Eq. (2) and further substituting for $\dot{m}_h$ in Eq. (1) yields:

$$\dot{q}_h = \dot{m}_t \times c_p \left[(T_m - \frac{\dot{q}_z}{\dot{m}_t c_p}) - T_c \right] \times \frac{(T_h - T_m)}{(T_h - T_c)}. \qquad (6)$$

Re-arranging the above equation in terms of $\dot{q}_z$ results in:

$$\dot{q}_z = \dot{m}_t \times c_p (T_m - T_c) - \dot{q}_h \frac{(T_h - T_c)}{(T_h - T_m)} \qquad (7)$$

Physically, $\dot{q}_z$ is expected to be a function of envelope, infiltration, ventilation, solar and internal loads. The envelope, infiltration and ventilation losses are a function of the outdoor and the indoor dry-bulb temperatures. The solar gains can also be assumed to be a function of the outdoor dry-bulb temperature (Vandon et al., 1991 and Knebel, 1983). Thus,

$$\dot{q}_z = U_o (T_{amb} - T_z) + \dot{q}_{i,s} \qquad (8)$$

Note that the sensible portion of the internal gains, $\dot{q}_{i,s}$, includes gains from lights, equipment and people. The gains from lights and equipment can be monitored, but the gains from people have to be estimated. Substituting for $\dot{q}_z$ in Eq. (7) and rearranging the terms yields:

$$U_o \overbrace{(T_{amb} - T_z)}^{X_h} = \overbrace{\dot{m}_t \times c_p (T_m - T_c) - \dot{q}_h \frac{(T_h - T_c)}{(T_h - T_m)} - \dot{q}_{i,s}}^{Y_h} \qquad (9)$$

Introducing an intercept term α to account for secondary energy flows which have been neglected and also to correct for small biases in our estimate of T_Z, we have:

$$Y_h = U_o X_h + \alpha \qquad (9a)$$

When the ambient and the zone set point temperatures are equal, all temperature dependent loads should be zero. Although solar load is assumed to be temperature dependent, its slope is much smaller. Therefore, linear regression is likely to assign part of the solar load contribution to the intercept term. Also, any change in the zone set point temperature will affect the intercept. All terms in Eq. (9) except for U_o can be monitored. Therefore, the quantities Y_h and X_h can be calculated at intervals for which continuous monitored data are available (either at hourly or daily intervals). Once Y_h and X_h are calculated, U_o can be obtained by regressing Y_h against X_h using ordinary least-squares linear regression. Since U_o is a building characteristic (assuming that infiltration and ventilation rates are constant), it is independent of the season.

An expression similar to Eq. 9 can be developed for the sensible cooling energy use by performing an energy balance on the building in the cooling mode:

$$U_o(T_{amb} - T_z) = \dot{q}_{c,s} \frac{(T_h - T_c)}{(T_m - T_c)} - \dot{m}_t \times c_p (T_h - T_m) - \dot{q}_{i,s} \qquad (10)$$

Re-arranging Eq. 10 in terms of $\dot{q}_{c,s}$ yields:

$$\dot{q}_{c,s} = \left[\dot{m}_t \times c_p (T_h - T_m) + U_o \times (T_{amb} - T_z) + \dot{q}_{i,s} \right] \times \frac{(T_h - T_c)}{(T_m - T_c)} \qquad (11)$$

Once U_o is evaluated from regression (Eq. 9) it can be used along with Eq. 11 to deduce the sensible energy use of the building. Finally, the latent cooling energy use is easily estimated, since it is the difference between the measured whole-building cooling energy use and the estimated sensible cooling energy use. The schematic of the methodology is shown in Figure 2.

APPLICATION OF THE METHODOLOGY

The methodology was applied to two buildings located in Central Texas: (i) a large engineering center (EC) and (ii) a large chemistry center (CC). The monitoring in EC was extensive and it included all the system parameters needed. However, the monitoring in CC was only limited to whole-building heating and cooling energy use and internal gains (lights and equipment). Therefore, one time measurements of the system parameters had to be used to apply the methodology to the CC.

Description of EC

The EC is a 324,000 gross ft^2 building (240,000 ft^2 net) located in Central Texas with four floors plus a basement parking level. It includes offices, classrooms, laboratories and computer rooms and is open 24 hours per day,

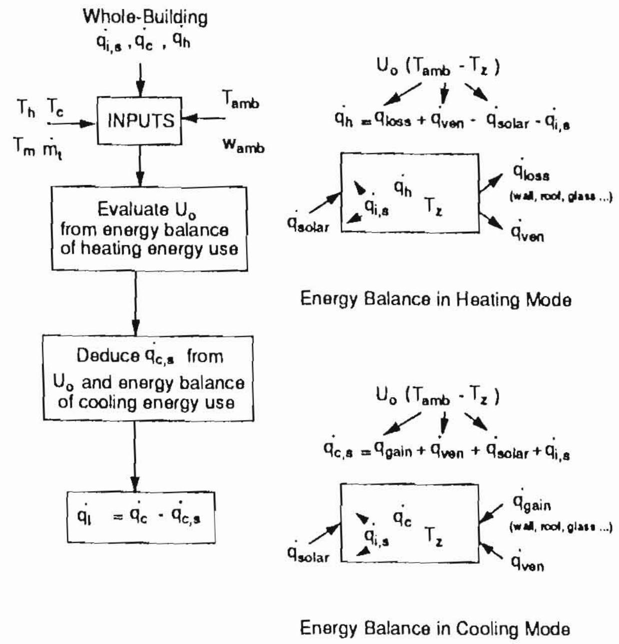

Figure 2 – Schematic of the Disaggregating Methodology.

365 days per year. Occupancy and electrical consumption shows marked weekday/weekend differences; weekday holiday occupancy is similar to weekend usage with intermediate usage on weekdays when class rooms are not in use, but laboratories and offices are occupied (Katipamula and Haberl 1991). The parking lot which is underground is lit but not conditioned.

The EC is a heavy structure with 6-inch concrete floors and insulated concrete walls. The DDCV system used to heat and cool the building is supplied with hot water, chilled water and electricity from the central campus plant. The campus does not individually meter buildings, but a data logger was installed in the EC to collect hourly consumption data beginning in May 1989. Whole building data collected included electricity use, air handler electricity, chilled water load (Btu), hot water load (Btu), and hot water and chilled water pump run times. A weather station on the roof of the EC collects outdoor dry-bulb temperature, relative humidity, horizontal solar radiation and wind velocity data.

Twelve identical DDCV systems with 40 hp (29.8 kW) fans rated at 35,000 cfm and eight smaller air handlers (2.7 hp average) are located around the perimeter of the building. While the large air handling units (AHU) are rated at 35,000 cfm, the air balance report shows flows of 20,000 cfm to 28,000 cfm with a total air flow of 320,000 cfm for the building. The outdoor air intake provides about 10% outdoor air when fully open; manual dampers are normally closed by the operators to limit outside air for several months when freezing outdoor temperatures are possible. There are 45 small exhaust fans with capacities ranging from 200 to 4,000 cfm, of which 15 are toilet and room exhausts (15,000 cfm) and the rest are fume and furnace exhausts. The fume and the furnace exhausts are in the laboratories and are only turned on to meet occasional exhaust requirements.

One of the twelve air handlers had been instrumented since April 1990 to record hourly values of: mixed and cold deck dry-bulb temperatures and relative humidities, hot deck temperature, total air flow rate, pressure drop across the fan and the filter assembly, and fan power consumption (Figure 3). The monitored air handler showed the flow rate to be between 20,000 to 22,000 cfm. The air balance report showed that this air handler was supplying about 20,430 cfm.

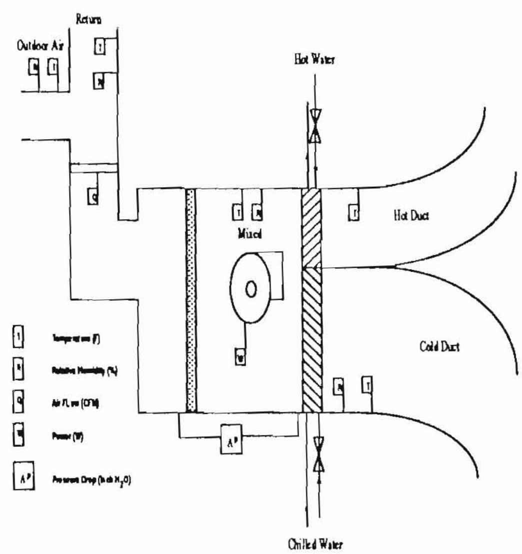

Figure 3 – Air Handling Monitoring Schematic.

The hot and cold deck supply temperatures in all twelve air handlers are controlled by a single controller (one each for hot and cold decks). Therefore, it is reasonable to assume the supply temperatures in the other eleven AHUs to be the same as that of the monitored AHU. Since the air handlers have the same outdoor intake capacities and since

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the outdoor dampers on all the air handlers are always fully open, the monitored mixed air temperature is assumed to be the average of all the twelve AHUs.

The major electric loads in the EC are motor control center (MCC), computer center, equipment and lighting. The electric metering in the EC monitored MCC, computer center and the whole-building consumption individually. Therefore, the equipment and the lighting (internal gains) load is the difference between the whole-building electric and the electric load from MCC and computer center. The number of people in the EC at any given time varies from few hundred to about 3000. For this analysis, an average of 1,500 people will be assumed. At 250 But/hr/person the sensible gains from people would be 9 MBtu/day (average number of people 1500 at 6000 Btu/person/day). The computer center was cooled by an auxiliary cooling unit; therefore, its cooling energy was not included in the whole-building monitored cooling energy.

Application of the Methodology to the EC

The monitored data needed for the analysis included: (i) hot deck supply temperature, (ii) cold deck supply temperature, (iii) mixed air dry-bulb temperature, (iv) outdoor dry-bulb temperature, (v) whole-building cooling energy use, (vi) whole-building heating energy use and (vii) sensible internal gains (equipment and lighting load). The total mass flow rate ($\dot{m}_t$=1.5 Mlbm/hr where M=10^6) was obtained from the air balance report. The zone set point temperature was assumed to be 76 F.

Although the EC is maintained at a constant temperature (no thermostat setbacks), it still exhibits some thermal mass effects. To reduce the mass effects the heating energy use, the cooling energy use, and the internal gains are summed to daily values (over 24 hours). The temperature quantities (T_h, T_c, T_m, and T_{amb}) are averaged over the day. One calendar year's data were used for this analysis.

The quantities Y_h and X_h of Eq. 9 were calculated for the entire dataset and U_o was estimated by regressing Y_h on X_h (following Eq. 9a):

$$Y_h = 3.446 \times X_h + 16.049$$

As described in the earlier section the linear regression is likely to assign part of the solar load contribution to the intercept term. The adjusted R-squared of the regression was 0.89, indicating that Y_h is strongly correlated to X_h. Y_h is plotted versus X_h in Figure 4, the solid line representing the model prediction. The spread of the residual is fairly constant over X_h. The residuals do not exhibit any obvious pattern, except for low values of X_h where the residuals are mostly positive (Figure 5).

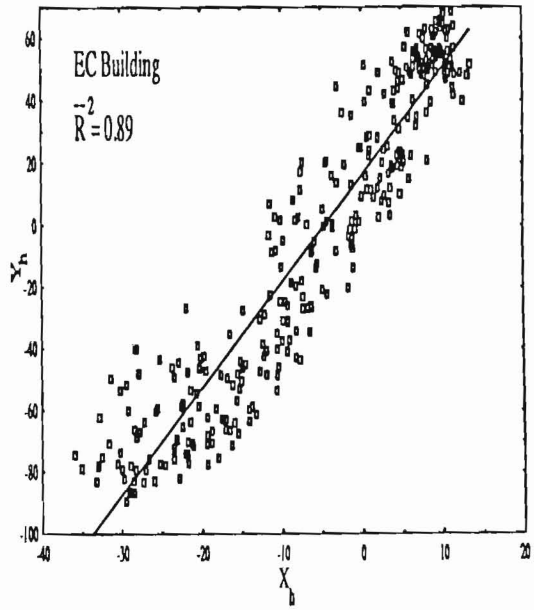

Figure 4 – Quantities Y_h and X_h (as defined in Eq. 9) Along With the Regression Model.

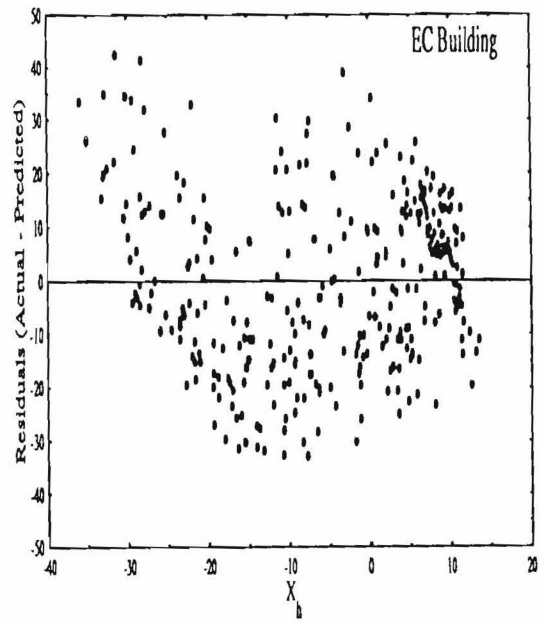

Figure 5 – Residuals vs Quantity X_h (as defined in Eq. 9).

The value of U_o estimated above was used with Eq. (11) to deduce the sensible cooling energy use. The latent cooling energy use is the difference between the measured cooling energy use and the estimated sensible cooling energy use. The disaggregated sensible and latent cooling energy use are shown as a function of the outdoor dry-bulb temperature in Figure 6 and the latent cooling energy use is shown as a function of the outdoor specific humidity in Figure 7. The sensible cooling energy use shows a slight change in slope below 60 F outdoor dry-bulb temperature. This could be due to the fact that all the external zones would require heating below 60 F outdoor dry-bulb temperature, whereas the internal zones would still require cooling. Since the internal gains are almost constant on a daily basis the cooling energy use below 60 F would thus, have a smaller slope.

The latent cooling energy use increases with outdoor specific humidity. There is scatter, but the scatter seems to decrease with an increase in outdoor specific humidity. Note that the latent to total cooling energy use increases from about 20% at outdoor specific humidity of 0.002 lbm/lba to about 30% at outdoor specific humidity of 0.018 lbm/lba. At an outdoor specific humidity of zero the latent cooling energy use of the EC is about 10 MBtu/day. When the outdoor air dew point temperature is less than the surface temperature of the cooling coil the ventilation latent load is zero. Any latent cooling energy, for outdoor dew point temperature below the cooling coil temperature, is due to the internal latent load from people. The internal latent load from people in the EC would be approximately 10 to 15 MBtu/day which is consistent with the intercept in Figure 7.

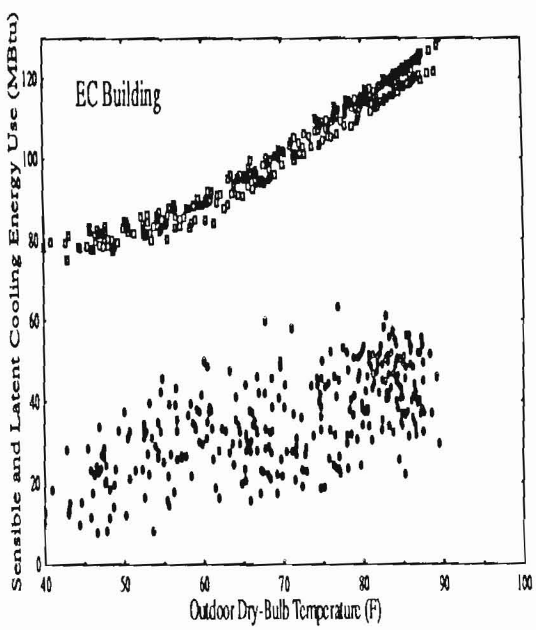

Figure 6 – Disaggregated Sensible and Latent Cooling Energy Use As a Function of Outdoor Dry-Bulb Temperature. Squares Represent Sensible and Circles Represent Latent Loads.

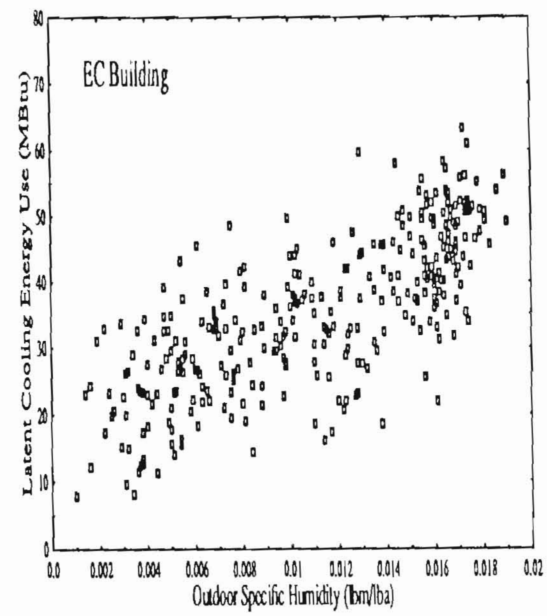

Figure 7 – Latent Cooling Energy Use As a Function of Outdoor Specific Humidity.

Description of CC

The CC is a six-storied building with 440,000 gross ft^2 (350,000 ft^2 net) located in Central Texas. It includes laboratories, offices and classrooms. Unlike the EC building discussed earlier, a major portion of the conditioned area is laboratories which require large amounts of fresh air intake. The building is open 24 hours per day, 365 days per year. Occupancy and electrical consumption show day/night and weekday/weekend differences.

The CC is a heavy structure with 6-inch concrete floors and insulated concrete walls. The DDCV system is supplied with steam, chilled water and electricity from the central campus plant. A data logger was installed in the building in January 1991 to monitor whole building electricity use, air handler electricity, chilled water load (Btu), and steam consumption (Btu). A weather station on a different LoanSTAR site (close to CC) collects outdoor dry-bulb temperature, relative humidity, horizontal solar radiation and wind velocity data. In addition, hourly dry-bulb and dew-point temperatures from the National Weather Service

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(NWS) (Austin airport) are also recorded.

The CC has three identical DDCV systems with six 100 hp fans (two each per system) and a small DDCV system with a 60 hp fan. The three big units are all capable of taking in 100% outdoor air. There are 12 exhaust fans which operate 24 hours a day and two 30 hp return air fans.

Application of the Methodology to the CC

As described in the earlier section this methodology requires certain system temperatures to be known explicitly. Although none of the air handlers was instrumented in detail like the building discussed earlier, one-time measurement of several key systems parameters were made. The three big air handlers were found to draw almost 100% outdoor air and the fourth air handler was found to draw about 20%. Therefore, the outdoor air intake was assumed to be about 95% of the total air flow.

According to the existing controls in the CC, the cold deck supply temperature is maintained at 55 F and the hot deck supply temperature is reset based on the outdoor air temperature (Table 1). The hot deck supply temperature between 40 and 80 F outdoor temperature was linearly interpolated. Therefore, for this analysis the cold deck supply temperature was set at 55 F and the hot deck supply temperature was reset with the outdoor dry-bulb temperature. The total air flow was taken as 1.68 MMlbm/hr; it was estimated from total fan power and total static pressure in the ducts.

Table 1 – Hot Deck Reset Schedule for the CC Building.

Outdoor Air Temperature (F)	Hot Deck Discharge Air Temperature (F)
80	80
40	120

The zone set point was assumed to be 76 F. The number of people occupying the building at any give time varied from a few hundred to a peak of 4,000. For this analysis an average of 1,500 people was assumed. At 250 Btu/person/hr the sensible load from people would be 9 MBtu/day. Ten months of data were used in this analysis (February to November 1991).

The quantities Y_h and X_h (Eq. 9) were calculated for all days when the average daily dry-bulb temperature was less than 76 F. As the outdoor dry-bulb temperature approached 80 F which is also the hot deck supply temperature (T_h), the difference between the hot deck supply temperature and the mixed air temperature (T_m) approached zero which, as can be seen from Eq. (9) would result in Y_h values approaching infinity (for the EC this problem did not arise because T_h was always greater than T_m). In order to overcome this, the analysis had to be limited to temperatures below 76 F.

U_o was estimated by regressing Y_h with X_h:

$$Y_h = 7.07 \times X_h + 14.83$$

The adjusted R-squared of the regression was 0.89, indicating that Y_h is strongly related to X_h. Y_h values are plotted versus the X_h values in Figure 8, the solid line representing the regression model. The residuals do not seem to exhibit any obvious pattern (Figure 9). Since U_o would be a building parameter independent of the season, the value determined by regression ought to be valid throughout the temperature range. Hence the value of U_o estimated above was used with Eq. (11) to estimate the sensible cooling energy use.

The disaggregated sensible and latent cooling energy use are shown as a function of the outdoor dry-bulb temperature (Figure 10), and the latent cooling energy use is shown as a function of the outdoor specific humidity (Figure 11). The latent cooling above 75 F is greater than the sensible cooling energy. The latent cooling energy use varies between 15% to 65% of the total cooling energy use.

The latent cooling energy use should be zero for outdoor dew point temperatures below the cooling coil surface temperature. Since the cold deck supply temperature was 55 F the cooling coil surface temperature would be between 45 and 50 F. The specific humidity corresponding to a dew point temperature of 47 F is about 0.007 lbm/lba. Therefore, below the outdoor air specific humidity of 0.007 lbm/lba the latent cooling energy use should be zero. However, Figure 11 shows some latent cooling energy use below the outdoor specific humidity of 0.007 lbm/lba. The presence of latent load below outdoor specific humidity of 0.007 lbm/lba is probably due to the fourth air handler taking only 20% outdoor air and conditioning a green-house.

DISCUSSION

Ideally, data spanning at least one calendar year are required for the analysis. If fewer data are available this methodology can still be applied provided the outdoor dry-bulb temperature is evenly distributed below and above the zone set point temperature. The hot deck supply temper-

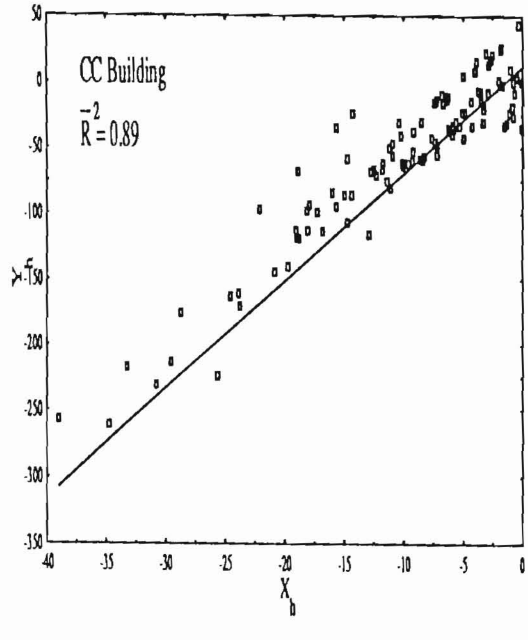

Figure 8 – Quantities Y_h and X_h (as defined in Eq 9) Along With the Regression Model.

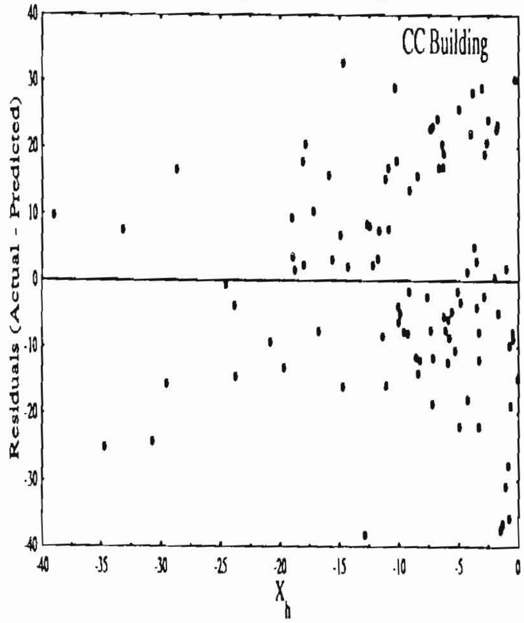

Figure 9 – Residuals vs Quantity X_h (as defined in Eq. 9).

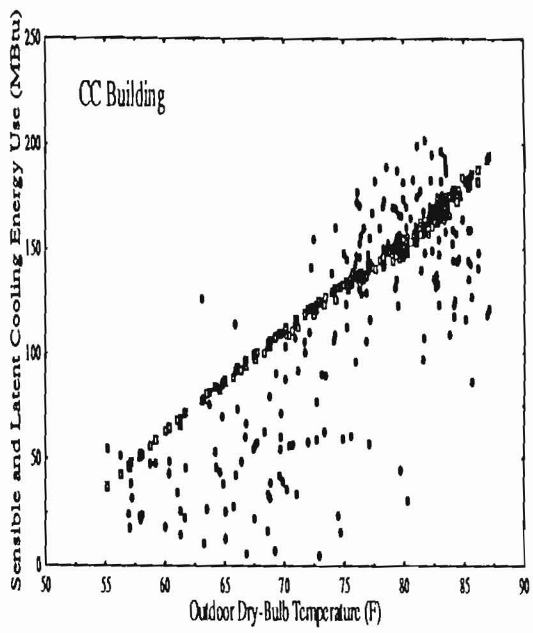

Figure 10 – Disaggregated Sensible and Latent Cooling Energy Use As a Function of Outdoor Dry-Bulb Temperature. Squares Represent Sensible and Circles Represent Latent Loads.

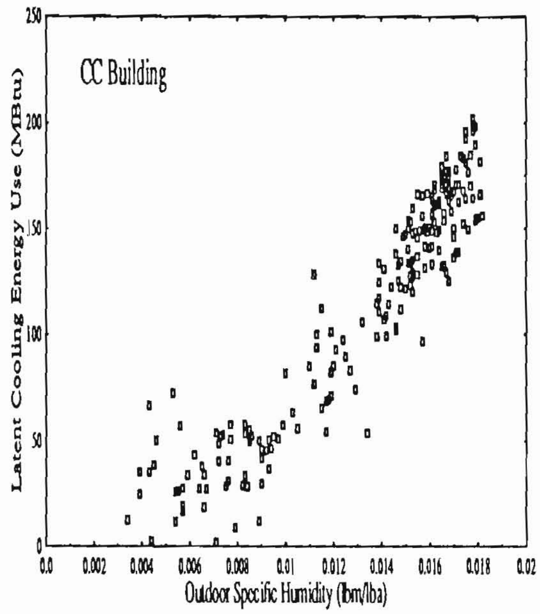

Figure 11 – Latent Cooling Energy Use As a Function of Outdoor Specific Humidity.

ature, in most commercial buildings, above 80 F outdoor dry-bulb temperature will be the same as the mixed air dry-bulb temperature. Therefore, U_o will have been evaluated for outdoor conditions below 80 F.

The monitored data (hourly/daily) needed to apply this methodology can be classified into three categories: (i) whole-building end use, (ii) local weather conditions and (iii) HVAC system parameters and operation. In the first category, the end uses include heating and cooling energy consumption and the internal gains (lighting, equipment and people). The local weather variables that are needed include the dry-bulb temperature and the specific humidity. The HVAC system parameters that are needed include: (i) hot deck supply dry-bulb temperature, (ii) cold deck supply dry-bulb temperature, (iii) mean zone set point temperature, (iv) mixed air dry-bulb temperature or the ventilation rate, and (v) total mass flow rate (not required for a VAV system).

In most of the LoanSTAR sites the whole-building data and the local weather conditions are available. However, the system temperatures (T_h, T_c and T_m) are monitored in only a few sites. The duct mount temperature sensors are reliable and easy to install. But the cost of installation varies from a few hundred dollars to up to $1,000 per point.

The mean zone temperature is difficult to monitor because in a typical commercial building there are several zones. Also, the total mass flow rate is difficult to monitor; however, realistic value can be assumed (for the constant volume system one-time measurement of the mass flow would be sufficient). In case the system temperatures are not monitored, the temperatures can be obtained from one-time measurement or from the operational schedules. In most of the LoanSTAR sites the cold deck supply temperature is constant (53 - 56 F). The hot deck supply temperature is normally reset based on the outdoor air temperature. If the system temperatures are obtained from the operational schedules, the maintenance schedules of the controls should be carefully reviewed.

The methodology was applied on two buildings, one of which had extensive monitored data and the other just the whole-building data. It appears that for this analysis continuous system data may not be needed if one time measurements of the key system parameters are available. Therefore, it is beneficial to measure the key system parameters at the time the audits for ascertaining the energy conservation opportunities of the building are done. However, there are several benefits of continuous monitoring of the systems, for example, operational and maintenance problems can be immediately detected and rectified. Therefore, when possible, the systems should be continuously monitored. The trend in building monitoring is to adapt/modify an energy management control system (EMCS) to perform the types of measurements in the whole building, the local weather conditions, and the systems temperatures needed in the proposed disaggregation methodology. In this regard, this methodology may hold promise of wide spread acceptance.

CONCLUSIONS

A methodology to disaggregate sensible and latent cooling from total cooling was developed and tested on two buildings. Although this methodology was illustrated for two DDCV systems, it can be readily modified and applied to a building with a different type of HVAC system.

The major benefit of this methodology is better understanding of the sensible and the latent fractions in the total cooling energy use. Future work would involve integrating this methodology along with statistical regression models.

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NOMENCLATURE

c_p = specific heat of air at constant pressure (Btu/lbm/F)

$\dot{m}_t$ = total mass flow rate (lbm/hr)

$\dot{m}_c$ = cooling mass flow rate (lbm/hr)

$\dot{m}_h$ = heating mass flow rate (lbm/hr)

T_c = cooling coil leaving air dry-bulb temperature (F).

T_h = heating coil leaving air dry-bulb temperature (F)

T_m = mixed air dry-bulb temperature (F)).

T_{amb} = outdoor air dry-bulb temperature (F)

T_r = mean return air temperature (F)

T_z = mean indoor air dry-bulb temperature (F)

$T_{z,s}$ = zone supply air dry-bulb temperature (F)

$\dot{q}_l$ = total building latent cooling (Btu/hr)

$\dot{q}_{c,s}$ = total building sensible cooling (Btu/hr)

$\dot{q}_{i,s}$ = total building internal sensible cooling load (Btu/hr)

$\dot{q}_{ven,s}$ = sensible ventilation load (Btu/hr)

$\dot{q}_{z,s}$ = sensible envelope load w/o ventilation (Btu/hr)

$\dot{q}_z$ = sensible envelope load with ventilation (Btu/hr)

U_o = overall heat transmission coefficient of envelope component (Btu/F)

w_o = outdoor air specific humidity (lbm/lba)

w_r = average return air specific humidity (lbw/lba)