ABSTRACT

The energy consumption in a building is affected by many parameters including the occupancy, equipment, schedule time, HVAC systems and outside environment conditions. Currently, the outside air dry-bulb temperature ($T_{OA}$) is the primary variable used in the data driven analysis for building energy use, including development of energy consumption models and measurement of savings. The measured building energy data analysis based on the variable of $T_{OA}$ has the drawback of overlooking several effects such as humidity, wind and solar.

The application of outside air enthalpy ($h_{OA}$) on a methodology name as “Energy Balance” for screening building energy data to study the influence of outside air humidity on building energy analysis has been presented in this paper. The variable of $h_{OA}$ has been implemented in a developed screening tool, which is the application of first law energy balance, to analyze the building energy use. The energy balance load ($E_{BL}$) for a whole building, which is the difference between the heating requirements plus the electric gain and the cooling load, has been presented by the two variables of $h_{OA}$ and $T_{OA}$, respectively. A design of experiment process is conducted to study the linear relations for the $E_{BL}$ as the function of $h_{OA}$ and as the function of $T_{OA}$. The comparison results lead the conclusion that the $E_{BL}$ in the high temperature range could be better presented with the application of $h_{OA}$ instead of $T_{OA}$. The energy analysis for buildings located in hot and humid climate would be better performed by using $h_{OA}$.

INTRODUCTION

The methodology of energy balance load has been proposed as a tool for screening building energy data which are separately recorded according to individual heating, cooling and electricity consumptions (Shao and Claridge, 2006). Although different air handle units (AHU) have different energy use patterns on individual heating and cooling, the air side simplified simulation shows that the defined $E_{BL}$ has the similar pattern for four basic AHUs. (CVRH: single duct constant air volume with terminal reheat; DDCV: dual duct constant air volume; DDVAV: dual duct variable air volume; and SVAV: single duct variable air volume) (Shao, 2005). The methodology of energy balance load provides the prospect application in the analysis of energy use for buildings having various AHUs. This methodology has been implemented into energy use analysis for quality assurance of the energy use data for buildings on the Texas A&M University campus (Baltazar et al., 2007).

It was found the slope and intercept of the defined $E_{BL}$ is changed with buildings. It is necessary to further study the effects of parameters and building functions on the $E_{BL}$ behaviors. Generally, the outside air temperature has been used to study the $E_{BL}$ behaviors. However, the pattern for $E_{BL}$ in the high temperature range has less linearity with the $T_{OA}$.

This paper presents the analytical study of the behaviors for $E_{BL}$ as function of $T_{OA}$ and $h_{OA}$. The slope and cross point of the $E_{BL}$ have been investigated through simplified air side model simulation, the analytical model, and validation by actual energy use data. The parameters effects have also been demonstrated using the method of design of experiments (DOE) to characterize the various effects of parameters. In order to improve the analysis of building consumption in high temperature, the enthalpy of outside air is used in study the behaviors of $E_{BL}$. Additionally,
the paper illustrates the application of $h_{OA}$ to analyze the energy data in summer.

**ANALYTICAL STUDY OF $E_{BL}$**

The energy balance load ($E_{BL}$) is defined from the whole building thermodynamic model based on the analytical redundancy (Shao and Claridge, 2006). The equation to represent the $E_{BL}$ is expressed as:

$$E_{BL} = W_{bele} + W_{heat} - W_{cool}$$

$$= - (Q_{Sol} + Q_{Air} + Q_{Con} + Q_{Occ})$$ (1)

Where $W_{bele}$ is the whole building electricity use for lighting and equipment in the building, $W_{heat}$ is the input heating to maintain the conditions in a building, and $W_{cool}$ is the input cooling to maintain the conditions in a building. $Q_{Sol}$ is the solar heating gain, $Q_{Air}$ is the ventilation and infiltration air via doors, windows and air handling units, $Q_{Con}$ is the heat transmission through the building structure, and $Q_{Occ}$ is the heating gain from occupants.

**Slope of the $E_{BL}$ as the function of $T_{OA}$**

Eqn. 2 indicates that the slope of $E_{BL}$ as a function of $T_{OA}$ depends on the amount of intake outside air and the $UA$ values.

$$E_{BL} = W_{bele} - W_{heat} - W_{cool}$$

$$= - (Q_{Sol} + Q_{Air} + Q_{Con} + Q_{Occ})$$

$$= - (Q_{sol} + V_{OA}C_{P}(T_{OA} - T_{j}) + \rho \frac{V_{OA}}{C_{V}^{OA}}(w_{OA} - w_{j}))$$

$$+ (Q_{Air} + V_{OA}C_{P}(T_{OA} - T_{j}) + Q_{Occ})$$

$$+ (Q_{heat} + V_{OA}C_{P}(T_{OA} - T_{j}) + Q_{Occ})$$

$$+ (Q_{cool} + V_{OA}C_{P}(T_{OA} - T_{j}) + Q_{Occ})$$ (2)

**Figure 1** Plots of energy balance load vs. outside air temperature with the variation of Intake outside air value (a), and the $UA$ value (b)

**Figure 2** Plots of energy balance load vs. outside air temperature for three different buildings using the daily data (A) and bin data (B)

Figure 1 shows simulation results of the slope change with the change of the value of intake outside air and the $UA$ value in the CVRH system (a). change of the value of intake outside air; (b). change of the $UA$ value. The same results have been achieved in the other three systems (DDCV, DDVAV, and SDVAV). Figure 2 shows the plot of energy balance load vs. outside air temperature ($E_{BL}$ vs. $T_{OA}$) using the actual data for three buildings with difference
functions ((a) using the daily data; (b) using the bin data). The value of $E_{BL}$ in Figure 2 is normalized with the area of a building with the unit of Btu/ft²/day. The slope of $E_{BL}$ in building with the function of laboratory is steeper than other two buildings which are library and residence hall, respectively.

**Cross point temperature in the $E_{BL}$**

The cross point temperature is defined as the temperature at the $E_{BL}$ equal to zero. Eqn. 3 shows the explanation of the items of $Q_{Air}$, and $Q_{Conv}$.

$$Q_{Air}=Q_{Air,Lat}+Q_{Air,Lat}$$

$$=V_{OA}C_{p}(T_{OA}-T_2)+(\rho h_{fg}V_{OA}w_{OA}w_{OA})$$

$$Q_{Conv}=UA(T_{OA}-T_2)$$

Substitute Eqn. 3 into Eqn. 1, Eqn. 4 has been achieved:

$$E_{BL}=(\text{WbHeat}-\text{WbCool})$$

$$=-Q_{Air}+V_{OA}C_{p}(T_{OA}-T_2)$$

$$+Q_{Air,Lat}+UA(T_{OA}-T_2)+Q_{Occ}$$

(4)

The boundary condition of $E_{BL}=0$ occurred at the cross point temperature,

$$E_{BL}=-Q_{Air}+V_{OA}C_{p}(T_{OA}-T_2)+Q_{Air,Lat}$$

$$+UA(T_{OA}-T_2)+Q_{Occ}=0$$

(5)

Rearrange the Eqn.5:

$$T_{OA}=T_2-\frac{Q_{Air}+Q_{Air,Lat}+Q_{Occ}}{V_{OA}/C_{p}+UA}$$

(6)

From the Eqn. 6, it could be drawn the conclusion that the cross point temperature is always lower than the zone temperature.

**Application of enthalpy ($h_{OA}$) in the $E_{BL}$ methodology**

Figure 3 shows the energy balance sensible load and latent load as the function of $T_{OA}$ using the simplified air side model simulation. The figure shows that the energy balance sensible load has the linear relationship with $T_{OA}$, but the energy balance latent load doesn’t have the linear relationship with $T_{OA}$. Because of this phenomena, the energy balance pattern didn’t have the clear linearity relationship with $T_{OA}$ when the latent load existed in high temperature, as shown in Figure 4 (a), but Figure 4 (b) shows a better linear behaviors when the enthalpy of outside air is applied to present the pattern of $E_{BL}$.

Following derived equation confirmed that the $E_{BL}$ has more linear behaviors as the function of enthalpy.

$$h = c_{pa}T_d + w (h_{g,ref} + c_{pw}T_d)$$

(7)

$c_{pa}$: Specific heat of dry air

$T_d$: Dry bulb temperature

$c_{pw}$: Specific heat of superheated water vapor

$h_{g,ref}$: Enthalpy of water vapor at appropriate reference temperature

$w$: Humidity ratio

$$E_{BL}=-V_{OA}C_{p}T_{OA}+(V_{OA}C_{p}+UA(T_{OA}-T_2)+Q_{Air}+$$

$$+Q_{Air,Lat}+UA(T_{OA}-T_2)+Q_{Occ})$$

$$=-[V_{OA}C_{p}T_{OA}+(\rho h_{fg}V_{OA}w_{OA})]$$

$$+[V_{OA}C_{p}+UA(T_{OA}-T_2)+Q_{Air}+$$

$$+Q_{Air,Lat}+UA(T_{OA}-T_2)+Q_{Occ})]$$

(8)

Compare the left of Eqn. 7 with the item of $(V_{OA}C_{p}T_{OA}+\rho h_{g,ref}V_{OA})$, the Eqn. 8 can be expressed with similar Eqn. 9.

$$E_{BL}=-[V_{OA}h_{OA}+(w_{OA}h_{g,ref})]$$

$$+(w_{OA}h_{g,ref})$$

$$=-h_{OA}+(w_{OA}h_{g,ref})$$

$$+(w_{OA}h_{g,ref}+UA(T_{OA}-T_2)+Q_{Air}+$$

$$+Q_{Air,Lat}+UA(T_{OA}-T_2)+Q_{Occ})]$$

(9)

The Eqn. 9 indicates that $E_{BL}$ as a function of $h_{OA}$ with the slope of

$$k = -(V_{OA}C_{p}+UA/C_{pa}+w_{OA}C_{pw})$$

and the interception of

$$b = (V_{OA}h_{g,ref}+UA/C_{pa}+w_{OA}h_{g,ref})$$

$$+UA(w_{OA}h_{g,ref}+UA/C_{pa}+w_{OA}h_{g,ref})$$

$$-\rho h_{OA}V_{OA}w_{OA}(Q_{Air}+Q_{Occ}+\rho h_{g,ref}V_{OA}w_{OA})$$
Figure 3 The simplified air side model simulation results of (a) Energy balance sensible load vs. Outside air temperature and (b) Energy balance latent load vs. Outside air temperature for the four basic AHUs.

Figure 4 The simplified air side model simulation results of (a) Energy balance load vs. Outside air temperature and (b) Energy balance load vs. Outside air enthalpy for the four basic AHUs.

Figure 5 (a) shows the plot $E_{BL}$ and energy use of electricity (ELE), chilled water (CHW) and heating hot water (HHW) as the function of $T_{OA}$ and Figure 5 (b) shows the plot $E_{BL}$ and energy use of electricity (ELE), chilled water (CHW) and heating hot water (HHW) as the function of $h_{OA}$ using the daily consumption data. Figure 6 show the similar plots to Figure 5 with the bin data.

Figure 5 (a) Plot of the $E_{BL}$, energy use of ELE, CHW and HHW vs. OA temperature (b) Plot of the $E_{BL}$, energy use of ELE, CHW and HHW vs. OA Enthalpy in a building using daily data.
FACTORS EFFECTS INVESTIGATION FOR THE $E_{BL}$

The method of full factorial design was used to study the effects of input parameters on $E_{BL}$ behaviors. A factorial design is widely used when there are several factors of interest in the experiments. In such designs factors are varied together. Specifically, with a factorial experiment, all possible combinations of the levels of the factors are investigated in each complete trial or replicate of the experiment. The effect of a factor is defined as the change in response produced by a change in the level of the factor. Five parameters are intake OA ratio, cold deck temperature, zone temperature, $UA$ value, and occupant density. In this factorial design, all five factors have two levels, denoted by “-1” and “+1”. Table 1 shows the set point for the parameters.

<table>
<thead>
<tr>
<th>Table 1 Parameter level for factor design</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1</td>
</tr>
<tr>
<td>OA Ratio</td>
</tr>
<tr>
<td>$T_{CL}$</td>
</tr>
<tr>
<td>$T_z$</td>
</tr>
<tr>
<td>$UA$</td>
</tr>
<tr>
<td>Occupant density</td>
</tr>
</tbody>
</table>

The corresponding effects of factors are analyzed by the normal probability plot of the effect and the Pareto charts. The normal probability plot of the effect estimates is a very helpful method in judging the significance of factors in a $2^5$ experiment, especially when many effects are to be estimated. If none of the effects are significant, then the estimates will behave like a random sample drawn from a normal distribution with zero mean, and the plotted effects will lie approximately along a straight line. Those effects that do not plot on the line are significant factors. (Montgomery and Runger, 2004) In the normal probability plot of the effect, the x-axis represents the effects, and the y-axis represents the cumulative probabilities. The scale of y-axis is constructed in such a way that if the data points follow a normal distribution, the cumulative probabilities will plot as a straight line. For effects that are from a normal distribution with mean zero, the plot of the effects should approximate a straight line with the line passing through the point ($x=0, y=0.5$). Significant effects much different from 0 will fall away from this line. Effects that are unusually small or large and fail to follow the straight line pattern are judged to be significant. (Ledolter and Swersey, 2007)

For the $2^5$ design in the operation, the number of estimated effects is $31 \times (2^5-1)$. The procedure for plotting normal probability of the effect is the following. First, the 31 effects have been ordered from small to large. The smallest among the 31 effects represents a cumulative probability between 0 and 1/31 and is assigned a cumulative probability (y-value) at the midpoint of that interval. The second smallest among the 31 effects represents a cumulative probability between 1/31 and 2/31 and is assigned a cumulative probability (y-value) at the midpoint of that interval. The third smallest among the 31 effects represents a cumulative probability between 1/31 between 2/31 and is assigned a y-value at the midpoint of that interval. The third smallest effect is assigned a cumulative probability at the midpoint of the interval 2/31 to 3/31, and so forth. In general, with $m$ effects, the $i$th smallest effect is plotted at a cumulative probability of ($i-0.5)/m$. (Ledolter and Swersey, 2007)
The software Minitab was used to analyze the parameter effects on the slope and intercept of the simulation results. The scale on the cumulative probability (y-axis) in the normal probability of the effect, such as Figure 7, Figure 8, Figure 9 and Figure 10, is not linear. This is where the normal distribution comes into play.

In the normal probability plot of the effect, the insignificant effects and significant effects have been distinguished by fitting a straight line to the middle portion of the graph. The value of Lenth’s pseudo standard error (PSE) (Lenth, 1989) is also added in normal probability plot in Minitab. The pseudo standard error (PSE) is defined as:

\[ PSE = 1.5 \times \text{median} |m_i| \]

The Pareto chart is a special type of bar chart where the values being plotted are arranged in descending order. In Minitab, the line is drawn at the margin of error (ME) on the Pareto chart. The margin of error is defined as:

\[ ME = t(\alpha/2, n) \times PSE \]

To analyze the parameter’s effect on energy balance load, it is assumed the energy balance load variable has an approximately linear relationship either \( T_{OA} \) or \( h_{OA} \) according to the simplified air side model simulation results. Generally, the relationship can be expressed as:

\[ y = k_1x + k_2 \]

Figure 7 and Figure 8 show the parameter effects on the \( EBL \) when the \( T_{OA} \) is used in presenting the function. Figure 7 show the plot of the parameter effects on the slope (variable: \( k_1 \), (a): the normal probability plot; (b): the Pareto plot.) Those plots show that the outside air ratio and the UA values have the significant negative effect on the slope while the cold deck temperature has the significant positive effect on the slope. Other factors (zone temperature and occupant density) have fewer effects on the slope of the energy balance load. Figure 8 shows the plot of the parameter effects on the intercept (variable: \( k_2 \), (a): the normal probability plot; (b): the Pareto plot). The effects of factor A (OA ratio) and D (UA value) are far away from the normalized line. The plots indicate the OA ratio and UA value have the highest influences on the intercept of the assumed regression line.

<table>
<thead>
<tr>
<th>Effect</th>
<th>Effect Type</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>A  OA Ratio</td>
<td>Significant</td>
<td>80</td>
</tr>
<tr>
<td>B  Outside Air Ratio</td>
<td>Significant</td>
<td>70</td>
</tr>
<tr>
<td>C  Zone Temp (TC)</td>
<td>Not Significant</td>
<td>50</td>
</tr>
<tr>
<td>D  UA Value</td>
<td>Significant</td>
<td>30</td>
</tr>
<tr>
<td>E  Occupant Density</td>
<td>Not Significant</td>
<td>10</td>
</tr>
</tbody>
</table>

Figure 7 (a) Parameters effects on the slope (x-T_{OA}, Y-EBL) and (b) Pareto chart of parameters effects on the slope (x-T_{OA}, y-EBL)

<table>
<thead>
<tr>
<th>Effect</th>
<th>Effect Type</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>A  OA Ratio</td>
<td>Significant</td>
<td>50</td>
</tr>
<tr>
<td>B  Outside Air Ratio</td>
<td>Significant</td>
<td>40</td>
</tr>
<tr>
<td>C  Zone Temp (TC)</td>
<td>Not Significant</td>
<td>20</td>
</tr>
<tr>
<td>D  UA Value</td>
<td>Significant</td>
<td>15</td>
</tr>
<tr>
<td>E  Occupant Density</td>
<td>Not Significant</td>
<td>10</td>
</tr>
</tbody>
</table>

Figure 8 (a) Parameters effects on the intercept (x-T_{OA}, y-EBL) (b) Pareto chart of parameters effects on the intercept (x-T_{OA}, y-EBL)
Alternative analysis is using the $h_{OA}$ instead of $T_{OA}$ for analysis of parameters effects on energy balance load. Figure 9 shows the plot of the parameter effects on the slope (variable: $k_1$, (a): the normal probability plot; (b): the Pareto plot). Similar to the plots of parameter effects using $T_{OA}$, it is shows that the outside air ratio and $UA$ value have the significant negative effect on the slope while the cold deck temperature has the significant positive effect on the slope. Other factors (zone temperature and occupant density) have fewer effects on the slope of the energy balance load. Additionally, the correlative items are distributed along the normalized line. It implies that the effects of the correlative items could be neglected in the engineering application. Figure 10 shows the plot of the parameter effects on the intercept (variable: $k_2$, (a): the normal probability plot; (b): the Pareto plot). It is obvious that the outside air ratio and the $UA$ value have the significant positive effect on the intercept. It presents that more conclusive results of parameter effects would be drawn by using the enthalpy in analysis instead of $T_{OA}$ based on the Figure 10, which shows that fewer items are marked having significant effects on the intercept of the energy balance load.

**APPLICATION OF $E_{BL}$ IN THE ENERGY DATA QUALITY ASSURANCE**

The methodology of the $E_{BL}$ have been applied to analyze the energy data to fulfill the quality assurance of utility bills (Baltazar et al., 2007). It is has been approved to be an effective data quality screening method for buildings having metering data for electricity, heating and cooling consumption. The methodology of the $E_{BL}$ as a function of $T_{OA}$ has the limitation in analysis of the summer data because of the high temperature and limited data range. Since the latent load in summer is larger than that in other seasons, and the latent load also varied with the buildings, it is difficult to analyze the energy data in one month in summer. Application of $h_{OA}$ in presenting $E_{BL}$
for summer data has the advantage in better representative patterns of building energy use than using the $T_{OA}$. Figure 11 shows the plot of $E_{BL}$ for three buildings on campus during August 2007 (a: $E_{BL}$ as a function of $T_{OA}$. b: $E_{BL}$ as a function of $h_{OA}$). The cross point temperature in $E_{BL}$ as function of $T_{OA}$ has the large range from negative to positive value. It is very hard to use the slope and intercept to apply the methodology of the energy balance in the data quality assurance. With the application the $h_{OA}$ in analysis of $E_{BL}$, the ranges of slope and intercept have been narrowed down. The equations to present the $E_{BL}$ pattern have been generated in Figure 11 (a) and (b). It shows that the linearity of $E_{BL}$ could be expressed better through $h_{OA}$ in stead of $T_{OA}$ in summer.

Figure 12 shows the energy use (ELE, CHW and HHW) and energy balance load for a office building during summer in College Station, TX ((a): the $E_{BL}$ and energy consumptions as a function of the $T_{OA}$; (b): the plot of $E_{BL}$, energy consumptions as a function of the $h_{OA}$). From the plot of Figure 12 (a), it is very hard to detect the failure in the consumption for the building since the data is drawn on a scale that may make the slope difficult to notice. Energy consumption trends are also correct. The bin data then was grouped to analyze the energy use for the building as shown in Figure 13. The linear model equation for the $E_{BL}$ shown in Figure 13 (b) has the negative x-intercept. That means that the building balance condition is at very low enthalpy. It indicates that there are some errors in the energy consumption. After further check, it was found that the CHW flow meter has wrong readings.
SUMMARY AND CONCLUSIONS

The further study for the methodology of the Energy balance load (E_BL) has been presented. The behaviors of the E_BL have been investigated by the analysis of the defined mathematical model of whole building energy balance. The simplified air side simulation has been conducted to study the patterns of E_BL. The actual measured energy use data has been applied to prove the conclusion of analytical study and simulation results. The factor effects analysis through the experimental design lead the conclusion of that the outside intake air volume and the UA value have the most negative effects on the slope of the E_BL pattern; while the cold deck temperature has the most significant positive effect on the slope of the E_BL pattern.

The behaviors E_BL have been studied using the variable of beside the T_OA. Analysis of E_BL as a function of h_OA have the advantage to present the energy data in high temperature since the latent load effect can be represented though the variable of enthalpy instead of the temperature. The E_BL has a better liner relationship to the h_OA than the T_OA. Using enthalpy in E_BL analysis for energy use data provided a beneficial approach to analyze the energy data in summer. The application of the E_BL as the function of h_OA to analyze the summer data for actual buildings has been presented. An example of the methodology of enthalpy for E_BL analysis applied to detect the failure of metering data of energy consumption has been also illustrated.

REFERENCES


Shao, X., (2005). First Law Energy Balance as a Data Screening Tool, M.S. Thesis, Mechanical Engineering Department, Texas A&M University, College Station, TX, May.