ANALYSIS OF COOLING REGRESSION MODELS FOR HOT AND HUMID CLIMATES BASED ON “OPERATIONAL EFFECTIVE ENTHALPY”

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ABSTRACT

Whole-building energy savings determination for energy efficiency projects is based on procedures established in the International Performance Measurement and Verification Protocol (IPMVP, 2012), specifically Option C. Energy use baseline models are developed from a regression analysis of the measured baseline data. These models generally use one or more independent variables, such as outdoor temperature, degree days, and/or occupancy. In practice, the most common variable that is used for these models is the outside air temperature (OAT). However, it has been observed that cooling model accuracy degrades when the latent load accounts for a significant proportion of the overall cooling load. Other studies have used the outside air enthalpy (OAE) to study the influence of outside air humidity on building energy analysis. Ji, et al. [2008], for example, used outside air enthalpy as an independent variable in the study of “Energy Balance Load” characteristics for screening building energy data.

Based on the physical cooling process in heating ventilation and air conditioning (HVAC) systems, a new variable called Operational Effective Enthalpy (OEE) is proposed to model cooling consumption. This paper shows that a chilled water regression model using OEE as the independent variable has a significantly lower coefficient of variation of the root mean square error (CV-RMSE) and a higher coefficient of determination (R²) than a model based on either OAT or OAE. Examination of 12 case-study models and sensitivity analysis shows that for eight buildings with OAT CV-RMSE values ranging from 11.2% to 21.4%, OEE CV-RMSE values ranged from 5.8% - 9.0%. Corresponding R² ranges are 0.8829 – 0.9675 for OAT and 0.9655 – 0.9872 for OEE. The remaining four buildings where latent loads constitute a smaller fraction of total cooling load show a more modest improvement using OEE instead of OAT.

INTRODUCTION

The International Performance Measurement and Verification Protocol (IPMVP, 2012) Option C provides procedures to determine savings at the whole-facility level. One or more variables are usually used to determine a baseline model by regression analysis. Theoretically, all parameters which influence the building energy use should be included in a regression model. Since some of them are difficult to estimate in an actual building; they seldom appear explicitly as variables in regression models [Katipamula et al., 1998]. A number of studies have shown the benefit of multiple regression (MLR) analysis [Wu et al., 1992; Katipamula et al., 1994]. However, the most important environmental variables, such as outside air temperature, humidity and solar radiation, are often linearly related, which cause multicollinearity in the regression models as discussed by Ruch et al. [1993a] and Reddy et al. [1998]. Kissock et al. [1998] showed that the uncertainties of the regression coefficients may be so large that the model’s usefulness for predicting purposes is compromised. In practice, the outside air temperature (OAT) is the most common variable used for inverse modeling. The OAT as the sole independent regression variable can adequately
model energy consumption in residential building [Fels, 1986] and in some commercial buildings [Greely et al., 1990; Kissock et al., 1993, 1998; Ruch et al., 1992a, 1993b].

However, it has been found that some issues appear when OAT based regression models are applied on some buildings, especially for the chilled water energy consumption estimation. Figure 1 presents the plot of a typical pattern of chilled water consumption versus OAT for a building on the Texas A&M University campus in College Station, TX. In the plot, less linearity can be seen as the OAT increases since the latent cooling load cannot be represented totally by the OAT. This observation indicates that the models based on OAT might have an application limit. It could have an advantage when applied to a chilled water consumption dominated by sensible cooling. However, the model accuracy degrades when the latent load energy accounts for a significant proportion of the overall cooling load.

![Figure 1. Plot of chilled water consumption vs. OAT](image1)

This pattern analysis showed that the chilled water regression model has less linearity in both high OAT and low OAE regions. In this study, a model performance improvement in all ranges of outside temperatures and enthalpies is proposed based on a new appropriate independent variable which relates the operational conditions of the air-handling units (AHU) and the outdoor conditions.

**METHODODOLOGY**

**Background of Cooling Process in HVAC Systems**

In HVAC systems, air is typically cooled by passing it over a cooling coil. If the humidity ratio of mixed air is lower than that of conditioned space, only sensible cooling occurs. In this situation no latent load exists since dehumidification is not required except for the reduction of the dry-bulb outside air temperature. Otherwise, water from the air is condensed on the cooling coil and removed from the mixed air, producing latent load.
The moisture of mixed air consists of internal sources in the buildings and outdoor sources. The internal sources of moisture in the buildings include, among others, the respiration and transpiration from people and the evaporation from open water surfaces. Outdoor sources mainly come from outdoor air carried in by the HVAC system for ventilation. Reddy et al. [1995] clarified that the internal latent load contribution in most commercial buildings is usually smaller than that of the ventilation load even under low outdoor intake fractions – outdoor air fractions about 10% of the total building air flow. Additionally, the internal latent load is weather-independent. So it seems to be reasonable to treat internal latent load as a constant value related directly to the operation of the building, such as building type and occupancy. The internal latent load could be a constant value once the building is ready to operate and occupancy schedule is identified.

**New Variable: Operational Effective Enthalpy**

Based on the physical cooling process in HVAC systems, a new variable called “Operational Effective Enthalpy (OEE)” is proposed to model chilled water consumption, and it is defined as,

\[
OEE = h_{OE} = \text{sensible enthalpy} + (\text{latent enthalpy} - \text{reference latent enthalpy})^+ \\
= h_{sen} + (h_{lat} - h_{ref,lat})^+ \\
\text{(1)}
\]

where, the ( )^+ symbol indicate that the quantities in the parenthesis should be valid for positive values.

When \( h_{lat} > h_{ref,lat} \), the latent load exits because the condensation occurs on the cooling coil, OEE is given by,

\[
h_{OE} = h_{sen} + h_{lat} - h_{ref,lat} \\
\text{(2)}
\]

Otherwise, only sensible cooling takes place and no moisture removal occurs. Thus \((h_{lat} - h_{ref,lat})^+ = 0\), OEE is given by,

\[
h_{OE} = h_{sen} \\
\text{(3)}
\]

The reference latent enthalpy should be equal to the latent enthalpy at the air condition when latent loads began to appear.

The reference value can be estimated by analyzing the humidity control. ANSI/ASHRAE Standard 62–2010, Ventilation for Acceptable Indoor Air Quality, addresses the recommendations for humidity control: “Occupied space relative humidity shall be limited to 65% or less when system performance is analyzed with outdoor air at the dehumidification design condition (that is, design dew point and mean coincident dry-bulb temperatures) and with the space interior loads (both sensible and latent) at cooling design values and space solar loads at zero (Section 5.9.1)”. The U.S. Environmental Protection Agency (EPA) presents a similar recommendation: “One way to help prevent mold is to maintain low indoor humidity, below 60 percent relative humidity, ideally 30–50 percent, if

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**Figure 3. Schematic of SDVAV system**

Figure 3 is a schematic representation of the main components of a single duct variable air volume (SDVAV) system. To avoid mold growth in the conditioned space and meet the human comfort needs, during the cooling process of a HVAC system the dehumidification occurs only when the mixed air go through from Point 3 to Point 4. The moisture of mixed air is the mix of return air and outside air – ventilation air. As it was discussed above, the moisture of return air from the internal source in the building is weather-independent and considered as a constant value. In this study, to simplify the analysis, the moisture carried in by the ventilation air at point 1 is assumed as the only source causing the change of latent load.
possible.” Therefore, the cooling coil should be designed in such a way that the humidity ratio of air leaving the cooling coil is close to the middle of the allowable indoor air humidity ratio range [Reddy T.A. et al., 1995]. A typical cooling coil leaving air condition of 55°F (~13 °C) and 95% RH has a humidity ratio approximately equal to that of a zone conditioned at 74°F (24 °C) and 50% RH.

Besides the studies on the effect of the outside air humidity on the building energy use made by Ji et al. [2008] and Masuda, et al. [2009], Kissock et al. [1998] previously simulated hourly cooling coil load for constant air volume (CAV) and variable air volume (VAV) systems and found that there is a clear change-point at 55°F (~13 °C) where latent loads begin to appear. Therefore, the latent enthalpy value at 55°F and 95% RH was selected as reference latent enthalpy (h ref, lat).

**Change-Point Cooling Regression Model Using OEE**

Change-point models typically combine search methods and least-square methods to find the best fitting model of segmented or piecewise linear regression. It identifies the change-point of an independent variable – either temperature, enthalpy, or as in this case, the operational effective temperature, the corresponding energy consumption at that change-point, and the slopes with the lowest square error over the selected sample. More studies about different forms and application of regression models have been discussed by Ruch et al. [1992a, 1992b, 1993b], Kissock et al. [1993, 1998] and Reddy et al. [1997a, 1997b]. The general description for these models could be the four-parameter (4P) model which is expressed as following:

\[ E_c = \beta_1 + \beta_2 (X - \beta_4) + \beta_3 (X - \beta_4)^2 \]  

(4)

where \(X\) is any independent variable, either temperature or enthalpy for example.

When \(\beta_2=0\), the four-parameter model will be simplified to three-parameter model as equation (5).

\[ E_c = \beta_1 + \beta_3 (X - \beta_4) \]  

(5)

Adapting the change-point models to include the OEE in the energy estimation methodologies, the expressions become

\[ E_c = \beta_1 - \beta_2 (\beta_4 - h_{OEE}) + \beta_3 (h_{OEE} - \beta_4) \]  

(6)

When \(h_{lat} > h_{ref, lat}\), the latent load exits because the condensation occurs on the cooling coil, thus

\[ E_c = \beta_1 - \beta_2 [\beta_4 - (h_{sen} + h_{lat} - h_{ref, lat})] + \beta_3 [h_{sen} + h_{lat} - h_{ref, lat} - \beta_4] \]  

(7)

Otherwise, only sensible cooling takes place and no moisture removal occurs. Thus \((h_{lat} - h_{ref, lat})=0\), the OEE change-point model is,

\[ E_c = \beta_1 - \beta_2 (\beta_4 - h_{sen}) + \beta_3 (h_{sen} - \beta_4) \]  

(8)

Models of equation (7) and equation (8) can be combined into a single regression model using an indicator variable, \(I\).

\[ E_c = \beta_1 - \beta_2 [\beta_4 - h_{sen} + I(h_{lat} - h_{ref, lat})] + \beta_3 [h_{sen} + I(h_{lat} - h_{ref, lat}) - \beta_4] \]  

(9)

When \(h_{lat} > h_{ref, lat}\), \(I=1\), the cooling energy consumption is given by equation (7). Otherwise, \(I=0\), the cooling energy consumption is given by equation (8).

**APPLICATION OF OEE COOLING REGRESSION MODEL**

For testing purposes the OEE regression model was applied to estimate the cooling energy consumption for twelve buildings at Texas A&M University. The criterion used to select the most appropriate model is to maximize the goodness-of-fit using the simplest model or combination of models [Draper and Smith 1981]. In this study, the coefficient of variation of the root-mean-square error (CV-RMSE) and coefficient of determination (R²) are used. The R² and CV-RMSE for OAT, OAE, and OEE models for the analyzed twelve buildings are listed in Table 1.
Compared to OAT and OAE base regression models, the OEE base models statistical indices have dramatically improved for eight buildings and kept in the same level for the other four buildings as shown in Figure 4(a) and (b), respectively.

For eight buildings, the chilled water regression models using OEE as the independent variable had a significant improvement in all temperatures regions, compared to the models based on OAT. The CV-RMSE values decreased between 33% and 62%, with an average reduction of 51%. The models based on OEE also showed an improvement with respect to models based on OAE, on the order of 9% to 31%, with an average decrease of 22%. Similar trends were obtained for the coefficient of determination ($R^2$). Though, for four buildings no improvement on either CV-RMSE or $R^2$ was observed with the application of OEE model, showing that there is certain limit of application on this approach.

The OAE and OEE parameters were introduced into the cooling energy consumption modeling in order to solve the problem caused by latent load. As described previously the latent load is mainly from the ventilation latent load. Therefore, the application of OEE cooling regression modeling has its major advantage when is applied on buildings with large outside air intake fractions in hot and humid climates.

Table 1. Models statistic parameters using outside air temperature, enthalpy, and operational effective enthalpy as independent regression variable for twelve buildings of Texas A&M University

<table>
<thead>
<tr>
<th>Building List</th>
<th>OAT Model</th>
<th>OAE Model</th>
<th>OEE Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R^2$</td>
<td>CV-RMSE</td>
<td>$R^2$</td>
</tr>
<tr>
<td>#1811 Vet Med Research Addition</td>
<td>0.9139</td>
<td>18.0%</td>
<td>0.9785</td>
</tr>
<tr>
<td>#1530 Interdisciplinary Life Science</td>
<td>0.9372</td>
<td>11.2%</td>
<td>0.9633</td>
</tr>
<tr>
<td>#1197 Vet Research Building</td>
<td>0.9083</td>
<td>15.5%</td>
<td>0.9739</td>
</tr>
<tr>
<td>#1085 Small Animal Hospital</td>
<td>0.9111</td>
<td>12.6%</td>
<td>0.9588</td>
</tr>
<tr>
<td>#1507 Bio-Bio</td>
<td>0.9105</td>
<td>21.4%</td>
<td>0.9718</td>
</tr>
<tr>
<td>#1904 TIPS</td>
<td>0.9115</td>
<td>17.6%</td>
<td>0.9569</td>
</tr>
<tr>
<td>#386 Jack E. Brown</td>
<td>0.8829</td>
<td>20.1%</td>
<td>0.9637</td>
</tr>
<tr>
<td>#376 Chemistry Building Addition</td>
<td>0.9675</td>
<td>13.0%</td>
<td>0.9824</td>
</tr>
<tr>
<td>#468 Evans Library</td>
<td>0.8763</td>
<td>10.4%</td>
<td>0.7520</td>
</tr>
<tr>
<td>#682 Wisenbaker</td>
<td>0.8917</td>
<td>15.8%</td>
<td>0.8630</td>
</tr>
<tr>
<td>#1560 Student Rec Center</td>
<td>0.9240</td>
<td>12.4%</td>
<td>0.8788</td>
</tr>
<tr>
<td>#1194 Large Animal Hospital</td>
<td>0.9572</td>
<td>11.2%</td>
<td>0.9565</td>
</tr>
</tbody>
</table>
Figure 4. Chilled water consumption models for the buildings sample as a function of the OAT, OAE and OEE.

**SENSITIVITY ANALYSIS**

To further study the influence of the reference latent enthalpy on the model stability, an analysis with the different reference latent enthalpy was carried out, still keeping the relative humidity of cooling coil at 95%. The change of reference temperature in the range 35°F to 90°F was analyzed. Figure 5(a) presents the change in CV-RMSE with the reference temperature for the eight buildings, which OEE base models have dramatic improvement.

The result shows that the reference temperature with minimum CV-RMSE is in the range of 54°F to 62°F as shown in Table 2.

The difference between the minimum CV-RMSE and CV-RMSE with reference conditions of 55°F, 95%RH is less than 1%. This result indicates that it is appropriate to select latent enthalpy with 55°F, 95% RH as the reference latent enthalpy and the OEE regression model is stable.
Figure 5(b) presents the change in CV-RMSE with the reference temperature for the four buildings that the OEE base models have no improvement. The result shows that the minimum CV-RMSE appears at the high reference temperature, greater than 66°F. This indicates that the ventilation latent load might not account for a significant proportion of the overall cooling load. The designed outdoor intake fractions for the buildings in Figure 5(b) are below 15%. This fraction is much lower than that of buildings shown in Figure 5(a). The designed outdoor intake fractions for some buildings in Figure 5(a) are even higher than 80%. Confirming that the OEE cooling regression model has its major advantage when is applied on buildings with the large outdoor intake fractions in hot and humid climates.

![Graph](image)

**Figure 5. Sensitivity analysis for the variation of the reference temperature with 95% RH, for the twelve buildings sample.**

<table>
<thead>
<tr>
<th>Building List</th>
<th>CV-RMSE&lt;sub&gt;min&lt;/sub&gt;</th>
<th>R&lt;sup&gt;2&lt;/sup&gt; with CV-RMSE&lt;sub&gt;min&lt;/sub&gt;</th>
<th>T&lt;sub&gt;ref&lt;/sub&gt; with CV-RMSE&lt;sub&gt;min&lt;/sub&gt;</th>
<th>w (lb/lb) with CV-RMSE&lt;sub&gt;min&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1811 Vet Med Research Addition</td>
<td>6.8%</td>
<td>0.9874</td>
<td>54.0</td>
<td>0.0084</td>
</tr>
<tr>
<td>#1530 Interdisciplinary Life Science</td>
<td>6.6%</td>
<td>0.9777</td>
<td>55.0</td>
<td>0.0087</td>
</tr>
<tr>
<td>#1197 Vet Research Bldg</td>
<td>5.8%</td>
<td>0.9936</td>
<td>56.0</td>
<td>0.0091</td>
</tr>
<tr>
<td>#1085 Small Animal Hospital</td>
<td>7.8%</td>
<td>0.9792</td>
<td>54.5</td>
<td>0.0086</td>
</tr>
<tr>
<td>#1507 Bio-Bio</td>
<td>7.9%</td>
<td>0.9874</td>
<td>57.0</td>
<td>0.0094</td>
</tr>
<tr>
<td>#1904 TIPS</td>
<td>8.2%</td>
<td>0.9805</td>
<td>59.5</td>
<td>0.0103</td>
</tr>
<tr>
<td>#386 Jack E. Brown</td>
<td>7.7%</td>
<td>0.9848</td>
<td>57.0</td>
<td>0.0094</td>
</tr>
<tr>
<td>#376 Chemistry Building Addition</td>
<td>7.7%</td>
<td>0.9942</td>
<td>62.0</td>
<td>0.0113</td>
</tr>
<tr>
<td>#468 Evans Library</td>
<td>10.1%</td>
<td>0.8906</td>
<td>74.0</td>
<td>0.0172</td>
</tr>
<tr>
<td>#682 Wisenbaker</td>
<td>13.2%</td>
<td>0.9278</td>
<td>66.0</td>
<td>0.0130</td>
</tr>
<tr>
<td>#1560 Student Rec Center</td>
<td>12.4%</td>
<td>0.9237</td>
<td>77.5</td>
<td>0.0194</td>
</tr>
<tr>
<td>#1194 Large Animal Hospital</td>
<td>9.2%</td>
<td>0.9718</td>
<td>71.0</td>
<td>0.0155</td>
</tr>
</tbody>
</table>

Note: OEE reference temperature is associated to a 95% RH.

**CONCLUSIONS**

Based on the physical performance of the cooling process in HVAC systems, a new variable called Operational Effective Enthalpy (OEE) was proposed to model building chilled water consumption. Examination of 12 case-study models...
and sensitivity analysis showed that for eight buildings the chilled water regression models using OEE as the independent variable has a significant improvement in all temperatures regions, compared to the models based on OAT, the CV-RMSE decreased between 33% and 62%, with an average decrease of 51%. The models based on OEE also showed an improvement with respect to models based on OAE, on the order of 9% to 31%, with an average decrease of 22%. Similar trends were obtained for the coefficient of determination ($R^2$). The remaining four buildings where latent loads constitute a smaller fraction of total cooling load show a more modest improvement using OEE instead of either OAT or OAE. These results indicate the application of OEE cooling regression modeling could have a major advantage when it is applied on buildings with large outside air intake fractions in hot and humid climates.

ACKNOWLEDGMENTS

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REFERENCES


The United States Environmental Protection Agency (EPA), 2008, Mold Remediation in schools and Commercial Buildings, pp.3.