ABSTRACT
Optimum economic operation in a large power plant can cut operating costs substantially. Individual plant equipment should be operated under conditions that are most favorable for maximizing its efficiency. It is widely accepted that boiler load significantly affects boiler efficiency.

In the study reported here, the measured performance of a 300,000 lb/h steam boiler was found to show more dependence on ambient air temperature than on boiler load. It also showed an unexplained dependence on the month of the year that is comparable to the load dependence.

INTRODUCTION
The Texas A&M University central power plant is a combined heat and power (CHP) plant with a total net steam rating of 750,000 lb/h at 600 psig, 750°F superheated steam and a total electricity generation capacity of 36.5 MW. There are four gas-fueled steam boilers, three steam turbine generators, and more than a dozen chillers.

In 1985, Texas A&M University retained an engineering consultant to perform an energy study of the plant system. The study included performance testing of major plant equipment such as the boilers, steam turbine generators, and the absorption and centrifugal chillers. Using the study test results, mathematical models were created to represent energy production and consumption for each piece of power plant equipment. These models were later connected to build a computer program that simulated the entire power plant operation.

The boiler investigated in this paper is a D-type water-tube boiler installed in 1973, with a rated steam capacity of 300,000 lb/h at a design pressure and temperature of 600 psig and 750 °F, respectively. As noted in Figure 1, the boiler feed water is first preheated to around 250°F (process A - 0) and then pressurized by the feed water pump to 700 psig (process 0 - 1). The pressurized feed water is then heated (process 1 - 2), evaporated (process 2 - 3) inside the boiler drum and finally superheated (process 3 -4).

The original boiler efficiency model created from the consultant’s energy study is shown in Figure 2. This is a typical 2nd order performance curve such as can be seen in most existing literature [1][2]. According to this particular model, the boiler efficiency is maximized when the boiler steam load is around 230,000 lb/h.

Figure 1. Steam boiler thermodynamic process
BOILER EFFICIENCY DETERMINATION

The following data are available from the plant’s control system on a continuous basis: steam flow (in lb/h), feed water flow (in lb/h), natural gas flow (in std. ft³/h), combustion air flow (in std. ft³/h), stack oxygen concentration level (in %), stack incombustible (carbon monoxide) concentration level (in %) and stack flue gas temperature (°F).

The input-output method and the heat loss method are the two best-known methods for boiler efficiency calculation; the latter is applied in this study, as recommended by ASME [4]. According to the heat loss method, the overall boiler efficiency can be determined as [4]

\[\eta = \frac{1}{1 + L_{\text{dry}} + L_{\text{fuel}} + L_{\text{rad}} + L_{\text{wt}} + L_{\text{other}}}\]

where each of the boiler losses is described and calculated as below:

1) Dry flue gas loss - heat loss caused by elevated flue gas temperature

\[L_{\text{dry}} = C_p \times (AF \times \rho_{\text{air}} + \rho_{\text{fuel}}) \times (T_g - T_a) / \text{HHV}\]

where
- \(C_p\) - specific heat of flue gas, 0.24 Btu/lb-°F
- \(AF\) - actual air to fuel ratio, mole-air/mole-fuel.
- The air to fuel ratio can be determined from a flue gas analysis [5][6].
- \(\rho_{\text{air}}\) - air density under standard conditions.
- \(\rho_{\text{fuel}}\) - fuel density, 0.04575 lb/ft³
- \(T_g\) - flue gas temperature, °F
- \(T_a\) - ambient air temperature, °F
- \(\text{HHV}\) - fuel higher heat value, Btu/ft³

2) Fuel hydrogen and moisture loss - latent heat loss of H₂O produced in combustion

\[L_{\text{fuel}} = \frac{9B \times h_{\text{v}}}{W_f} \times \rho_{\text{fuel}} \times (h_{\text{v}} - h_{\text{aw}}) / \text{HHV}\]

where
- \(B\) - moles of hydrogen in 1 mole of fuel
- \(W_f\) - fuel molecular weight
- \(h_{\text{v}}\) - enthalpy of steam at partial pressure of vapor in flue gas (1 psia for simplicity) and temperature of flue gas, 1239.9 Btu/lb when flue gas temperature is 399 °F
- \(h_{\text{aw}}\) - enthalpy of water at ambient temperature, 65 Btu/lb at 97 °F

3) Air moisture loss - heat loss caused by moisture in combustion air

\[L_{\text{air}} = \rho_{\text{air}} \times W_f \times h_{\text{v}} \times (h_{\text{v}} - h_{\text{aw}}) / \text{HHV}\]

where
- \(W_f\) - combustion air humidity ratio, lb water per lb dry air
- \(h_{\text{v}}\) - enthalpy of saturated vapor at ambient air temperature, 1103.4 Btu/lb at 97 °F

4) Radiation loss (\(L_{\text{rad}}\)), blowdown loss (\(L_{\text{bd}}\)), and other losses (\(L_{\text{other}}\)) are assumed to be independent of boiler load, and are estimated as 0.015, 0.03 and 0.005 respectively [4].

Twelve months of hourly data (from January to December, 1999) were retrieved from the control system. Using the formulas described above, boiler efficiency and air-fuel ratio can be calculated for each of the data records retrieved. The calculated boiler efficiency data are shown in Figure 3. It is interesting to note that the efficiency data are almost evenly distributed in a range from 79% to 82%, with the corresponding boiler steam load similarly distributed between 100,000 and 200,000 lb/h. The efficiency characteristic shown in this figure is significantly different from the one shown in Figure 2 that is currently imbedded in the simulation program. In fact, Figure 3 indicates that either the boiler steam load has an insignificant effect on boiler efficiency or its influence is overshadowed by a much stronger factor.

BOILER EFFICIENCY DATA ANALYSIS

A closer look at the data in Figure 3 revealed noticeable shifts in boiler efficiency from month to month. This is more clearly demonstrated in Figure 4, where data for each month is individually marked. Only four months were chosen to show the clear stratification from month to month. As shown in this figure, boiler efficiency is generally higher in a summer month.
than in a winter (or spring) month, which indicates the possible involvement of outdoor temperature in the models.

To estimate the influence of air temperature on the boiler efficiency, the efficiency data were reproduced as a function of outdoor air temperature, as shown in Figure 5.

It is obvious that the boiler efficiency has a very strong positive correlation with outside air temperature, indicating air temperature is possibly a dominant factor in determining boiler efficiency, which is not reflected in the original model at all. The spread in boiler efficiency at a specific outdoor temperature may be caused by the variation in the boiler load.

To clarify the unique effect of outdoor air temperature on boiler efficiency, one can remove the possible influence of boiler load by displaying those data that have identical load conditions. Figure 6 shows the group of data with the boiler load within the range from 139,500 to 140,500 lb/h. A strong relationship between boiler efficiency and outside air temperature is demonstrated, though the scatter is only partially reduced.

Figure 5 together with Figure 6 conclusively demonstrates that the boiler efficiency is primarily a function of the outdoor air temperature, but is also affected by other secondary factors.
The influence of outside air temperature on boiler efficiency can be naturally explained. Under comparable conditions, more fuel heat is spent on heating combustion air when the outside air temperature is low; therefore, the boiler efficiency is decreased. Meanwhile, since the air density increases as the temperature decreases, meaning that for the same steam load, more (excess) air is introduced as combustion air in cooler weather than in warmer weather (provided that the volumetric air-fuel ratio is being maintained by the control system), which further decreases the boiler efficiency in colder weather.

Similarly, in order to evaluate the influence of steam load on boiler efficiency, the effect of the outdoor air temperature has to be eliminated first. That means the relationship between steam load and boiler efficiency should be evaluated under the same (or very close) outdoor air temperature conditions. One such observation was made by filtering all the data and leaving only those data records whose corresponding outdoor air temperatures fall into the range from 74.5°F to 75.5°F, as shown in Figure 7. This figure suggests that the overall boiler efficiency may be a weakly curved pattern as a function of the boiler load when outdoor air temperature is more or less constant, though it is not a very clear pattern. This pattern is consistent with the earlier hypothesis that the steam load influences boiler efficiency.

**BOILER EFFICIENCY MODEL**

Figure 5 suggests the boiler efficiency data might be modeled as a simple linear function of the outside air temperature in the form of

$$\eta = A + D \times T_{oa}$$

The best values for those coefficients can be determined from any readily available optimization routine, such as the "Solver" imbedded in Microsoft Excel. The mathematical equation for this model is determined as

$$\eta = 77.49 + 0.042 \times T_{oa}$$

The boiler efficiencies modeled by this equation, together with the original efficiency data are shown Figure 8. Even though the predicted data match the general pattern of the measured data, the scatter in the latter is not reflected. Some of the statistics associated with this model are:

- Average Error = 0.236%
- RMSE = 0.289 %
- $R^2 = 0.790$

![Figure 8. Boiler efficiency model as a function of outside air temperature](image)

At this point, it is natural to try to model the boiler efficiency based on the two influential factors - the outside air temperature and the boiler steam load. The general signatures shown in Figure 6 and Figure 7 suggest the model should involve a linear dependence on outdoor temperature and a second order dependence on the boiler load. The mathematic equation for this model is determined as

$$\eta = A + B \times T_{oa} + C \times T_{oa}^2 + D \times L$$

where $L$ is the boiler steam load.

![Figure 7. Boiler efficiency when outside air temperature is around 75 °F](image)
The comparison between the predicted boiler efficiencies by this equation and the original efficiency data are shown in Figure 9. Compared with the model shown in Figure 8, this model has only marginal improvement. There is still considerably more scatter in the measured data than in the predicted data. Some of the statistics associated with this model are:

Average Error = 0.232 (%)  
RMSE = 0.287 (%)  
$R^2 = 0.792$

The regression model generally fits the measured data well, but explains only 79% of the efficiency variation observed. The discrepancy between the model and the measurements suggests that there is at least one other factor influencing boiler efficiency in addition to the outside air temperature and the boiler load. This suggests another examination of the data as a function of time-of-year. The data of Figure 7 is re-constructed so that the data is further separated into groups according to the month the data points lie in, as shown in Figure 11 (only those data points occurring in January, April, May, and June are displayed to avoid data overlap).

Figure 9. Predicted and measured boiler efficiency vs. outside air temperature

Figure 10 shows the same comparison with regard to the boiler load. It shows that the model predictions cover the range of the observed data.

Figure 10. Predicted and measured boiler efficiency vs. boiler load

It is interesting to note that the efficiency data are still stratified on a monthly basis even though the effect of the outdoor air temperature has been eliminated. In fact, the efficiency data for each individual month shows a much clearer pattern than when they are mingled together. This stratification can only be explained with factors other than the outside air temperature and the boiler steam load that have been discovered so far. It looks like the specific month within which the boiler is operated has caused the unexplained stratification. It is desirable to see how well the measured efficiency data can be modeled with similar polynomial equations, only this time one model will be created for each month. Figure 13, for example, shows the model developed specifically for the May data where the model coefficients are:

$A = 73.8173, B = 0.05775, C = -0.00017, D = 0.03092$
The corresponding statistics for the regression are:

- Average Error = 0.08 (%)
- RMSE = 0.10 (%)
- \( R^2 = 0.91 \)

Boiler 11 efficiency model (May)

<table>
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<tr>
<th>Month</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>Avg. Error</th>
<th>RMSE1</th>
<th>RMSE2</th>
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<td>Jan</td>
<td>77.028</td>
<td>0.01282</td>
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<td>0.02433</td>
<td>0.160</td>
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<td>71.851</td>
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<td>0.03960</td>
<td>0.332</td>
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<td>79.873</td>
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<td>0.03145</td>
<td>0.202</td>
<td>0.246</td>
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<tr>
<td>Apr</td>
<td>74.820</td>
<td>0.03860</td>
<td>-0.00012</td>
<td>0.03446</td>
<td>0.117</td>
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<td>0.338</td>
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<tr>
<td>May</td>
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<td>0.080</td>
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<td>0.02574</td>
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CONCLUSIONS

Boiler efficiency modeling based on the measured operational data for a 300,000 lb/h boiler shows that the boiler efficiency is not only a function of boiler load, as the original model indicates, but is a stronger function of the outside air temperature. The newly created boiler efficiency model also shows interesting monthly behavior that cannot be fully explained at this time. The original boiler efficiency model implemented in the plant optimization program, as do those documented in many papers in the literature does not reflect boilers' practical operation correctly and therefore should be replaced by the newly developed models.

The direct impact of this finding is that for different weather conditions, the boiler might need to be loaded differently in order to maximize its efficiency. In a multiple boiler system, the optimized load distribution should be determined in the context of ambient weather conditions. The boiler performance data provided by boiler manufacturers needs to include a set of boiler performance curves corresponding to different weather conditions.
REFERENCES