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# OPERATIONAL PERFORMANCE EVALUATION OF BOILER 9 AT THE TAMU POWER PLANT AT COLLEGE STATION

**Submitted to the**
**Power Plant of Texas A&M University**
**by the Energy Systems Laboratory**

**Guanghua Wei**
**Bryan Veteto**
**Mingsheng Liu**

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## Executive Summary

As part of the engineering assistance project, the ESL staff worked with operating staff at the power plant: (1) to evaluate the boiler efficiency of boiler 9 by using combustion analysis; (2) to evaluate gas and steam meters by using measured air flow rate; (3) to identify air leakage through the pre-heater by balancing $O_2$ before and after the pre-heater; and (4) to correct air and steam metered data.

Boiler efficiency was measured to be 77 ± 2% when the load ratio was 59% on June 20, 1996. The boiler efficiency varied from 73% to 79% when the load ratio increased from 55% to 90%. It is recommended the load ratio should be maintained higher than 60% to maintain efficiency higher than 77%.

The measured gas consumption from Westinghouse agreed with the predicted value. It appears that the gas meter are now operating properly after the calibration. The actual air flow rate was 10 times higher than the meter measured data. The predicted steam production was 20% lower than the measured value which caused an unrealistic boiler efficiency value of 104%. A temporary correction factor of 0.797 is suggested until new steam meters can be installed.

The air leakage through air pre-heater was found to be 27% using an oxygen balance method and 29% using a carbon dioxide balance method. Over 579,000 kWh/yr electricity can be saved by reducing air leakage to the 10% level.

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# OPERATIONAL PERFORMANCE EVALUATION OF BOILER 9 AT THE TAMU POWER PLANT AT COLLEGE STATION

## 1. INTRODUCTION

As part of the engineering assistance project, the ESL staff worked with the operating staff at the power plant: (1) to evaluate the boiler efficiency of boiler 9 using a combustion analysis; (2) to evaluate gas and steam meters using measured air flow rates; (3) to identify air leakage through the pre-heater by balancing $O_2$ before and after the pre-heater; and (4) to make recommendations to correct air and steam metered data. The results can be used by the operation staff to evaluate the daily operation and improve the pre-heater operation, which can potentially reduce fan power consumption by 579,000 kWh/yr. This report presents the method and results.

## 2. GENERAL INFORMATION FOR BOILER 9

Boiler 9 was installed in 1962 with a rated capacity of 175,000 lbs/hr. The electric driven feedwater pump has a capacity of 468 GPM (234,300 lbs/hr). The supply air fan has a capacity of 63,750 CFM. A VFD is used to control the fan speed to accommodate the load change. The boiler is equipped with an air preheater to warm the air by using the flue gas. A metal wheel is used to transfer the waste heat to the incoming air. A superheater heats the steam after the steam leaves the drum (See Figure 1 for detail).

Boiler 9 is equipped with extensive metering devices to measure the boiler production and evaluate the performance. The key parameters measured are boiler feedwater flow and temperature, steam pressure and temperature, steam production, natural gas consumption, air flow, flue gas temperature, and $O_2$ level. These data were also recorded by the Westinghouse control system.

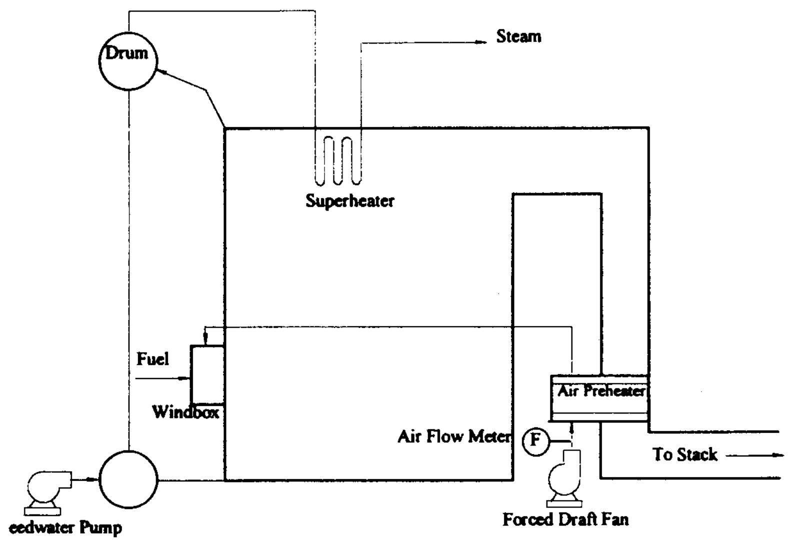


Figure 1: Systematic Diagram of Boiler 9

Based on the measured steam flow rate, the monthly average load ratio varied from 10% to 80%. Figure 2 presents the measured monthly average load ratio, maximum load ratio, and operation frequency. The boiler was operated 100% of the time from September 1995 to December 1995. The load ratio is defined as actual load divided by theoretical maximum load for the month, the load ratio varied from 65% to 125%. During January and February 1996, the boiler was used only 15% and 37%, respectively.

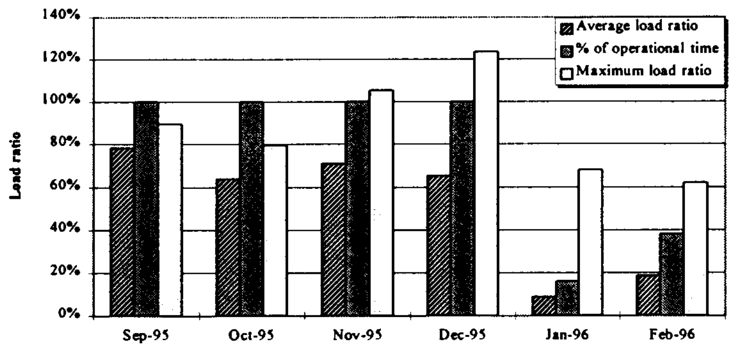


Figure 2: Monthly average and maximum load ratio and the operation frequency.

Figure 3 presents the boiler efficiency determined by the measured steam and the gas consumption from August 22,1995 through January 5,1996. Apparently, significant error exists in the measurement because the calculated "boiler efficiency" was higher than 100%. The gas meter was calibrated during February and March 1996, the old data was corrected by applying the new calibrated meter constant (See Appendix A for detail). The boiler efficiency was then calculated and the results are presented in Figure 4.

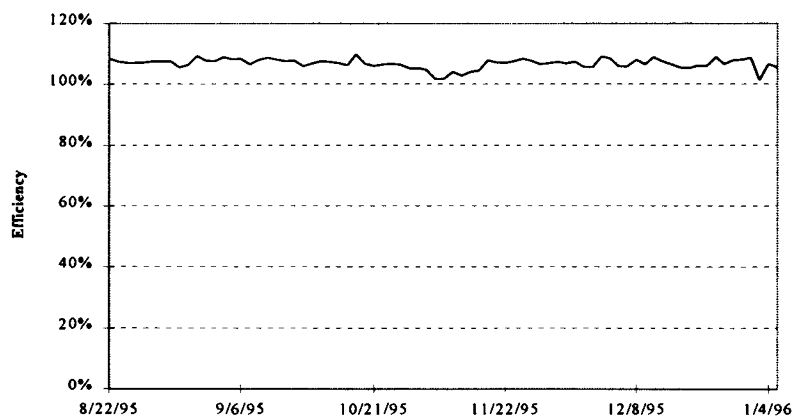


Figure 3: Daily average boiler efficiency (uncorrected).

After gas data correction, the calculated "boiler efficiency" was still higher than 90%, and exceeded 100% during some periods, which is impossible for this type of boiler. Therefore, it appears that significant metering errors still exist.

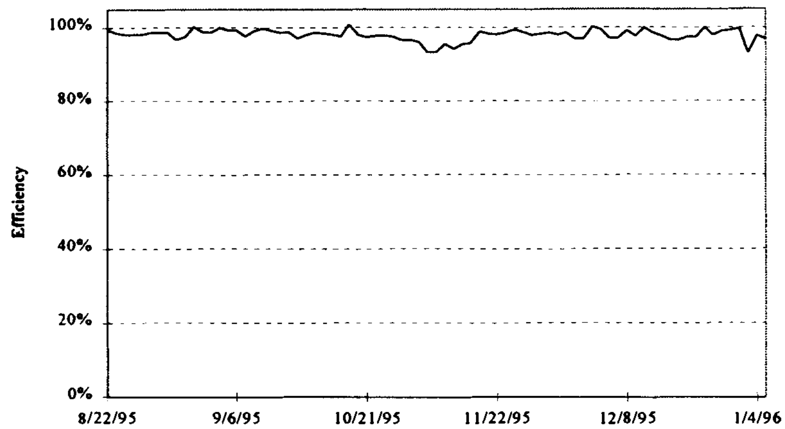


Figure 4: Daily average boiler efficiency (based on corrected gas flow rate).

# 3. BOILER EFFICIENCY EVALUATION

The boiler efficiency can be determined by measuring gas consumption and steam production. However, it was impossible to obtain accurate steam and gas data due to metering errors. In this study, the boiler efficiency was determined using a combustion analysis. The method and the results are presented below.

## 3.1 METHOD

Boiler efficiency can be determined by subtracting all the losses from a 100% efficient or an ideal system. The boiler losses include dry flue gas loss, fuel hydrogen loss, air moisture loss, radiation loss, blowdown loss, and other losses if there are any.

$$\eta = 1 - \text{dry flue gas loss} - \text{fuel hydrogen loss} - \text{air moisture loss} - \text{radiation loss}$$
$$- \text{blowdown loss} - \text{other losses}$$

The dry flue gas loss represents the sensible heat lost from the flue gas leaving the air preheater. It depends on the amount of excess air and flue gas temperature at the stack. Fuel hydrogen loss is due to the combustion of hydrogen. This produces moisture that leaves the air preheater as water vapor, therefore, the latent heat is lost. Moisture that is carried into the boiler by the combustion air is heated to the stack temperature, and the heat lost is called air moisture loss. Radiation loss is due to the heat loss from the hot boiler envelope to the ambient air. Blowdown loss represents the heat loss due to the blowdown of saturated water in the boiler drum in order to control the water quality. Other losses include incomplete combustion and other unaccounted for losses.

Generally, for gas-fired boilers, dry flue gas loss and the fuel hydrogen loss are the main sources of efficiency loss.

### 3.2 Measured Data and Results

It is necessary to measure flue gas composition to determine the dry flue gas loss, fuel hydrogen loss, air moisture loss, etc. A flue gas measurement was performed on June 20, 1996. The measured results are summarized in Table 1. Other boiler operation parameters were also recorded during the test period. The results are summarized in Table 2.

Based on the measured results, the heat losses were determined. The results are summarized in Table 3. The detailed analysis is attached in Appendix B.

Table 1: Flue gases analysis @ 2:25 pm , June 20, 1996.

| Measured by | $O_2$ (%) | CO (PPM) | $CO_2$ (%) | Stack temperature (°F) | Combustible (PPM) |
|---|---|---|---|---|---|
| Troy | 4.6 | 0 | 9.1 | 338.1** | 0 |

** Due to air preheater leakage, actual stack temperature was 399 °F. (see Appendix E)

Table 2: Westinghouse system data recorded for test period.

| Steam flow (lb/hr) | Steam temperature (°F) | Steam pressure (psig) | Feedwater flow (lb/hr) | Feedwater temperature ( °F) | Air flow (SCFH) | Fuel flow (SCFH) | Load |
|---|---|---|---|---|---|---|---|
| 102,776 | 724 | 601 | 95 | 260 | 169,075 | 109,296 | 59% |

Table 3: Summary of boiler losses.

| Item | Losses |
|---|---|
| Dry flue gas loss | 0.07 |
| Fuel hydrogen and moisture loss | 0.1073 |
| Air moisture loss | 0.0024 |
| Radiation loss | 0.015 |
| Blowdown loss | 0.030 |
| Other loss | 0.005 |

The boiler efficiency was determined to be 77 ± 2% (See Appendix B for details). It can be seen that the major losses are dry flue gas loss and fuel moisture loss, which account for 70% of the total losses.

## 4. EVALUATION OF GAS AND STEAM METERS ACCURACY

When the boiler efficiency is known, the gas consumption and the steam production can be determined by the following method.

Step 1: Determine the air to fuel ratio by flue gas analysis;

Step 2: Measure the total air flow to the boiler;

Step 3: The gas consumption is the air flow rate divided by air to fuel ratio;

Step 4: The steam production is the product of the gas consumption and boiler efficiency.

The accuracy of gas and steam meters were evaluated by comparing the measured and the predicted data. The critical items of the method are the accuracy of air flow measurement and the boiler efficiency.

Boiler 9 has a double intake variable frequency drive fan providing the combustion air. The schematic diagram of the fan is shown in Figure 5. A field test was carried out on June 20, 1996. The air dynamic pressures were measured at 15 points at each side of the inlet of the fan. The relative positions of the measuring points are also shown in Figure 5. Due to the constraints of the motor and shaft bearing, the dynamic pressure at the lower side was not measured. It was assumed to have the average dynamic pressures of the other three sides.

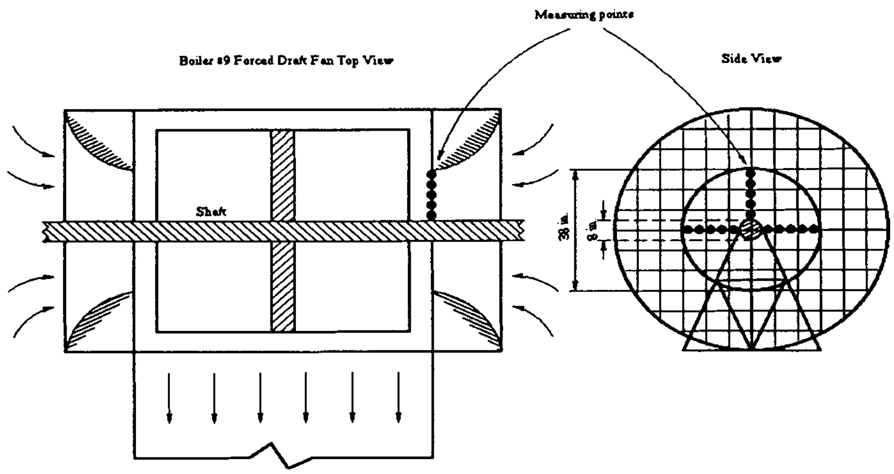


Figure 5: Schematic of forced draft fan of boiler 9

The dynamic pressures were measured by a standard pitot-static tube with a resolution of 0.01 in$H_2O$. The measured dynamic pressure varied from 0.1 in$H_2O$ to 0.5 in$H_2O$. The dynamic pressure was converted into air velocity with a range from 22 ft/s to 50 ft/s. The total air flow was determined to be 1928 KCFH with an error of 3.21% (See Appendix C for details).

According to the measured air to fuel ratio and the boiler efficiency, the gas consumption and the steam production were calculated. Since the heating value of natural gas for the test day was unavailable, the heating value was assumed to be 1045 Btu/SCF based on historical data from the Lone Star company. Table 4 compares the field measured air flow and predicted gas consumption and steam production with the meter measured data.

Table 4: Comparison of the field measured air flow and predicted gas consumption and steam production with meter measured data.

| | Air kCFH | Gas KCFH | Steam lb/hr | Efficiency |
|---|---|---|---|---|
| Field Measurement | 1928 | 108.6 | 81,922 | 77% |
| Meter Measured | 169 | 109.3 | 102,776 | 104% |
| Difference | 1759 | -0.7 | -20,854 | |
| Percentage difference | 1040% | -0.6% | -20.3% | |

It appears that the actual air flow rate was 10 times higher than the measured data from the Westinghouse system. The measured gas consumption agreed with the predicted value. It therefore seems that the gas meter is in good condition at the temperature and pressure levels experienced during the test. The predicted steam production was 20.3% lower than the measured value which caused an unrealistic boiler efficiency value of 104%.

## 5. DATA CORRECTIONS

Both steam and air flow data need to be corrected. The air flow can be corrected by a factor of 10. Although a correction factor of 0.797 for steam flow was identified under 59% of load condition, the correction factor has to be investigated carefully for other load conditions.

To correct the steam production under other load conditions, the following approaches were used. The first approach assumed a constant bias of 20,854 lb/hr regardless of the load ratio. In other words, the steam production was determined by subtracting 20,854 lbs/hr from the metered steam production. The boiler efficiency was then determined by this steam production and the measured gas consumption. A second approach assumed that the actual steam production was 20.3% lower than the measured steam production. In other words, the steam production was determined to be 79.7% of the metered production. Then, the boiler efficiency was determined by using this corrected steam production and the gas consumption. The results are shown in Figure 6.

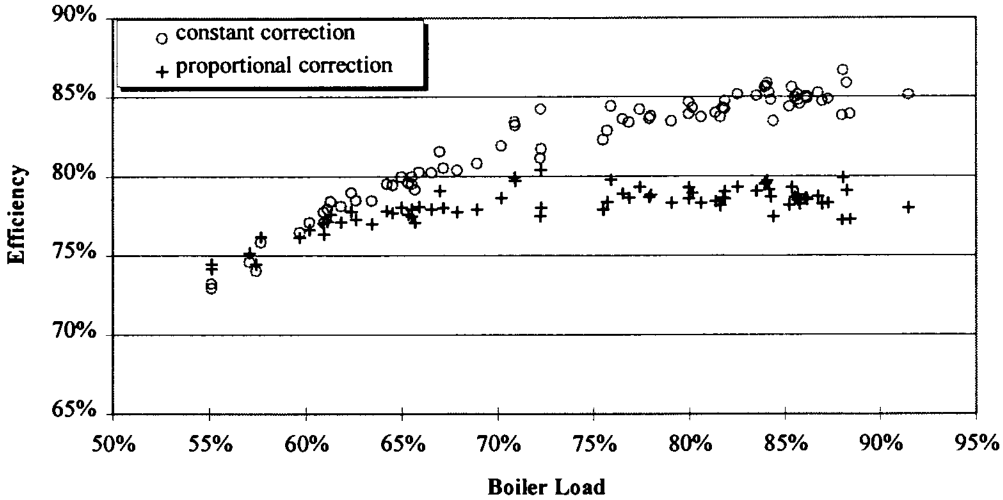


Figure 6: Boiler efficiency vs. load using constant and proportional steam corrections.

Figure 6 shows that when the constant steam flow rate bias was assumed, boiler efficiency increased more than 10% as the load varied from 60% to 90%. This is impossible for a gas fired boiler with nearly constant excess air. Thus this assumption was not used.

When the proportional bias was used, the boiler efficiency varied from 74% to 80% and was almost constant as the load varied from 65% to 90%. This trend is consistent with the manufacturer's curve. It appears that the steam flow meter should be corrected with a correction factor of 0.797±0.032 (See Appendix D for the uncertainty analysis).

In summary, the air flow rate meter reading has to be multiplied by a factor of 10, a multiplication factor of 0.797 should be applied to the steam meter, and the gas meter is accurate. However, gas meter data recorded before the calibration should be corrected by multiplying by a factor of 1.09. Figure 7 presents the corrected daily air flow, steam flow, and gas flow.

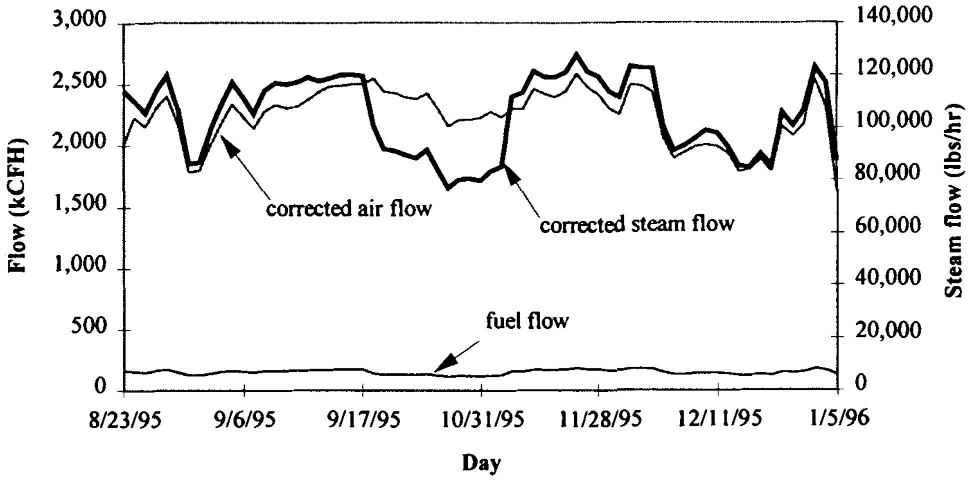


Figure 7: Corrected daily air, gas and steam flow rate for boiler 9.

## 6. AIR LEAKAGE THROUGH THE AIR PREHEATER

A Ljungstrom-type air preheater is used to preheat the incoming combustion air by the flue gas. Figure 8 presents the systematic diagram. A heavy metal wheel slowly rotates to transfer heat from the flue gas to the incoming air. The static pressure on the incoming air side is much higher than that of the flue gas side. Unfortunately, this leads to significant air bypass and consumes unnecessary fan power. When the incoming air bypasses to the flue gas side, the flue gas temperature decreases. The lower stack temperature due to air leakage gives a false indication that the boiler is operating efficiently.

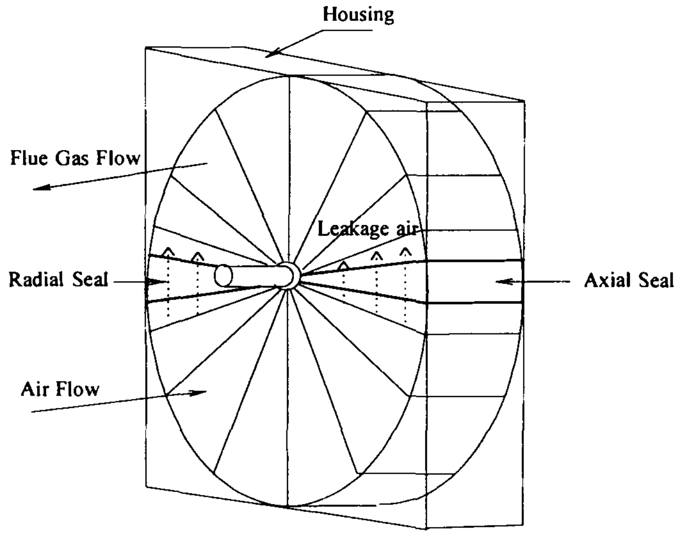


Figure 8: Schematic of regenerative air preheater

The air leakage can be determined by balancing the $O_2$ or $CO_2$ components before and after the pre-heater. The $O_2$ and $CO_2$ concentration in the flue gas and air can be measured by flue gas analyzer. Three flue gas analyses were taken. One before the air preheater, another at the stack outlet, the other one right after the air preheater. The oxygen concentration was much higher right after the preheater than at the stack outlet, which indicated that the gas sample right after the preheater was not thoroughly mixed. Thus, the gas composition at the stack outlet was used to calculate the air leakage rate. The leakage rate was found to be 27% using an oxygen balance method and 29% using a carbon dioxide balance method. Table 5 is a summary of the gas analysis before and after the air preheater. Appendix E is the University of Wisconsin's Engineering Equation Solver (EES) program used to calculate the leakage rate.

Table 5: Summary of gas analysis before and after the air preheater.

| | Before air preheater | After air preheater | Ambient air | Leakage rate |
|---|---|---|---|---|
| $O_2$ concentration | 4.6% | 8.9% | 21% | 27% |
| $CO_2$ concentration | 9.1% | 6.5% | 0% | 29% |

If the air leakage rate can be reduced from 27% to 10%, the fan power can be reduced to $(1 - 0.17)^3$ % = 57.2%, or 42.8% of the fan power can be saved. If the boiler is used at an annual average load of 70% , the potential electricity savings are:

$$270\text{hp}\times0.736\text{kW/hp}\times0.7^3\times0.428\times8760\text{hr/yr} = 579{,}090 \text{ kWh/yr}.$$

# 7. CONCLUSIONS

The boiler efficiency varied from 73% to 79% when the load increased from 55% to 90%. The load ratio should be maintained above 60%, or 100,000 lb/hr in order to obtain high efficiency.

The natural gas meter seems to be working properly after calibration. The air flow meter should be corrected by a factor of 10. The steam flow meter should be corrected by a factor of 0.797. The calculations in the Westinghouse air metering algorithm should be checked to determine what goes wrong. There is 27% air leakage in the air preheater. Seals for the air preheater should be inspected and replaced during the next scheduled maintenance. This can save 579,090 kWh/yr, or about $17,000/yr at $0.03/kWh.

## ACKNOWLEDGMENTS

Many people contributed to the completion of this work. We would like to thank Dr. Darren Habetz for his help in performing the test. Help from Troy, Roy, and Steve of the power plant are greatly appreciated. Thanks also to our colleagues, Jason Fleming, Eliezer Maldonado, and Timothy Giebler. Special thanks goes to Mr. Thomas Hagge, Associate Director for Utilities Physical Plant, for his enthusiasm and support in this project. We would also like to thank Jean Mahoney for her editing assistance.

# APPENDIX A: MEASURED GAS FLOW CORRECTION

Figure A1 shows the gas consumption versus Steam production for boiler 9 from August 1995 to March 1996. It can be seen that there are two distinct lines. The upper line corresponds to data recorded after the gas meter was calibrated in February 1996. Since the "as found" condition for the meter when it was calibrated was not available, and these two lines are parallel, the pre-calibration gas data was corrected by a factor of 1.09. The result is shown in Figure A2. As indicated, all data cluster around a narrow band. Thus the correction factor of 1.09 was assumed to be valid.

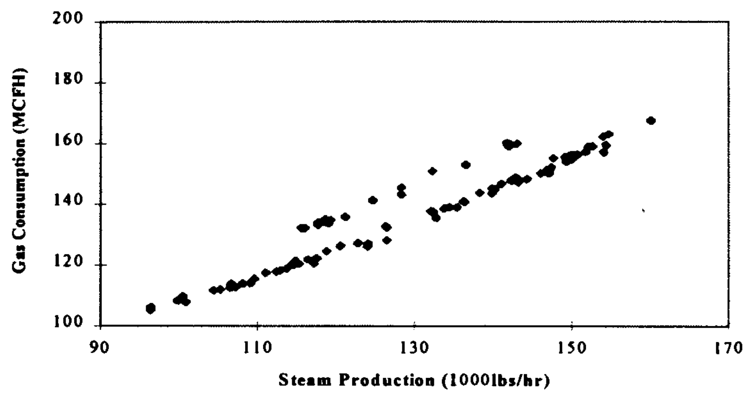


Figure A1: Relationship between gas consumption and steam production.

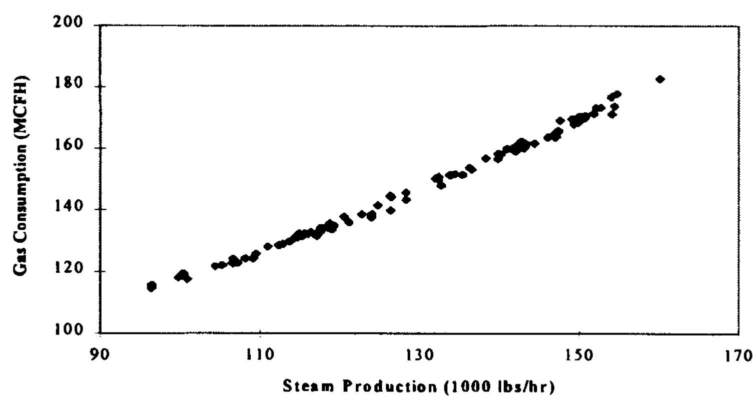


Figure A2: Relationship between corrected gas consumption and steam production.

# APPENDIX B: BOILER EFFICIENCY DETERMINATION

## 1. CHEMICAL FORMULA FOR NATURAL GAS:

$X_1C_{A1}H_{B1}+X_2C_{A2}H_{B2}+...+X_nC_{An}H_{Bn}+\alpha_1N_2+\alpha_2H_2O+\alpha_3O_2+\alpha_4C+\alpha_5H_2+\alpha_6S+\alpha_7CO_2$

For gas currently used in the power plant:

$0.9105CH_4+0.0557C_2H_6+0.0031C_3H_8+0.0001C_4H_{10}+0.0001C_6H_{14}+0.0089N_2+0.0216O_2$

## 2. THE EQUIVALENT HYDROCARBON:

$\alpha C_AH_B = \sum X_iC_{Ai}H_{Bi} = 0.9105CH_4+0.0557C_2H_6+0.0031C_3H_8+0.0001C_4H_{10}+0.0001C_6H_{14}$

Where

$\alpha$ = mole fraction of equivalent hydrocarbon fuel

$= 0.9105+0.0557+0.0031+0.0001+0.0001$

$= 0.9695$

A = number of atoms of carbon

$= \alpha^{-1}[0.9105+0.0557\times2+0.0031\times3+0.0001\times4+0.0001\times6]$

$= 1.0647$

B = number of atoms of hydrogen

$= \alpha^{-1}[0.9105\times4+0.0557\times6+0.0031\times8+0.0001\times10+0.0001\times14]$

$= 4.1293$

Thus,

$\alpha C_AH_B = 0.9695C_{1.0647}H_{4.1293}$

## 3. MOLECULAR WEIGHT OF $C_AH_B$:

$W_{CAHB}$=12A+B=12×1.0647+4.1293=16.9054 lb/lb-mole

## 4. MOLECULAR WEIGHT OF FUEL:

$$W_F = \alpha\, W_{CAHB} + \alpha_1 W_{N2+}\, \alpha_7 W_{CO2}$$

$$= 0.9695\times16.9054+0.0089\times28+0.0216\times44$$

$$= 17.5894 \text{ lb/lb-mole}$$

Specific heat of the fuel:

$$C_{P,F} = \frac{\sum Wi\alpha iC_{P,CAiHBi}}{W_F}$$

$$=(16\times0.9105\times0.532+30\times0.0557\times0.418+44\times0.0031\times0.59+58\times0.0001\times0.406$$

$$+86\times0.0001\times0.75+28\times0.0089\times0.248+44\times0.0216\times0.201)\div 17.5894$$

$$= 0.4998 \text{ Btu/lb-°F}$$

Density of the fuel

$$\rho_F = 0.61 \times 0.075 = 0.04575 \text{ lb/ft}^3$$

Enthalpy of formation of the fuel

$$h_f^0 = HHV - [169297(\alpha A+\alpha_7) + 61485(\alpha B)] \div W_F$$

$$= 1026 \div 0.04575 - [169297(0.9695\times1.0647+0.0216) + 61485(0.9695\times4.1293)]$$

$$\div 17.5894$$

$$= -1710.71 \text{ Btu/lb}$$

## 5. COMBUSTION EQUATION:

$$\alpha C_A H_B + \alpha_1 N_2 + \alpha_7 CO_2 + a(O_2 + 3.76N_2) \rightarrow (\alpha A + \alpha_7)CO_2 + 0.5\alpha BH_2O + (\alpha_1 + 3.76a)N_2$$

Oxygen balance gives

$$2a + 2\,\alpha_7 = 2(\alpha A + \alpha_7) + 0.5\alpha B$$

$$a = \alpha A + 0.25\alpha B = 2.033066$$

Theoretical air to fuel ratio isAF = 4.76a = **9.6773** mole-air/mole-fuel

## 6. DETERMINE THE EXCESS AIR:

$$\alpha C_A H_B + \alpha_1 N_2 + \alpha_7 CO_2 + (a+y)(O_2 + 3.76N_2)$$

$$\rightarrow (\alpha A + \alpha_7 - m)CO_2 + mCO + 0.5\alpha BH_2O + [\alpha_1 + (\alpha A + 0.25\alpha B)\times 3.76]N_2 + bO_2 + 3.76yN_2$$

Oxygen balance gives

$$\alpha_7 + \alpha A + 0.25\alpha B + y = \alpha A + \alpha_7 - m + 0.5m + 0.25\alpha B + b \Rightarrow b = y + 0.5m$$

Measured carbon monoxide concentration in the dry flue gas can be expressed as

$$CO\% = \frac{100m}{\alpha A + \alpha_7 - m + m + \alpha_1 + (\alpha A + 0.25\alpha B)\times 3.76 + y + 0.5m + 3.76y}$$

$$= \frac{100m}{8.90 + 4.76y + 0.5m}$$

thus,

$$m = \frac{(8.707 + 4.76y)CO\%}{100 - 0.5CO\%}$$

Measured oxygen concentration in the dry flue gas is

$$EO\% = \frac{100(y + 0.5m)}{\alpha A + \alpha_7 - m + m + \alpha_1 + (\alpha A + 0.25\alpha B)\times 3.76 + y + 0.5m + 3.76y}$$

$$= \frac{100(y+0.5m)}{8.90+4.76y+0.5m}$$

Substitute $m = \frac{(8.707+4.76y)CO\%}{100-0.5CO\%}$ into the above equation, rearrange to get

$$y = \frac{435.348CO\% - 870.7EO\%}{476EO\% - 188CO\% - 10{,}000}$$

Excess air

$$EA\% = \frac{100y}{a} = 100 \times \frac{435.348CO\% - 870.7EO\%}{476EO\% - 188CO\% - 10{,}000} \times \frac{1}{2.03305}$$

$$= 100 \times \frac{435.348 \times 0 - 870.7 \times 4.6}{476 \times 4.6 - 188 \times 0 - 10{,}000} \times \frac{1}{2.03305}$$

$$= 25.223\%$$

## 7. EFFICIENCY CALCULATION:

1.) Dry flue gas loss

$L_1 = Cp \times (AF \times (1+EA) \times \rho_{air} + \rho_{fuel}) \times (Tg - Ta) / HHV$

$= 0.249 \times [9.6773 \times (1+0.25223) \times 0.075 + 0.04575] \times (399-97) / 1026$

$= 0.070$

2.) Fuel hydrogen and moisture loss

$L_2 = (9\,H + Water) \times (hwv - hw) / HHV$

$= (9 \times \alpha B \div W_F + 0) \times (1239.9-65)/(1026 \div 0.04575)$

$= (9 \times 0.9695 \times 4.1293 \div 17.5894) \times (1239.9-65)/(1026 \div 0.04575)$

$= 0.1073$

3.) Air moisture loss

$L_3 = 0.46 \times W(\text{lb-water/lb-dry-air}) \times Q_{air} \times (hwv - hv)/(HHV \times Q_{fuel})$

$= 0.46 \times 0.01 \times AF \times (1+EA) \times 0.075 \times (1239.9-1103.4)/1026$

$= 0.0024$

4.) Radiation loss

$L_4 = 0.015$(estimate)

5.) Blowdown loss

$L_5 = 0.03$

6.) Other loss

$L_6 = 0.005$ (estimate)

Efficiency

$\eta = 1 - L_1 - L_2 - L_3 - L_4 - L_5 - L_6$

$= 1 - 0.07 - 0.1073 - 0.0024 - 0.015 - 0.03 - 0.005$

$= 0.7703$

$= 77\%$

The probable accuracy of each measurement is as follows:

1.) Dry flue gas loss

Approximate accuracy

| | |
|---|---|
| O2 determination | ±5.0% |
| Specific heat | ±1.0% |
| (Tg - Ta) | ±3.0% |
| HHV | ±0.35% |

Net Accrued Error = NAE = $\sqrt{5^2 + 1^2 + 3^2 + 0.35^2} = 5.93\ \%$

2.) Wet flue gas loss

| | |
|---|---|
| Hydrogen | ±5.0% |
| (Tg - Ta) | ±3.0% |
| HHV | ±0.35% |

Net Accrued Error = NAE = $\sqrt{5^2 + 3^2 + 0.35^2} = 5.84\ \%$

3.) Air moisture loss

| | |
|---|---|
| Humidity ratio | ±5.0% |
| Tg-Ta | ±3.0% |
| HHV | ±0.35% |

Net Accrued Error = NAE = $\sqrt{5^2+3^2+0.35^2} = 5.84\%$

4.) Radiation and unaccounted loss ±50%

5.) Blowdown loss ±50%

Total tolerance error

$$= \pm \frac{\sqrt{\sum (losses \times NAE)^2}}{losses}$$

$$= \pm \frac{\sqrt{\sum (0.07\times 5.93)^2 + (0.1073\times 5.84)^2 + (0.0024\times 5.84)^2 + (0.015\times 50)^2 + (0.03\times 50)^2 + (0.005\times 50)^2}}{0.2297}$$

= 8.07%

The cumulative total measurement error $= \pm \frac{100-77.03}{77.03} \times 8.07 = \pm\ 2.41\%$

The effect of compounding the errors $= \pm \frac{77.03 \times 2.41}{100} = 2\ \%$

So the efficiency is probably within the range **77 ± 2 %**

# APPENDIX C-1: MEASURED DATA AND VELOCITY PROFILES

Table C1: Measured data for left intake side.

| | left | | right | | up | |
|---|---|---|---|---|---|---|
| point | Δp (in.wc) | velocity (ft/s) | Δp (in.wc) | velocity (ft/s) | Δp (in.wc) | velocity (ft/s) |
| 1 | 0.105 | 22.24 | 0.135 | 25.22 | 0.145 | 26.14 |
| 2 | 0.105 | 22.24 | 0.15 | 26.59 | 0.14 | 25.68 |
| 3 | 0.11 | 22.77 | 0.145 | 26.14 | 0.135 | 25.22 |
| 4 | 0.12 | 23.78 | 0.158 | 27.29 | 0.145 | 26.14 |
| 5 | 0.132 | 24.94 | 0.18 | 29.12 | 0.155 | 27.03 |
| 6 | 0.145 | 26.14 | 0.195 | 30.31 | 0.172 | 28.47 |
| 7 | 0.15 | 26.59 | 0.2 | 30.70 | 0.175 | 28.72 |
| 8 | 0.158 | 27.29 | 0.208 | 31.31 | 0.19 | 29.92 |
| 9 | 0.162 | 27.63 | 0.232 | 33.06 | 0.198 | 30.54 |
| 10 | 0.192 | 30.08 | 0.252 | 34.46 | 0.225 | 32.56 |
| 11 | 0.204 | 31.00 | 0.302 | 37.72 | 0.252 | 34.46 |
| 12 | 0.225 | 32.56 | 0.335 | 39.73 | 0.295 | 37.28 |
| 13 | 0.244 | 33.91 | 0.385 | 42.59 | 0.325 | 39.13 |
| 14 | 0.264 | 35.27 | 0.445 | 45.79 | 0.36 | 41.19 |
| 15 | 0.275 | 36.00 | | | 0.37 | 41.75 |
| 16 | 0.345 | 40.32 | | | | |

Table C2: Measured data for right intake side.

| | left | | right | | up | |
|---|---|---|---|---|---|---|
| point | Δp (in.wc) | velocity (ft/s) | Δp (in.wc) | velocity (ft/s) | Δp (in.wc) | velocity (ft/s) |
| 1 | 0.205 | 31.08 | 0.18 | 29.12 | 0.18 | 29.12 |
| 2 | 0.21 | 31.46 | 0.185 | 29.52 | 0.188 | 29.76 |
| 3 | 0.216 | 31.90 | 0.18 | 29.12 | 0.208 | 31.31 |
| 4 | 0.226 | 32.63 | 0.19 | 29.92 | 0.215 | 31.83 |
| 5 | 0.26 | 35.00 | 0.19 | 29.92 | 0.22 | 32.20 |
| 6 | 0.275 | 36.00 | 0.195 | 30.31 | 0.232 | 33.06 |
| 7 | 0.315 | 38.53 | 0.215 | 31.83 | 0.238 | 33.49 |
| 8 | 0.342 | 40.14 | 0.215 | 31.83 | 0.248 | 34.18 |
| 9 | 0.345 | 40.32 | 0.22 | 32.20 | 0.265 | 35.34 |
| 10 | 0.375 | 42.04 | 0.238 | 33.49 | 0.285 | 36.65 |
| 11 | 0.415 | 44.22 | 0.25 | 34.32 | 0.315 | 38.53 |
| 12 | 0.455 | 46.30 | 0.265 | 35.34 | 0.35 | 40.61 |
| 13 | 0.495 | 48.30 | 0.305 | 37.91 | 0.38 | 42.31 |
| 14 | 0.545 | 50.68 | 0.31 | 38.22 | 0.435 | 45.27 |
| 15 | | | 0.38 | 42.31 | 0.49 | 48.05 |
| 16 | | | 0.41 | 43.95 | 0.495 | 48.30 |

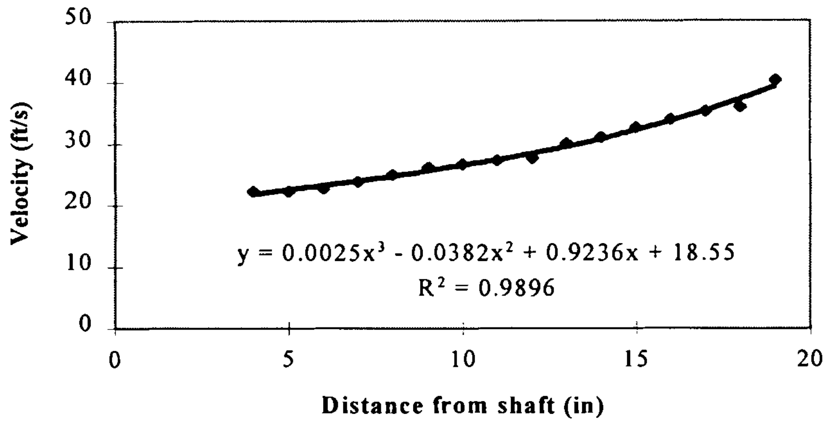


Figure C1: Left side

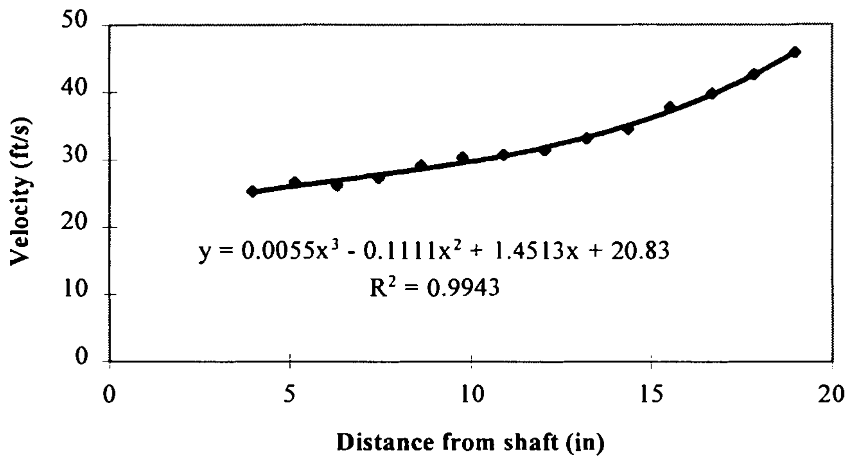


Figure C2: Right side

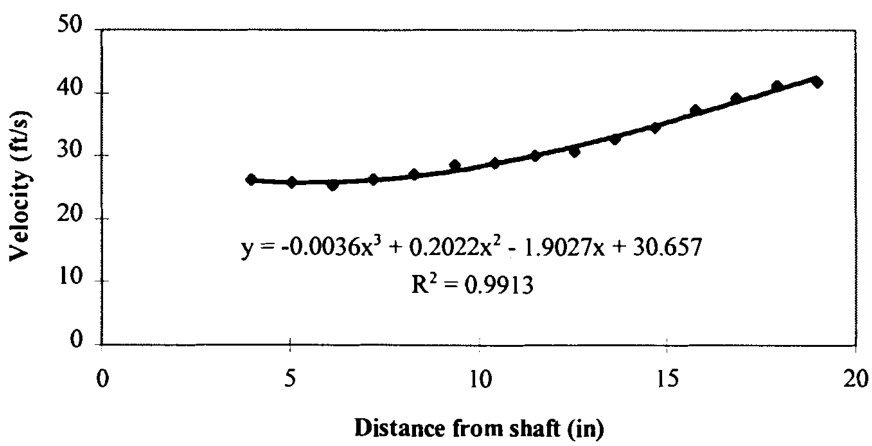


Figure C3: Upper side

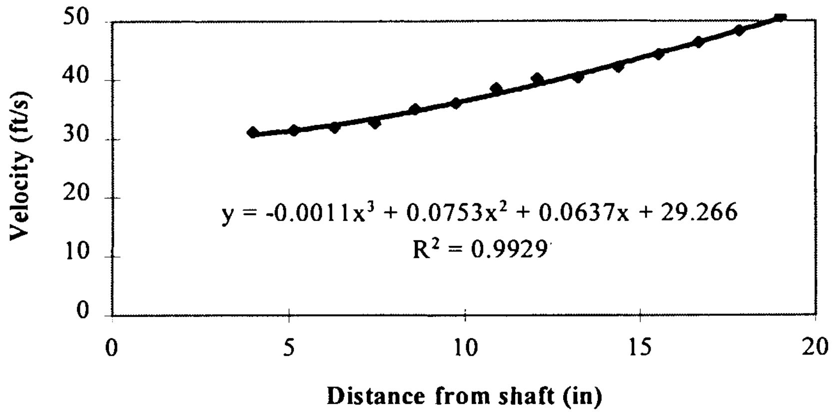


Figure C4: Left side

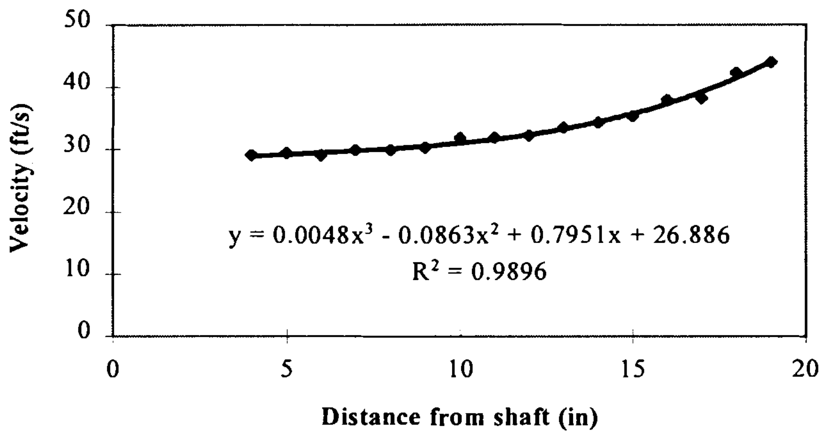


Figure C5: Right side

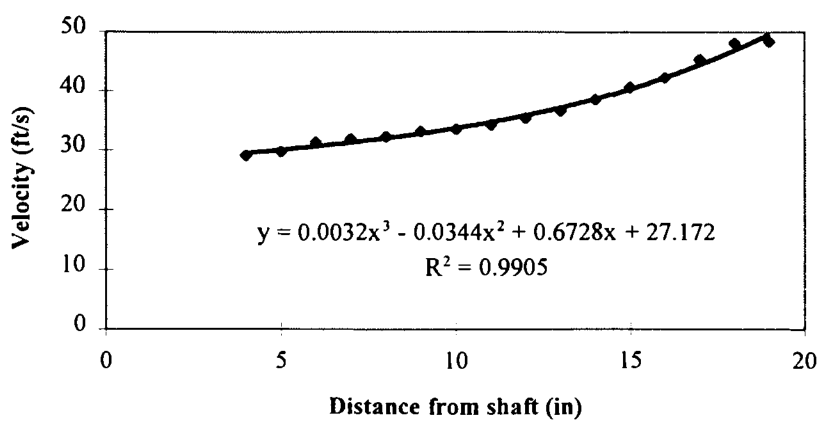


Figure C6: Upper side

## APPENDIX C-2: VELOCITY CALCULATION AND ERROR ANALYSIS

Determine the velocity uncertainty when $\Delta p$ = 0.2 inches of water:

The velocity of air entering the fan is calculated as:

$$V = \sqrt{\frac{2\Delta p}{\rho}} = \sqrt{\frac{2\Delta p \cdot RT}{p}} = \sqrt{\frac{2 \times 0.2 \times 0.0361 \times 144 \times 32.17 \times 53.34 \times 557}{14.5 \times 144}} = 30.92 \text{ ft/s}$$

where $\Delta p$ = Velocity pressure at entering point;
$\rho$ = Density of air;
T = Air temperature;
p = Air pressure.

It is a function of $\Delta p$, T, and p and can be expressed as

$V = V \pm W_v$

where $W_v = f(W_{\Delta p}, W_T, Wp)$

$W_{\Delta p}$, $W_T$, $W_p$ are the uncertainties of velocity pressure, air temperature and pressure measurements.

$W_{\Delta p}$ = 5% of $\Delta p$;

$W_T$ = 1°F;

$W_p$ = 0.05 psi.

$W_v$ can be determined by

$$W_v = \sqrt{(\frac{\partial V}{\partial \Delta p} W\Delta p)^2 + (\frac{\partial V}{\partial T} W_T)^2 + (\frac{\partial V}{\partial p} Wp)^2}$$

$$= \sqrt{\frac{RT}{2p \cdot \Delta p}(W\Delta p)^2 + \frac{\Delta p \cdot R}{2pT}(W_T)^2 + \frac{\Delta p \cdot RT}{2p^3}(Wp)^2}$$

$$= \sqrt{\frac{53.34 \times 560}{2 \times 2088 \times 33.4465}(1.672)^2 + \frac{33.4465 \times 53.34}{2 \times 2088 \times 560}(1)^2 + \frac{33.4465 \times 53.34 \times 560}{2 \times 2088^3}(7.2)^2}$$

$= 0.776$ ft/s

Where

$p = 14.5 \times 144 = 2088$ lbf/in$^2$

$\Delta p = 0.2 \times 0.0361 \times 144 \times 32.17 = 33.4465$ lbf/in$^2$

$W_{\Delta p} = 0.05 \times 33.4465 = 1.672$ lbf/in$^2$

$W_p = 0.05 \times 144 = 7.2$ lbf/in$^2$

Root mean square error of regression is $Wr = 0.6165$ ft/s.

Total error is $\sqrt{Wv^2 + Wr^2} = \sqrt{0.776^2 + 0.6165^2} = 0.9911$ ft/s.

Total percentage error is $\frac{0.9911}{30.92} = 3.21\%$

# APPENDIX C-3: AIR FLOW RATE CALCULATION

$Flow_{L,l}$, $Flow_{L,r}$ and $Flow_{L,u}$ were flow rates of the left, right and upper quarters of the left intake side, $Flow_{R,l}$, $Flow_{R,r}$ and $Flow_{R,u}$ were flow rates of the left, right and upper quarters of the right intake side. The followings are the integration equations.

$$Flow_{L,l} = 0.25 \cdot \frac{\int (2 \cdot 3.14 \cdot x \cdot (0.0025 \cdot x^3 - 0.0382 \cdot x^2 + 0.9236 \cdot x + 18.55)\, dx)}{144} \cdot 3600$$

$$Flow_{L,r} = 0.25 \cdot \frac{\int (2 \cdot 3.14 \cdot x \cdot (0.0055 \cdot x^3 - 0.1111 \cdot x^2 + 1.4513 \cdot x + 20.83)\, dx)}{144} \cdot 3600$$

$$Flow_{L,u} = 0.25 \cdot \frac{\int (2 \cdot 3.14 \cdot x \cdot (-0.0036 \cdot x^3 + 0.2022 \cdot x^2 - 1.9027 \cdot x + 30.657)\, dx)}{144} \cdot 3600$$

$$Flow_{R,l} = 0.25 \cdot \frac{\int (2 \cdot 3.14 \cdot x \cdot (-0.0011 \cdot x^3 + 0.0753 \cdot x^2 + 0.0637 \cdot x + 29.266)\, dx)}{144} \cdot 3600$$

$$Flow_{R,r} = 0.25 \cdot \frac{\int (2 \cdot 3.14 \cdot x \cdot (0.0048 \cdot x^3 - 0.0863 \cdot x^2 + 0.7951 \cdot x + 26.886)\, dx)}{144} \cdot 3600$$

$$Flow_{R,u} = 0.25 \cdot \frac{\int (2 \cdot 3.14 \cdot x \cdot (0.0032 \cdot x^3 - 0.0344 \cdot x^2 + 0.6728 \cdot x + 27.172)\, dx)}{144} \cdot 3600$$

Below is the results in actual CFH ($ft^3/hr$)

| $Flow_{L,l}$ | $Flow_{L,r}$ | $Flow_{L,u}$ | $Flow_{R,l}$ | $Flow_{R,r}$ | $Flow_{R,u}$ |
|---|---|---|---|---|---|
| 207,574 | 235,191 | 226,577 | 278,586 | 235,897 | 262,117 |

Total flow rate is

(207,574+235,191+226,577+278,586+235,897+262,117)×4÷3=1,928,000 CFH

Convert to standard cubic feet,

$$1{,}928{,}000 \times \frac{460+60}{460+97} = 1{,}790{,}000 \text{ SCFH}$$

Consider 26.8% leakage to the flue gas, actual air flow rate to the boiler is

1,790,000×0.73=1,308,000 SCFH.

## APPENDIX D: ERROR ANALYSIS FOR STEAM CORRECTION FACTOR

The correction factor is defined as

$$F = \frac{S_p}{S_m}$$

$$= \frac{\eta \times G \times HHV}{\Delta h \times S_m}$$

where

$S_p$ = predicted steam flow;

$S_m$ = measured steam flow;

$\eta$ = boiler efficiency;

G = gas flow;

HHV = gas higher heating value;

$\Delta h$ = enthalpy change of steam.

It can be expressed as

$$F = F \pm W_f$$

where

$$W_f = f(W_\eta, W_G, W_{HHV}, W_{Sm}, W_{\Delta h})$$

$W_\eta$, $W_G$, $W_{HHV}$, $W_{Sm}$, and $W_{\Delta h}$ are uncertainties of efficiency, gas flow, heating value, measured steam flow and steam enthalpy change. Their values are obtained by multiply the uncertainty with measured value.

$$W_\eta = 0.0185 \times 0.7703 = 0.01425$$

$$W_G = 0.025 \times 109296 = 2732.4 \text{ SCFH}$$

$$W_{HHV} = 0.0035 \times 1026 = 3.591 \text{ Btu/SCF}$$

$W_{Sm} = 0.2 \times 102776 = 20555$ lb/hr

$W_{\Delta h} = 0.03 \times 1133 = 34$ Btu/lb

$W_f$ can be determined by

$$W_f = \sqrt{\left(\frac{\partial F}{\partial \eta} W\eta\right)^2 + \left(\frac{\partial F}{\partial G} W_G\right)^2 + \left(\frac{\partial F}{\partial HHV} W_{HHV}\right)^2 + \left(\frac{\partial F}{\partial \Delta h} W_{\Delta h}\right)^2 + \left(\frac{\partial F}{\partial S_m} W_{Sm}\right)^2}$$

$$= \sqrt{\left(\frac{G \times HHV}{S_m \times \Delta h} W\eta\right)^2 + \left(\frac{\eta \times HHV}{S_m \Delta h} W_G\right)^2 + \left(\frac{\eta \times G}{S_m \Delta h} W_{HHV}\right)^2 + \left(\frac{\eta \times G \times HHV}{S_m \times \Delta h^2} W_{\Delta h}\right)^2 + \left(\frac{\eta \times G \times HHV}{S_m{}^2 \times \Delta h} W_{Sm}\right)^2}$$

$= 0.0322$

Percentage uncertainty is $\frac{W_f}{F} = \frac{0.0322}{0.797} \times 100\% = 4\%$

# APPENDIX E: COMBUSTION EFFICIENCY AND AIR PREHEATER LEAKAGE RATE CALCULATION (EES PROGRAM)

**EQUATIONS:**

{ Fuel analysis}

{composition}

CH4=0.9105

C2H6=0.0557

C3H8=0.0031

C4H10=0.0001

C6H14=0.0001

Alpha_N2=0.0089

Alpha_CO2=0.0216

{Formula}

Alpha=CH4+C2H6+C3H8+C4H10+C6H14

A=(CH4+2*C2H6+3*C3H8+4*C4H10+6*C6H14)/Alpha

B=(4*CH4+6*C2H6+8*C3H8+10*C4H10+14*C6H14)/Alpha

{Molecule weight}

W_CAHB=12*A+B

W_fuel=Alpha*W_CAHB+28*Alpha_N2+44*Alpha_CO2

{property}

P=14.5

Rho_air=0.075

omega=0.02

W_air=0.79*28+0.21*32

W_h2o=18

Rho_specific=0.61

Rho_fuel=Rho_specific*Rho_air {lb/SCF}

HHV=1026{Btu/SCF}

h_formation=HHV/Rho_fuel-(169297*(Alpha*A+Alpha_CO2)+61485*Alpha*B)/W_fuel

{Flue gas analysis}

V_O2_1=0.046

V_CO2_1=0.091

V_CO_1=0

V_N2_1=1-V_O2_1-V_CO2_1-V_CO_1

T_1=545

T_1_actual=T_1+T_ambient

T_ambient=100

{W_1=32*V_O2_1+44*V_CO2_1+28*V_CO_1+28*V_N2_1}

W_1=((Alpha*A+Alpha_CO2m)*44+m*28+(Alpha_N2+3.76*c+3.76*y)*28+(y+0.5*m)*32)

/(Alpha*A+Alpha_CO2+Alpha_N2+(Alpha*A+0.25*Alpha*B)*3.76+y+0.5*m+3.76*y)

V_O2_2=0.089

V_CO2_2=0.065

V_CO_2=0

V_N2_2=1-V_O2_2-V_CO2_2-V_CO_2

T_2=223.6

T_2_leak=T_2+T_ambient

W_2=32*V_O2_2+44*V_CO2_2+28*V_CO_2+28*V_N2_2

{Theoretical A/F for combustion equation

```
Alpha*CAHB+Alpha_N2*N2+Alpha_CO2*CO2+c(O2+3.76N2) --->

(Alpha*A+Alpha_CO2)CO2+0.5Alpha*B*H2O+(Alpha_N2+3.76c)N2 }

c=Alpha*A+0.25*Alpha*B

Ratio_air_to_fuel=4.76*c

{ Excess air for combustion equation

Alpha*CAHB+Alpha_N2*N2+Alpha_CO2*CO2+(c+y)(O2+3.76N2) --->(Alpha*A

 +Alpha_CO2-m)CO2+mCO+0.5Alpha*B*H2O+(Alpha_N2+3.76c)N2+dO2+3.76yN2 }

V_CO_1=m/(Alpha*A+Alpha_CO2+Alpha_N2

          +(Alpha*A+0.25*Alpha*B)*3.76+y+0.5*m+3.76*y)

V_O2_1=(y+c-0.25*Alpha*B-0.5*m- Alpha*A)/(Alpha*A+Alpha_CO2+Alpha_N2

       +(Alpha*A+0.25*Alpha*B)*3.76+y+0.5*m+3.76*y)

ExcessAir=100*y/c

{V_CO2_1=(Alpha*A+Alpha_CO2-m)/(Alpha*A+Alpha_CO2+Alpha_N2

              +(Alpha*A+0.25*Alpha*B)*3.76+y+0.5*m+3.76*y)}

{Combustion Efficiency}

M_air_to_fuel=4.76*(c+y)*W_air/W_fuel

M_dryflue_to_fuel=((Alpha*A+Alpha_CO2-m)*44+m*28+(Alpha_N2+3.76*c+3.76*y)*28

                     +(y+0.5*m)*32)/W_fuel

M_h2o_to_fuel=(0.5*Alpha*B*W_h2o+4.76*(c+y)*omega*W_air)/W_fuel

h_1=h_formation+0.497*(T_ambient-77)

h_2=M_air_to_fuel*(0.24*(T_ambient-77)+omega*(0.445*(T_ambient-77)

       +ENTHALPY(H2O,t=77)))
```

h_3=M_dryflue_to_fuel*(ENTHALPY(CO2,t=77)*44*V_CO2_1/W_1+0.25*(T_2_unleak-77))+M_h2o_to_fuel*(ENTHALPY(H2O,t=77)+0.445*(T_2_unleak-77))

eta_c=(ABS(h_3)-ABS(h_1+h_2))/(HHV/Rho_fuel)

{leakage}

Q_air=1928{1000 CFH}

m_air=Q_air*Rho_air*(460+60)/(460+T_ambient)

Q_fuel=((m_air-m_leak)/Rho_air)/((1+ExcessAir/100)*Ratio_air_to_fuel) { 1000 SCFH}

m_fuel=Q_fuel*Rho_fuel

Q_air_to_boiler=(m_air-m_leak)/Rho_air

{$O_2$ balance}

(m_fuel+m_air-m_leak)/(P/(1545/W_1*T_1_actual))*(P/(1545/32*T_1_actual))*V_O2_1

+m_leak/(P/(1545/28.97*T_ambient))*(P/(1545/32*T_ambient))*0.21

= (m_fuel+m_air)/(P/(1545/W_2*T_2_leak))*(P/(1545/32*T_2_leak))*V_O2_2

ratio_leak=m_leak/m_air

(m_fuel+m_air-m_leak)*(T_2_unleak-T_2_leak)=m_leak*(T_2_leak-T_ambient)

**SOLUTIONS:**

A=1.065

Alpha=0.970

Alpha_CO2=0.022

Alpha_N2=0.009

B=4.129

c=2.033

C2H6=0.056

C3H8=0.003

C4H10=0.000

C6H14=0.000

CH4=0.911

eta_c=0.807

ExcessAir=25.223

HHV=1026.000

h_1=-1700.767

h_2=-2194.226

h_3=-22003.712

h_formation=-1710.707

m=-0.000

m_air=134.995

M_air_to_fuel=19.869

M_dryflue_to_fuel=18.821

m_fuel=4.968

M_h2o_to_fuel=2.446

m_leak=36.308

omega=0.020

P=14.500

Q_air=1928.000

Q_air_to_boiler=1315.823

Q_fuel=108.582

Ratio_air_to_fuel=9.677

ratio_leak=0.269

Rho_air=0.075

Rho_fuel=0.046

Rho_specific=0.610

T_1=545.000

T_1_actual=642.000

T_2=223.600

T_2_leak=320.600

T_2_unleak=398.922

T_ambient=97.000

V_CO2_1=0.091

V_CO2_2=0.065

V_CO_1=0.000

V_CO_2=0.000

V_N2_1=0.863

V_N2_2=0.846

V_O2_1=0.046

V_O2_2=0.089

W_1=29.696

W_2=29.396

W_air=28.840

W_CAHB=16.905

W_fuel=17.589

W_h2o=18.000

y=0.513