Refuse-Fired Boiler Heat Balance

John S. Austin, P.E.
Hampton/NASA Steam Plant
50 Wythe Creek Road
Hampton, Virginia

Municipal waste combustor operators are becoming more aware of boiler efficiency, for many have been experiencing periods of refuse fuel shortages. Most operators know the heat balance of their energy plants in terms of kilowatt hours per ton of refuse, or pounds of steam per pound of refuse.

Actual refuse scale and energy meter data can be used to calculate these overall heat balances rather precisely over long periods. Satisfying these parameters are often sufficient for an operator to meet performance benchmarks.

Some MWC Plant Heat Rates

$$\textbf{Electric Heat Rate} = \frac{\textbf{kWhrs}}{\textbf{Ton Refuse}}$$

$$\textbf{Steam Heat Rate} = \frac{\textbf{Pounds Steam}}{\textbf{Pound Refuse}}$$

While these plant heat balances give reliable benchmark information over long periods, precise short term measurement of refuse weight data and it's chemical energy stored are difficult to achieve. These overall heat rates also give little insight into the efficiency of the boiler units for short periods.

The First Law of Thermodynamics is applied to measured performance data when using either the "input-output" or "heat loss" methods as prescribed in *Power Test Code 4, Boilers*.

The First Law states that energy is conserved. The energy leaving a boiler unit is equal to the energy coming in. Data gathered is used to calculate the energy in and out of the boiler unit. For fossil fuel boilers, we could simply get instantaneous measurements of steam energy leaving and the energy of the fuel and air entering the boiler. This direct method is an extreme challenge with refuse fired units, because of the varying fuel moisture content.

The ASME *Performance Test Code 33, Large Incinerators*, does set out methods for waste combustors, but these methods are driven toward calculating an incineration efficiency. How well has the combustor unit burnt the refuse? That is the question asked by PTC 33.

Boiler efficiency over the short term can be achieved by measuring boiler losses, and using a "heat balance" method. Add up all the energy coming into the boiler and that is equal to all of the energy exiting the boiler unit. Therefore, the energy in is equal to the useful steam energy out plus the sum of all boiler losses.

$$\sum \textbf{Energy In} = \sum \textbf{Energy Out}$$

$$= \textbf{Steam Energy Out} + \sum \textbf{Losses}$$

A boiler heat and mass balance can determine the boiler unit efficiency without considering the refuse fuel energy coming into the boiler. We don't need to measure the weight of the refuse or it's fuel heat value to know efficiency.

Refuse Fired Boiler Efficiency

The American Society of Mechanical Engineers has two test codes that prescribe methods for boiler efficiency analysis. The ASME *Power Test Code 4, Boilers*, uses the 1st Law of Thermodynamics in two methods commonly referred to as the "input-output" and "heat loss" methods. In past waste to energy literature, the heat loss method has been referred to as the "boiler as a calorimeter" method.

ASME *Performance Test Code 33, Incinerators*, sets out methods for waste combustors. These methods are also based upon the laws of conservation of mass and energy, but these methods are more driven toward calculating an incineration efficiency. The methods of PTC 33 are valuable to measure and calculate casing and ash losses.

We attempt here to simplify the concepts of a refuse fired boiler efficiency. The current ASME/ANSI Test Codes provide excellent evaluation and documentation, and these should be required upon start-up of new units. This works well when PTC 4 and PTC 33 are run as independent performance tests.

A heat and mass balance of a refuse-fired boiler uses the intrinsic enthalpy, or energy per pound, to analyze the losses and efficiency of a boiler unit. Essentially, we must measure and account for all steam energy output and boiler losses until the physical laws of conservation of mass and energy are satisfied, or balanced.

The methods prescribed in PTC 4, Boilers, depend heavily on knowing quantity and heat value of the fuel input. The fuel heat value is directly input into the 1st Law equations:

$$\sum \textbf{Energy In} = \sum \textbf{Energy Out}$$

$$\eta_{MWC} = \frac{\textbf{Useful Heat Out}}{\textbf{Total Heat In}}$$

$$\eta_{MWC} = \frac{\textbf{Steam Energy Out}}{\textbf{Steam Energy Out} + \sum \textbf{Losses}}$$

Knowing the total net energy input from the refuse fuel is an extreme challenge because of the varying refuse moisture content.

A relatively accurate boiler efficiency over the short term can be achieved by measuring boiler losses, and using a method hybrid of the two ASME Test Codes. Such a method was developed and is presently used for the waste fired boilers Hampton/NASA Steam Plant.

A Method for Heat Balance Analysis

The basic method of analysis is to measure all the outputs from the boiler. The useful output is in the form of steam, and is typically measured with a differential pressure flow element and transmitter. Accuracy of ±1% are common, and many other parameters of this analysis are even less accurate. The analysis has been repeatable.

The refuse fired boiler losses include those from the stack, casing, and residue ash. Most of the losses leave the boiler unit as latent and sensible heat in the stack flue gasses. The accuracy of this method is greatly improved when done in conjunction with scheduled stack testing.

Moisture and nitrogen balances are done to cross correlate and verify the air balance, so to calculate tramp air infiltration. These also help to analyze the refuse fuel during back solving.

Boiler Stack Losses

Moisture in the flue gas leaving the boiler unit is a large "heat bandit." It is the greatest single loss for most refuse fired boiler units. Moisture in the flue is why gas firing a boiler will get a lower efficiency than oil firing the same boiler. Moisture is why refuse boilers have relatively low thermodynamic efficiencies. The moisture requires over a thousand BTU/lbm to raise its energy from reference ambient vapor pressure to the temperature of the flue gas. In addition, a latent heat loss of 970 BTU per pound of water to vaporize the water.

The water vapor is superheated steam, and the intrinsic enthalpy (BTU/lbm) can be taken from the superheated steam tables. The pressure used would be the partial vapor pressure of the steam when calculated as an ideal gas. The temperature is that of the flue gas. This analysis had a water vapor mass flow of 6583 pounds per hour, and a net heat loss of more than ten million British Thermal Units per hour.

The sensible heat loss from the stack is the heat that was used to raise the temperature of the dry gasses to the boiler exit temperature 413° F. The dry flue gas for this analysis has essentially three component gasses: Nitrogen (81%), Carbon Dioxide (10%), and Oxygen (9%). These three percent volume numbers have to be rounded up slightly to sum to 100%, and this will account for the mass of other minor gasses.

During the extensive testing the pollutant gases hydrogen chloride, nitrogen oxides and sulphur dioxide are also included. Sensible heat losses can then be correlated to the composite specific heat of the gas mixture, assuming real gas.

The large amount of nitrogen makes it the second greatest "heat bandit." This analysis measured 50,862 pounds per hour nitrogen, for a heat loss of almost four and a half million BTU's each hour of operation. The total of sensible heat lost up the stack with the dry flue gas was almost six million BTU's per hour with a dry gas flow of 14,463 dscfm.

A smaller component of stack losses are the chemical losses due to carbon monoxide and other hydrocarbons in the flue gas. While these are minor, measuring and understanding these losses gives us an important perspective to air pollution from our waste combustors.

Most refuse boilers directly measure the wet or dry carbon monoxide emissions on a continuous basis. This carbon monoxide is holding energy waiting to become carbon dioxide. This product of incomplete combustion represents lost heat to the system. PTC 33 directs the analysis to assume chemical losses from hydrogen carbons equal to that of an equal amount of hydrogen as the measured dry carbon monoxide. These components seldom exceed 1% of stack losses.

Stack losses for this analysis was 16.4 million BTU's per hour of operation. These losses were 96% of all the boiler losses. Stack flow and gas analysis is done on a real time basis for many refuse fired boilers. This data can be analyzed with the facility's data acquisition system to allow operators to see the heat balance live. The accuracy of the analysis lies primarily on the instrumentation for flue gas analysis and flow.

Residue Ash Losses

Energy is lost with the residue in several ways. The residue ash leaves the furnace at a high temperature compared to the reference ambient. This sensible heat is lost. Also, the unburned fraction of the ash is removing chemical energy that could have been converted in the boiler.

Most units have an ash quenching system, and water vapor is returned to the boiler unit with infiltration air. While that does lead to greater boiler losses at the stack, it is actually a heat credit entering the boiler at the ash system. This latent heat exchange at the system boundary causes the greatest residue ash loss to be from the unburnt refuse fraction of the ash.

Repeated testing of unburnt material in the ash and components of the unburnt material indicate the fuel heat value of the dry unburnt material is much less than the refuse fuel. This may be due to volatile off gassing in the furnace and the greater survival of low BTU refuse. For this analysis, a fuel heat value of 2025 BTU per pound of the unburnt fraction mass. The total residue losses were under a million BTU/hour.

Methods to analyze waste combustion ash are available from the ASME Performance Test Code 33, Large Incinerators. Laboratories have other more accurate methods to analyze the ash.

Boiler Casing Losses

Most refuse fired boilers are well insulated to prevent casing destruction by acid gasses, so casing losses are less than other boilers of similar size casing surface area. The data needed for this analysis is ambient air conditions and boiler casing segment surface temperatures. The heat losses can be modeled as natural convection and radiation. The casing temperatures are usually not high, so the heat lost through convection is predominant.

PTC 33 does offer an empirical method that yields remarkably similar results as a heat transfer model. With that method, casing segment temperatures are used graphically to get a combined convection and radiation heat transfer coefficient. That is multiplied by the segment surface areas and summed for the total casing heat loss from the refuse fired boiler. For this analysis, casing losses was just over 200 thousand BTU per hour of operation.

Refuse Fired Efficiency Results

The total losses from the refuse fired boiler was 17,013,143 BTU per hour of operation for this analysis. The useful steam energy out of the boiler was 38,606,896 BTU/hour. Therefore:

$$\eta_{MWC} = \frac{38{,}606{,}896 \text{ BTU/hr}}{(38{,}606{,}896 + 17{,}013{,}143) \text{ BTU/hr}}$$

$$\eta_{MWC} = 69.4\%$$

The thermodynamic efficiency of the refuse fired boiler was calculated without ever knowing the fuel heat value or the actual weight of the refuse being processed. Fuel testing and batch weighing has been done in conjunction to give insight into and to improve the analysis. The measured efficiency can be backed into a refuse heat value, essentially using the boiler as a calorimeter. Additional energy and mass balances are used to check the results and relate them to the heat inputs and refuse fuel.

Boiler Nitrogen Mass Balance

Refuse fuel has a significant amount of nitrogen, and some off that does end up in the flue gases as nitrogen and its oxides. This amount is very small compared to the mass of nitrogen coming from the combustion air and infiltrated tramp air. Balancing the nitrogen leaving the stack with the measured combustion air allows us to calculate the amount of tramp air that has unwantedly infiltrated the boiler. The tramp air is at a higher temperature and humidity than the combustion air, so this is very important to calculate the energy credits coming into the system from other than the refuse. That is an essential part of backing out the refuse fuel heat value from the analysis.

This is another important aspect for operators to understand how infiltrated tramp air can reduce the efficiency of the refuse fired boiler.

Boiler Moisture Balance

Flue gas moisture content can be measured by condensation and weighing, or it can simply be calculated from measured wet and dry oxygen.

Some moisture does enter the boiler with air coming in, but most of it comes from the fuel. Moisture in the refuse fuel can be free moisture on the refuse or moisture contained within the refuse fuel. The refuse combustion process also creates water when the hydrogen fraction of the refuse fuel is reacted into water vapor.

The large variation of moisture in the refuse fuel is primarily due to the free moisture in the refuse. That characteristic of the refuse fuel is tricky to measure directly. This free moisture is leaving the refuse as soon as the truck leaves the scale. This free moisture continues to leave the refuse fuel during pre-processing and while stored in the refuse pit. When refuse fuel sampling is done, accuracy of the results rely heavily on accounting for moisture loss during the sample preparation. A water mass balance can give a more accurate measure of refuse fuel moisture content.

Refuse Fuel Heat Value

The energy and mass balance data gathered can then be directly applied to the 1st Law of Thermodynamics to calculate the refuse fuel heat energy coming into the boiler. The total of refuse fuel heat energy plus the heat credits into the boiler is equal to the steam energy out plus the boiler losses.

$$H_{Refuse} = \text{Steam Energy} + \Sigma \text{ Losses} - \text{Credits}$$

$$h_{Refuse\ (BTU/lbm)} = \frac{H_{Refuse}}{m_{Refuse}}$$

With accurate weight data, or estimate, the intrinsic fuel heat value of the refuse can be calculated. The boiler is used as a calorimeter.

Analysis at the Hampton/NASA Steam Plant

Since 1991, boiler heat balances have been done at the facility for two reasons. First, regulators are using refuse throughput for determination of unit size category and applicable requirements. Second, this is important information for evaluating plant performance. With refuse fuel shortages at many plants, efficiency is also becoming important to economics. A third benefit has been realized as an operator aid .

Every two years, the analysis is done extensively during the bi-annual environmental testing. Data from concurrent stack testing, ash testing, and refuse fuel testing are utilized to calculate heat mass balances hourly and over that one month period. The heat and mass balances are correlated to refuse fuel analysis. This extended data is used to improve the methods and constants set through empirical trials.

The heat balance analysis has demonstrated repeatability of the method and little variance in the process. Calculated efficiencies come within 2 percentage points of the boilers rated efficiency of 69%. With constant firing rates at the Hampton/NASA Steam Plant, parameters not regularly measured can be effectively correlated to surrogate parameters for use in the regular less extensive heat and mass balances.

As a follow on to the 1996 heat balance, the data acquisition system was programmed to calculate an "instantaneous heat balance" of Boiler #1. This is used for operator information and a training aid. Data acquisition points for inlet air temperature and stack gas flow were installed at minimal cost to improve the error of the calculation. New monitors being installed at the facility will give live data for wet and dry oxygen, and then flue moisture content can be directly calculated. This new data point will improve accuracy while giving insight into refuse fuel moisture content and heat value.

The live boiler heat balance application was developed to be used as a tool by the boiler operators at the Hampton/NASA Steam Plant. With the outputs of the boiler heat balance being refuse heat value and boiler efficiency, the operators will find it very useful during daily operation. The data and calculations are presented to the operators on live data acquisition screens developed with Intellution software. In addition to efficiency and refuse heat value, the operators can move to other screens to see live calculations of the various losses and inputs. Operators can understand a system by observing its live process data. This application has been valuable to enable operators to understand the process and losses.

Conclusions

Many still consider waste combustion an art not science, this project demonstrates science can be applied to combustors with readily available information with reasonably accurate results. Furthermore, information can be presented to operators on data acquisition screens to enable their better understanding of the process system.

Using the First Law of Thermodynamics can get results with a less extensive analysis than the ASME Test Codes. This model can also easily be calculated with the data being supplied by the refuse fired boiler's industrial measuring devices while yielding fairly accurate and repeatable results. Thus enabling a live calculation of the refuse fired boiler efficiency.

The ASME Power and Performance Test Codes are important information, especially for boiler start-up and acceptance. These should continue to be used until such a time when a test code is developed specifically for refuse fired boilers.

General References

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