Determining & Testing Boiler Efficiency for Commercial/Institutional Packaged Boilers

Introduction

[This paper pertains primarily to commercial/institutional packaged boilers. Although certain concepts contained in this paper may also be technically applied to other boiler types, this is not the purpose of this paper. Because this is a general overview of packaged firetube and watertube boiler efficiency, the reader is strongly urged to discuss their specific needs and conditions with their boiler manufacturer or manufacturer representative.]

Today's process and heating applications continue to be powered by steam and hot water. The mainstay technology for generating heating or process energy is the packaged boiler. The packaged boiler, either in firetube or the various watertube forms, has proven to be highly efficient and cost effective in generating energy for many process and heating applications.

Conducting a thorough evaluation of boiler equipment requires a review of boiler type, feature and benefit comparison, maintenance requirements and fuel usage requirements. Of these evaluation criteria, a key factor is fuel usage or boiler efficiency.

Boiler efficiency, in the simplest terms, represents the difference between energy input and energy output. A typical boiler will consume many times the initial capital expense in fuel usage annually. Consequently, a difference of just a few percentage points in boiler efficiency between units will result in substantial fuel savings. The efficiency data used for comparison between boilers must be based on proven methods to produce an accurate comparison of fuel usage. Over the years, however, efficiency has been represented in confusing terms or in ways where the efficiency value did not accurately represent proven fuel usage values. Sometimes, the representation of "boiler efficiency" does not truly represent the comparison of energy input and energy output of the equipment.

Remember: the initial capital cost of a boiler is the lowest portion of your boiler investment. Fuel costs and maintenance costs represent the largest portion of your boiler equipment investment. **<u>Not all boilers are created equal</u>**. Some basic design differences can reveal variations in expected efficiency performance levels. Evaluating these design differences can provide insight into what efficiency value and resulting operating costs can be expected. However, all boilers operate under the same fundamental thermodynamic principles. Therefore, a maximum theoretical efficiency can be calculated for a given boiler design. The maximum value represents the highest available efficiency of the unit. If you are evaluating a boiler where the stated efficiencies are higher than the theoretical efficiency value, watch out! The efficiency value you are utilizing may not truly represent the fuel usage of the unit.

In the end, efficiency comes down to properly testing the performance of the boiler and the performance of the burner. Proper testing methods will help predict the fuel usage. By forecasting the future fuel costs and maintenance expenses, you will be able to determine the full life cycle cost of the boiler.

CONSIDERATIONS WHEN CHOOSING THE MOST EFFICIENT BOILER

When you buy a boiler you are really making a down payment on the future purchase of steam or hot water. The payments to generate the power are ongoing over the life of the equipment and are driven by fuel costs, fuel-to-steam efficiency and maintenance costs. Even with economical fuel costs, the selection of a high efficiency boiler will result in substantial cost savings. A boiler installation costing $200,000 can easily consume over $1,000,000 in fuel every year it operates. Selection of a boiler with “designed-in” low maintenance costs and excellent fuel-to-steam or fuel-to-water efficiency will provide substantial savings and maximize your boiler investment.

Efficiency is only useful if it is repeatable and sustainable over the life of the equipment. Choosing the most efficient boiler is more than just choosing the vendor who is willing to state that they will meet a given efficiency value. The burner technology must be proven to be capable of maintaining the air/fuel ratio year in and year out. Make sure the burner design includes reliable and repeatable features. How can you tell? Ask any boiler technician who has worked on a variety of boiler/burner designs. Burner-pressure drop should be optimized by evaluating fan HP requirements against such things as burner turndown requirements and combustion chamber heat release. Quality fan and damper designs, and simple linkage assemblies -- or preferably linkage-less drives -- are easy to tune and accurately hold the air-to-fuel ratios.

Why choose the most efficient boiler? Because, the dividends that are paid back each year from high efficiency far outweigh any initial cost savings of a less efficient design. What is the most efficient boiler? It is a boiler that not only starts up efficiently but continues to operate efficiently year in and year out.

Replace or Repair

The decision to purchase a new boiler is typically driven by the needed replacement of an old boiler, an expansion of an existing boiler room, or construction of a new boiler room facility.

When considering the replacement of an old boiler, review the following points to make sure you are performing a comprehensive evaluation of your situation.

Efficiency

Check out the efficiency of your old boiler with a simple stack analysis or preferably for a more accurate assessment, measure the gas input vs. steam or hot water output. The data will give you a general idea of the difference between the fuel cost of the existing boiler and a new unit. Based on the results of the stack evaluation, a more comprehensive evaluation of your boiler room requirements should be performed. Boiler size, load characteristics, turndown requirements, back-up requirements, fuel type, control requirements, and emission requirements, all should be evaluated. The result will be an accurate review of the potential savings in fuel, maintenance, and boiler room efficiency that can mean substantial cost improvement for your facility.

Efficiency Design Feature Comparisons

There are key design feature differences between various packaged boilers. High efficiency is the result of tangible design considerations incorporated into the boiler. Reviewing some basic design differences from one boiler to another can provide you with valuable insight on expected efficiency performance. The following design issues should be considered during your boiler evaluation:

- Pressure Vessel Design**.** Pressure vessel design is regulated by strict ASME code requirements. There are many variations in vessel design, however, that will still meet the ASME codes. Water circulation (forced or natural), low stress design and accessibility are key criteria for proper pressure vessel design. The boiler should include proper heat exchanger design. Fully accessible maintenance points for ease of inspection and low maintenance costs are also key design criteria for which to look.

- Number of Boiler Passes**.** The number of boiler passes simply represents the number of times the hot combustion gas travels through the boiler. A boiler with two passes provides two opportunities for the hot gasses to exchange heat to the water in the boiler. A 4-pass unit provides four opportunities for heat transfer. While it would seem that a boiler with more passes would be more efficient, this may not be true. There have been advances in heat transfer tube design which can nearly double the heat transfer rate of the new tube compared to a standard smooth tube. Do not evaluate boiler efficiency simply by the number of passes.

- Boiler Heating Surface. The heating surface in square feet per boiler horsepower represents, in general terms, how hard the vessel is working. The standard heating surface for many packaged boilers has been five square feet per boiler horsepower. In the past, heating surface has been a good indicator of the potential efficiency for a boiler. Forced circulation designs may require, however, significantly less heat transfer surface per boiler horsepower. In addition, with new, enhanced heat transfer tube technology and other boiler design considerations, five or more square feet per horsepower does not necessarily result in higher efficiency. This makes proper boiler efficiency testing even more important when evaluating boiler selection.

Maintenance Costs

Review your maintenance costs carefully. The old unit could be costing you money in various ways, including emergency maintenance, downtime, major maintenance requirements (past and pending), difficult-to-find and expensive parts requirements, operator time in keeping the unit on-line, and overall vessel, burner, and refractory problems. You may be paying a premium for having outdated boiler room equipment. These costs need to be thoroughly investigated and evaluated.

Repeatable Air/Fuel Control

The efficiency of the boiler depends on the ability of the burner to provide the proper air-to-fuel mixture throughout the firing range, day in and day out, without the need for complex set-up or adjustments. When it comes to choosing the burner insist on linkage-less technology or, alternatively, a simple linkage assembly with minimal hysteresis, as well as accessible burner design for true efficiency and real savings. The burner should also be able to provide suitable turndown and low excess air. Low excess air capability is one factor that will improve the boiler efficiency.

Type of Fuel Fired

If your old unit is designed to fire heavy fuel oil, or if you need to evaluate propane or any other different fuel capability, review the conversion costs along with existing maintenance, performance and efficiency issues to see if the time is right to consider a new boiler purchase. Many times an investment is made in an old unit when the costs required for the next major maintenance requirement will justify a new unit. The result is wasted money on the old unit upgrade, with likely continued high fuel cost due to the lower efficiency associated with an old boiler.

SEVERAL METHODS FOR DETERMINING BOILER EFFICIENCY

The several different methods of defining the efficiency of boilers can present a confusing picture. There are only two methods, or terms, however, that really matter to the end-user, these are Combustion Efficiency and Fuel-to-Steam or Fuel-to-Water Efficiency.

Combustion Efficiency

Combustion efficiency is an indication of the burner's ability to burn fuel and the ability of the boiler to absorb the heat generated. The amount of unburned fuel and excess air in the exhaust are used to assess a burner's combustion efficiency. Burners performing with extremely low levels of unburned fuel while operating at low excess air levels are considered efficient. Burners firing gaseous and liquid fuels operate at excess air levels of 15% or less and negligible amounts of unburned fuel. By operating at only 15% excess air, less heat from the combustion process is being used to heat excess air which increases the available heat for the boiler load. Combustion efficiency is not the same for all fuels; generally, gaseous and liquid fuels burn more efficiently than do solid fuels. As combustion efficiency does not account for several other factors needed to determine a boiler's fuel usage, it should not be the sole factor used in economic evaluations. Combustion Efficiency is also referred to as "Flue Loss or Stack Loss Efficiency."

Fuel-To-Steam or Fuel-to-Water Efficiency

Fuel-to-steam or fuel-to-water efficiency is a measure of the overall efficiency of the boiler. It accounts for the effectiveness of the heat exchanger as well as the radiation and convection losses. For space heating boilers and in the BTS-2000 testing procedure, this type of efficiency is called "thermal efficiency." It is an indication of the true boiler efficiency and should be the efficiency method used in economic evaluations.

Fuel-to–Steam or Fuel-to-Water efficiency may also be referred to as "Boiler Efficiency", on occasion, as well as "Thermal Efficiency" in Federal Standards and certain market segments.

When the term "Thermal Efficiency" is used it is important to confirm that radiation and convection losses (jacket losses) are included.
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INDUSTRY-RECOGNIZED EFFICIENCY TEST STANDARDS

The two most prominent industry-wide testing standards for boilers are ASME PTC 4 and BTS-2000. The Federal government requires that all packaged commercial space heating boilers meet federal minimum efficiency requirements when tested according to BTS-2000. The BTS-2000 Standard is designed to facilitate laboratory testing and allows a fair comparison of boiler efficiency ratings under standard conditions. There are no mandatory federal test procedures for boilers intended to provide heat for applications other than building heating.

ASME PTC 4 is a more appropriate test standard for industrial and utility boilers, particularly those firing solid fuels, and for determining boiler efficiency once the boiler is installed and operating.

ASME PTC 4

As prescribed by the ASME Power Test Code, PTC 4, the fuel-to-steam efficiency of a boiler can be determined by two methods: the Input-Output Method, and the Heat Loss Method.

- Input-Output Method. The Input-Output efficiency measurement method is based on the ratio of the output-to-input of the boiler. It is calculated by dividing the boiler output (in BTUs) by the boiler input (in BTUs) and multiplying by 100. The actual input and output of the boiler are determined through instrumentation and the resulting data is used in calculations that determine the fuel-to-steam efficiency.

- Heat Loss Method**.** The Heat Balance efficiency measurement method is based on accounting for all the heat losses of the boiler. The actual measurement method consists of subtracting from 100 % the total percentage of: A) stack, B) radiation, and C) convection losses. The resulting value is the boiler's fuel-to-steam efficiency. The heat loss method accounts for stack, radiation and convection losses.

BTS-2000

The standard BTS-2000 test conditions, for purposes of comparison, limit steam pressure to a maximum of 2 psig and steam quality to a minimum of 98 percent. Water tests require boiler inlet temperatures between 35 deg. F and 80 deg. F (75 deg. F and 85 deg. F for condensing boilers) and, for hot water boilers, outlet water temperatures between 178 and 182 deg. F. These low inlet temperatures and low flow rates conveniently allow the use of ordinary unheated city water for laboratory testing. The performance ratings derived from laboratory testing are likely to differ from actual performance when the boiler is installed in a heating system, because of the difference between operating conditions and test conditions.

COMPONENTS OF EFFICIENCY (PRINCIPAL FACTORS)

Boiler efficiency, when calculated by the ASME Power Test Code, PTC 4, or BTS-2000 includes stack, radiation and convection losses. But what factors have the most impact on boiler efficiency? As discussed earlier, the basic boiler design is the major factor. However, there is room for interpretation when calculating efficiency. If desired, you can make a boiler appear more efficient than it really is by using "favorable" factors in the efficiency calculation.

The following are the principal factors affecting efficiency calculations:

- Flue gas temperature
- Stack Losses
- Heating medium temperatures (steam pressures in the case of steam boilers)
- Radiation and convection losses
- Excess air
- Ambient air temperature
- Heating Medium Temperatures
- Turndown
- Fuel specification
- Steam quality (in the case of steam boilers)

Flue Gas Temperature. Flue gas temperature is the temperature of the combustion gases as they exit the boiler. The flue gas temperature must be a proven value for the efficiency calculation to be reflective of the true fuel usage of the boiler. A potential way to manipulate an efficiency value is to utilize a lower-than-actual flue gas temperature in the calculation. When reviewing an efficiency guarantee or calculation, check the flue gas temperature. Is it realistic? Is it near or less than the saturation temperature of the fluid in the boiler? Can the vendor of the equipment refer you to an existing jobsite where these levels of flue gas temperatures exist? Jobsite conditions will vary and have an effect on flue gas temperature. However, if the efficiency value is accurate, the flue gas temperatures should be repeatable in similar applications. One of the parameters affecting flue gas temperature is the boiler fluid temperature; thus, care should be taken to ensure that efficiency comparisons between boilers are made at the same bulk water temperature or steam pressure.

The use of flue gas economizers should be considered in certain types of applications, particularly those in which high pressure steam is used. Economizers are available in both condensing and non-condensing types. Typically an economizer preheats boiler feedwater using the heat available in the flue gases, thus saving energy, and, inasmuch as the flue gas temperature is now the economizer exit temperature rather than the boiler flue exit temperature, the overall boiler efficiency is enhanced.

Stack Losses. Stack temperature is a measure of the heat carried away by dry flue gases and the moisture loss. It is a good indicator of boiler efficiency. The stack temperature is the temperature of the combustion gases (dry and water vapor) leaving the boiler and reflects the energy that did not transfer from the fuel to the steam or hot water. The lower the stack temperature is, the more effective the heat exchanger design and the higher the fuel-to-steam or fuel-to-water efficiency.

Heating Medium Temperatures. Similarly, the efficiency of a boiler typically is higher when the heating medium is cooler. This effect is most pronounced in condensing hot water boilers, which do not even condense when feedwater temperatures exceed the dew point temperature of the flue gases. Be sure that when comparing boilers, you compare efficiency ratings at similar system operating temperatures. A boiler's efficiency can increase by several percentage points when testing at extremely and unusually cool feedwater temperatures and high flow rates.

Radiation and Convection Losses. All boilers have radiation and convection losses. Radiation and convection losses represent the heat losses radiating from the boiler vessel. Boilers are insulated to minimize these losses. Radiation and convection losses, expressed in Btu/hr, are essentially constant throughout the firing range of a particular boiler, but vary between different boiler types, sizes, and operating pressures. Radiation and convection losses also are a function of air velocity across the boiler. A typical boiler room does not have high wind velocities. However, boilers operating outside will have higher radiation and convection losses. Sometimes efficiency is represented without any radiation and convection losses. This is not a true reflection of fuel usage of the boiler.

Excess Air. Excess air is the extra air supplied to the burner beyond the air required for complete combustion. Excess air is supplied to the burner because a boiler firing without sufficient air or "fuel rich" is operating in a potentially dangerous condition. Therefore, excess air is supplied to the burner to provide a safety factor above the actual air required for combustion.

Excess air uses energy from combustion, however, thus taking away potential energy for transfer to water in the boiler. In this way, excess air reduces boiler efficiency. A good quality burner design will allow firing at minimum excess air levels of 15% (3% as O_2) or less while maintaining acceptable carbon monoxide levels (generally accepted at less than 100 ppm). Excess air is measured by sampling the O_2 in the flue gas. If 15% excess air exists, the oxygen analyzer would measure the O_2 in the excess air and show a measurement of approximately 3%.

Seasonal changes in temperature and barometric pressure can cause the excess air in a boiler to fluctuate 5%-10%. Furthermore, firing at low excess air levels can result in high CO and boiler sooting.

When reviewing an efficiency guarantee or calculation, check the excess air levels. If 15% excess air is being used to calculate the efficiency, the burner should be of a very high quality design with repeatable damper and linkage features. Without these features, your boiler will not be operating at the low excess air values being used for the calculation, at least not for long. If less than 15% excess air is being used for the calculation, you are probably basing your fuel usage on a higher efficiency than will be achieved in your day to day operation. You should ask the vendor to recalculate the efficiency at realistic excess air values.

Ambient Air Temperature. Ambient air temperature can have a dramatic effect on boiler efficiency. A 40 deg. F variation in ambient temperature can affect efficiency by 1% or more. Most boiler rooms are relatively warm. Therefore, most efficiency calculations are based on 80 deg. F ambient temperatures. When reviewing an efficiency guarantee or calculation, check the ambient air conditions utilized. If a higher than 80 deg. F value was utilized, it is not consistent with standard engineering practice and will result in a higher efficiency. If the boiler is equipped with combustion air heating, this should be noted in the calculations. If the boiler is going to be outside, the actual efficiency will be lower due to lower ambient air temperatures regardless of the boiler design. To determine your actual fuel usage, ask for the efficiency to be calculated at the actual ambient air conditions.

Turndown. Turndown is the ability of the boiler to achieve a wide range (from low to high) of output. The higher the turndown the wider the range of output capabilities. Boilers with higher turndown ratios are capable of supplying steam or hot water at lower rates without shutting down and re-starting. Generally speaking, higher turndowns can offer efficiency improvements when load demand varies. The burner should be able to maintain a reasonable excess air level at the low fire position. Efficiency calculations should be made at low, fifty percent and high-fire boiler rates.

Fuel Specification. The fuel specification can also have a dramatic effect on efficiency. In the case of gaseous fuels, the higher the hydrogen content, the more water vapor is formed during combustion. The water vapor uses energy as it changes phases in the combustion process. Higher water vapor losses when firing the fuel result in lower efficiency. This is one reason why fuel oil fires at higher efficiency levels than natural gas. To get an accurate efficiency calculation, a fuel specification that represents the jobsite fuel to be fired must be used. When reviewing an efficiency guarantee or calculation, check the fuel specification. Is it representative of the fuel you will use in the boiler? The representation of efficiency using fuel with low hydrogen content will not provide an accurate evaluation of your actual fuel usage.

Other Efficiency Considerations. Some boiler designs can supply steam or hot water with very little start-up or warm-up time. When load demands fluctuate or are intermittent, consideration for optimum use of fuel and steam should recognize this factor. The ability to quickly start a boiler and produce steam vs. operating in a standby mode will improve the operational efficiency of your boiler installation.

In order to get a complete picture of boiler energy use, such items as fan, air compressor and other electrical requirements, and the system related requirements of water treatment make-up and blowdown rates should all be evaluated. On oil burning equipment, the use of steam atomization also has an energy impact.

SUMMARY

Selection of a boiler with “designed-in” low maintenance costs and high efficiency can really pay off by providing ongoing savings and maximizing your boiler investment. Remember, first cost is a very small portion of your boiler’s total life-cycle cost.

High boiler efficiency is the result of specific design criteria, including:

- Pressure vessel design
- Maintenance costs
- Repeatable air/fuel control
- Fuel-to-steam or fuel-to-water calculations that are accurate and representative of actual boiler fuel usage requiring the use of proven and verified data, including:

    1. Accurate flue gas temperature
    2. Proper representation of radiation & convection losses
    3. Accurate excess air levels
    4. Accurate ambient air temperature
    5. Accurate fuel specification
    6. Accurate measurement of steam quality in the case of steam boilers

When evaluating your boiler purchase, ask your boiler vendor to go through the fuel-to-steam or fuel-to-water efficiency calculation to verify that it is realistic and proven. Also review the type of boiler/burner being utilized to check if the unit's performance will be consistent and repeatable.

The facts regarding boiler efficiency make it clear that optimal high efficiency boiler designs are available. You will get superior performance with these premium designs, providing the efficiency calculations are verified and proven. Make sure the efficiency data you are using for your boiler evaluation is guaranteed, accurate and repeatable over the life of the equipment, and be certain your actual fuel usage requirements of the boiler are understood before you buy.

In the end, the time spent evaluating efficiency will be well worth the effort. Insisting on a high efficiency, repeatable design boiler will pay off every time your new boiler is fired, for the entire life of the equipment.

Determining & Testing Boiler Efficiency for Commercial/Institutional Packaged Boilers is a product of the Commercial Systems Product/Market Group of the American Boiler Manufacturers Association and was approved by members of the Group, as well as the ABMA Board of Directors, in May 2008.

The American Boiler Manufacturers Association (ABMA) is the national, nonprofit trade association of commercial, institutional, industrial and electricity-generating boiler system manufacturing companies (> 400,000 Btuh heat input), dedicated to the advancement and growth of the boiler and combustion equipment industry.