Technical White Paper

Boiler Efficiency

Volume 1, Issue 1

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The emphasis on green technologies has increased the use of and specifications for high-efficiency hydronic systems. Environmental regulations have mandated lower emissions of greenhouse gases. We do not want efficiency and emission control to adversely impact boiler operation and reliability. Efficient operation requires proper combustion as well as performing necessary maintenance. Necessary maintenance requirements will vary based upon the boiler design as well as operating conditions. Low maintenance cost depends on good daily operating control.

Combustion Analysis

The (3) essential components of combustion are fuel, air and heat. Combustion is the rapid chemical reaction between oxygen and a combustible material that releases heat and light. Usually the combustible material is a hydrocarbon and ambient air supplies the oxygen. Understanding this process is essential for safe and efficient operation. Perfect combustion is the proper mixture of fuel and air under exacting conditions where both the oxygen and fuel are completely consumed in the combustion process. Having just the right amount of oxygen (no more, no less) is called the stoichiometric point, simply the ideal air to fuel ratio for combustion.

With hydrocarbons, complete combustion occurs when there is sufficient oxygen to convert the entire carbon to carbon dioxide and all of the hydrogen to water. Incomplete combustion means that there is either unburned or partially reacted fuel (combustibles), i.e., carbon monoxide, hydrogen, etc. Methane is the main constituent of natural gas. It reacts with oxygen to form carbon dioxide and water.

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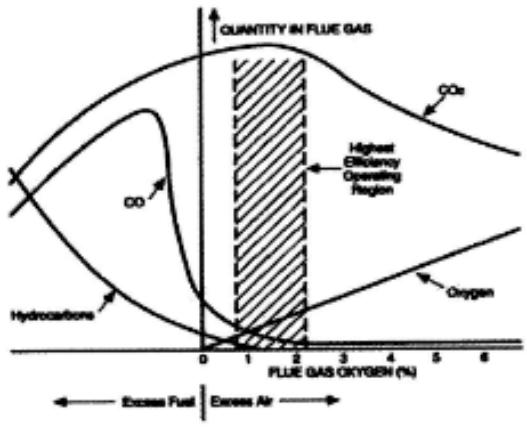
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$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

This stoichiometry is typical of all hydrocarbons. One atom of carbon requires one molecule of oxygen and four atoms of hydrogen require one molecule of oxygen. Air basic constituents are Nitrogen (N_2) 78.084 ± 0.004 % + Oxygen (O_2) 20.946 ± 0.002%, and Argon (Ar) 0.934 ± 0.001%. The theoretical air is that needed, for complete combustion of the carbon and hydrogen: 2 molecules of oxygen for 1 molecule of methane; i.e., 1 cu. ft. of methane (at standard temperature and pressure) will burn completely with 9.53 cu. ft. of air. The ratio of 9.53 to 1 is known as the stoichiometric air-fuel ratio. The heat released when the fuel burns completely is known as the heat of combustion.

The Importance of Excess Air

Excess air is that supplied in addition to what is required. For example, 20% excess air means that the air supplied is 1.2 times the stoichiometric amount. In actual applications it is impossible to achieve stoichiometric combustion because burners cannot perfectly mix air and fuel. It is extremely undesirable to operate a burner with less-than-stoichiometric combustion air. This will result in a smoky exhaust, yellow flame, flame failures, sooty boiler tube and significantly reduce the energy released by the fuel. To ensure that all of the fuel is burned and little or no combustibles appear in the flue gas, it is common practice to supply some amount of excess air. Too much excess air is inefficient because it enters the burner at ambient temperature and leaves the stack hot-thus stealing useful heat from the process.[1]



It follows then that the most immediate way to reduce fuel costs and atmospheric emissions is to ensure that excess air levels are optimized. This is done through tuning of the air and fuel controls which maximizes combustion efficiency by providing just enough excess air to assure complete combustion; while maintaining flame stabilization and preventing flame impingement over a range of firing rates.

How much excess air is enough to assure complete combustion and maintain reliable and efficient operation? The answer to that question depends upon the design of the boiler and burner, as different burners require different amounts of excess air and have different turndown ratios. The turndown ratio is the maximum inlet fuel or firing rate divided by the minimum firing rate. Boiler designs certified by CSA International and meeting the requirements of ANSI Z21.13, CSA 4.9 mandate that the manufacturer's specified minimum input shall not be less than 20% of the manufacturer's specified normal input rate, i.e. turn down ratio of 5 to 1. Burners with turndown ratios greater than 5 to 1, typically achieve that turndown with high quantities of excess air.

An advantage of high turndown burners include the reduction of standby losses, limiting thermal cycling and saves "wear and tear" of burner components. Disadvantages include Initial cost and complexity, increased maintenance, and limitations of the boiler/burner system. These system limitations include fuel/air mixing requirements, material temperature issues, flame shape characteristics, flow control limitations and greatly reduced combustion efficiencies at low turndown.

An efficient natural gas burner requires only 2% to 3% excess oxygen, or 10% to 15% excess air in the flue gas, to burn fuel. To this end it is desirable to maintain a constant amount of excess air across the entire firing range. To ensure the combustion process is optimized, yearly flue gas analysis is required to keep the fuel-air mixture at the manufacturer's recommended settings.

Modulating Burners

The following paragraph is taken from the "Rulemaking Framework Document...RIN:1904-AD01" (pg.28) dated August 28, 2013 from the U.S. Department of Energy:

Two-stage and modulating burners can decrease losses caused by burner cycling at partial loads. However, modulating burners may not accomplish net energy gains if excess combustion air levels must be increased at low firing rates (in order to maintain combustion performance) or if electrical power requirements for the burner do not decrease in linear proportion to the firing rate. In condensing boiler applications, an increase in excess combustion air ratio can result in reduced latent heat recovery due to decreased flue gas dew point temperatures. This can result in an energy loss that outweighs the benefit of reduced burner cycling.

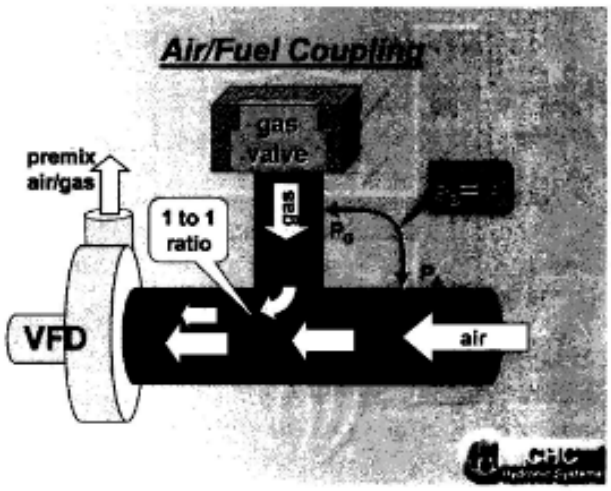
Burner Control Type

Maintaining the optimum level of excess air across the entire firing range is accomplished with the use of burner controls; including parallel positioning controls, cross-limiting controls, oxygen trim controls and fuel-air-linked-negative-pressure gas valves. These types of controls are superior alternatives to traditional mechanical jackshaft controls. A brief description of each burner control type is provided below:

Mechanical jackshaft control can be the simplest type of modulating burner control. In the basic design it is also called single point control because one mechanical linkage assembly controls both air and fuel. These controls cannot measure airflow or fuel flow. The range of control is limited, resulting in excessive levels of excess air to ensure safe operation under all conditions and firing rates. In a modulating boiler application the jackshaft control linkage consists of various arms, connecting rods, and swivel ball joints that transmit motion from the modulating motor to the metering cams, rotary air damper, and gas butterfly valve. Hysteresis in the linkages makes accurate and repeated control difficult, and requires regular maintenance and adjustment.

Parallel positioning controls use separate motors to adjust fuel flow and airflow allowing each to be adjusted over the entire firing range of the boiler. During setup, many points are "mapped," typically 10 to 25 points, to create a curve of airflow and corresponding fuel flow. The air-fuel ratio can therefore vary across the entire firing range to provide the optimal ratio under all firing conditions. With the use of electronic servo-motors, this method of control provides consistent performance and repeatability, but requires frequent inspection and maintenance to assure optimum performance.

Oxygen trim control is used in conjunction with standard parallel positioning or cross-limiting controls. It analyzes the oxygen in the flue gas and adjusts the air-fuel ratio accordingly to maintain a set amount of excess oxygen. These controls are usually installed on larger boilers with high annual fuel usage, and can increase energy efficiency by one or two percent beyond what is achieved with the standard control alone.[2]



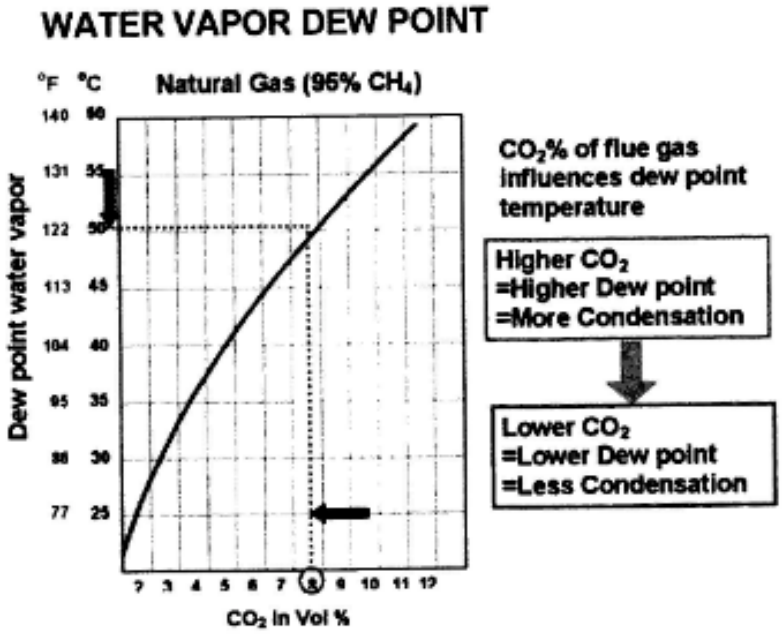
Negative pressure gas valve controls maintain the air-fuel ratio with air-fuel coupling that matches gas pressure with VFD blower air pressure. The microprocessor control senses boiler water temperature and controls the VFD blower based on temperatures being above or below set point. When the VFD blower ramps up, it brings in more CFM of air which in turn creates a greater differential across the air orifice. The negative pressure gas valve reacts to the increase in air pressure by "opening" which lets in more gas through the orifice to maintain the air-fuel ratio. In this way the air-fuel ratio is maintained as the VFD blower modulates anywhere from low to high fire. This air-fuel ratio control is linkage-less; which eliminates linkage slippage, minimizes burner maintenance and provides constant combustion quality and repeatability.

The Science of Boiler Efficiency

The advent of highly efficient and condensing hydronic hot water heating systems has changed how engineers design and specify boiler equipment. Manufacturers are offering gas fired boilers with up to 99% efficiency. That is impressive indeed but not totally objective with regard to how the equipment will actually perform in the environment the equipment is going to live and operate in. In order to ensure that specifications comply with good engineering practices, the science of efficiency and the flue gas water vapor dew point must be taken into account.

Water Vapor Dew Points

Looking at the Dew Point Chart for example 1 (good combustion), we see that 10.6% CO2 has a dew point of ~133°. That is the temperature we begin to condense water vapor out of the flue gas. In example 2, with the bad combustion, we saw combustion with 6.4% CO2, and looking at the Dew Point Chart, we see this has its dew point at ~114° before condensation can begin. The opportunity to condense is much greater with the higher combustion efficiencies. [3]



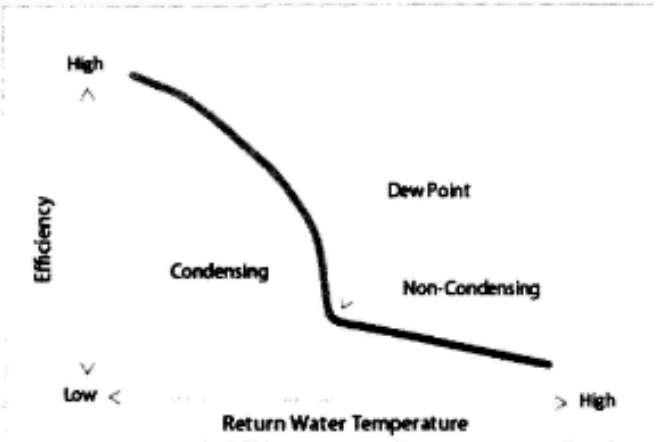
The Dew Point chart for natural gas illustrates that with an increase in the excess air level, a decrease in the CO2, the dew point temperature drops. Put another way, the extra excess air will hold more water at the lower temperature. So the extra excess air not only steals valuable Btu's, but it prevents the big gains in Btu's from flue gas condensation.

Condensing Boilers @ 102% Efficiency?

Both the system design and operating conditions are critical to the successful operation and performance of a condensing boiler. Return water temperatures below dew point are required to get the rated efficiency out of a condensing boiler. Return water temperatures above dew point prevent condensation of the flue gas and result in the boiler operating no more efficiently than a traditional boiler.

Any boiler can be run at 99% efficiency. And one could even set one up to run at over 100% efficiency, with the right conditions. How does that work?

Hot combustion gas cools as it contacts the relatively cold boiler wall temperature as it passes through the boiler. About 12% of the potential heat in the combustion gas from burning natural gas is in the form of water vapor. So unless water vapor condenses, giving up its latent heat energy, approx. 970 BTU/Lb, to the boiler water, the maximum efficiency cannot exceed 88%. Obviously to get the 99% efficiency advertised, nearly ALL of the water vapor must condense. Condensation occurs when the water vapor molecules contact a surface below the dew point. If the entering and leaving water temperatures in the boiler are both above the dew point, no condensation is possible.



It doesn't matter if there are countless water vapor molecules or just a single one. To increase the efficiency above 88% there must be condensation of water vapor in the flue gas. In order to condense that water vapor, there must be metal temperatures below the dew point. To get that cool metal temperature, cold water must be introduced into the boiler. The colder the water, the more water vapor is condensed and the higher the efficiency becomes. But only to a point; there are other factors.

The goal of boiler designers is to have each flue gas molecule hit a metal surface to give up heat energy. Turbulators, baffles, pins and other items are used to help reach that goal. The time a flue gas molecule spends inside the boiler also increases its chance to hit metal too, so surface area is used to help as well. Obviously trade-offs are used or the boiler cost would soar out of control.

Let's say that there are a zillion molecules of flue gas and only an extremely small surface of cold metal. There won't be much condensation. Let's say that there are only a few molecules of flue gas and an enormous surface of cold metal. Perhaps ALL of the water vapor will condense. There are fewer flue gas molecules put into the boiler when on low firing rates compared to high rates. Therefore there is a smaller velocity and longer time for a given molecule to bounce around in the boiler. But because there is turbulence built into the boiler, there is a greater chance of a water vapor molecule hitting cold metal. More water vapor condenses at lower firing rates and higher efficiency results.

To achieve higher than 88% efficiency in a boiler, there must be cold water brought into it. ANY boiler will be a condensing boiler when you bring cold water into it! ANY boiler can operate at even 102% efficiency if the water temperature is say 40°F and the firing rate is low enough. With that condition, the flue gas can be lower than the incoming air and fuel temperature: thus efficiencies over 100%. While that might be good, the water temperature will be too low to do any sort of heating. 4

Manufacturers Operating Specifications

As we have established the correlation between dew points and combustion efficiencies, the following set points are taken from the O&M manuals of various manufacturers. This shows that generally speaking, at high turndowns, the low fire combustion efficiency is poor at best; consequently the dew point temperature lowers. The combustion science must be understood as a design factor; consideration as to how often boiler will be at lower firing rates and return water below applicable dew point temperature defines ability to condense, defines how often boiler can achieve high efficiency.

MODEL	% FIRE	CO_2	O_2	DEW POINT
Aerco Benchmark 2.0	16% 45% 100%	7.5% 8.0% 9.2%	60% 50% 30%	119F 122F 127F
Cleaver Brooks Clear Fire	20-100%	8.4 - 9.0%	32-42%	123-126F
Lochinvar Crest	4% 100%	3.5% (not clear in IOM) 7.8%	190-120% 55-40%	95-108F 120-124F
Laars Neotherm	20% 100%	8.3-8.5% 8.8-9.0%	42% 34-32%	123-124F 125-126F
Harsco Patterson Kelley Mach	20% 100%	8.8% 9.0%	34% 32%	125F 126F
Mestek HydroTherm KN	20% 100%	8.5% 9.7%	40% 23%	124F 131F

In Conclusion

- Excess air lowers combustion efficiency
- Excess air lowers the dew point temperature
- Return water must be at or below dew point to condense water vapor in flue gas
- Maximum efficiency is limited to 88% until condensation occurs

References:
1. *Boiler Plant and Distribution System Optimization Manual*, Harry Taplin
2. The Boiler Burner Consortium, an organization of the Energy Solutions Center, Inc.; Washington, DC
3. *Tech Talk Bulletin TT-06-10*, June 4, 2010; Ajax Boiler Company
4. *102%-How does that work?*; Blesi-Evans; Minneapolis, MN