White Paper
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Safer, More Efficient Combustion Control for Fired Heaters

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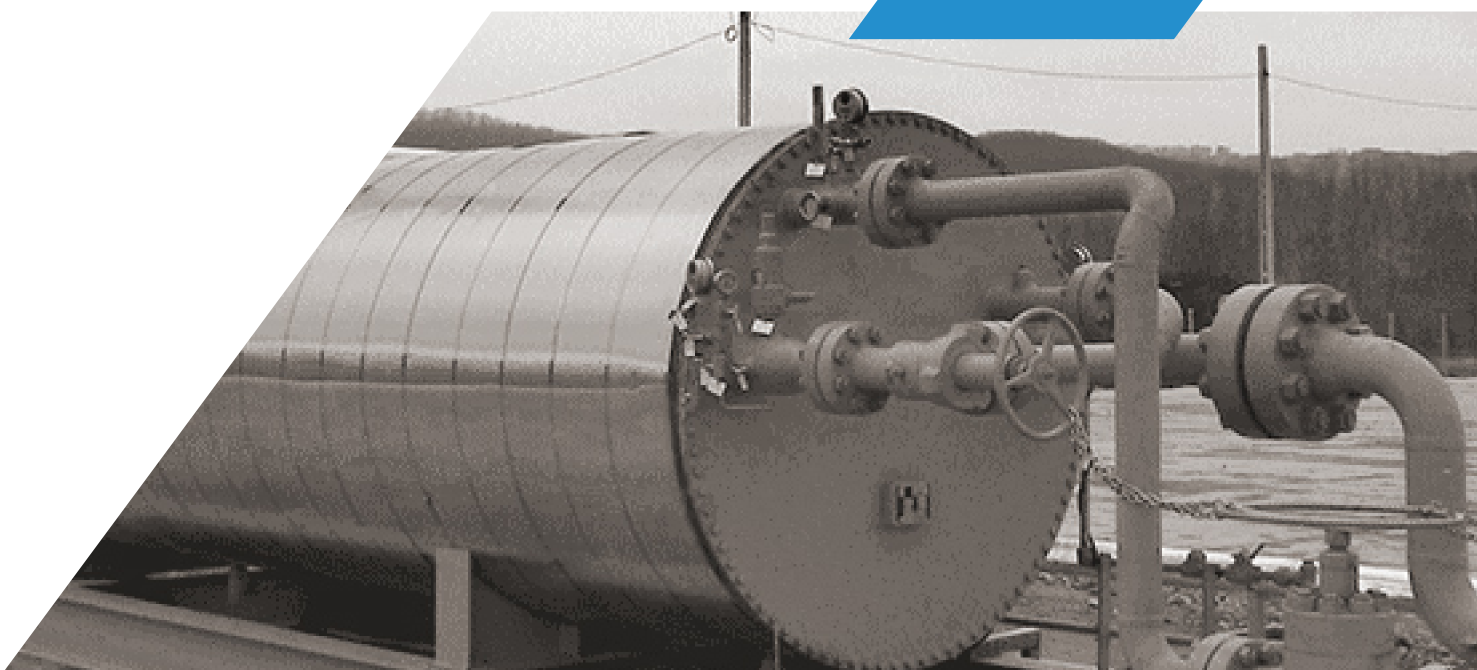

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Introduction

Fired Heaters are devices used for high-temperature heating. A fired heater is used in boiler applications to produce steam, to provide heat for chemical reactions such as ethylene cracking, and as the heat source for fractionation or distillation columns. The heat energy that fuels most furnaces in a refinery or petrochemical plant is supplied by combustion, usually by burning natural gas or fuel gas.

In this whitepaper, we will discuss challenges associated with safe, efficient, and regulatory compliant fired heater operation. We also provide details on control scheme options and a net present value study to evaluate various methods of fuel gas control for natural draft fired heaters.

Many of these concepts also apply to combustion control in energy intensive industries such as steel manufacturing, ammonia and urea production, methanol, and power generation but are not addressed in this white paper.

Challenges

The biggest challenge for fired heater operations is to keep them safe and at the same time, energy efficient and environmentally friendly/compliant.

The best and most common measure of combustion efficiency is monitoring the percent O_2 in the flue gas. High levels of O_2 in the flue gas assures an added margin of safe furnace operation, but has negative implications for thermal efficiency and environmental compliance.

High levels of flue gas O_2 have other implications. High levels of O_2 in the flue gas can lead to increased emissions, and permitting issues. Depending on the burner type, an increase of 2% O_2 could cause an increase of 25% - 30% in NO_x emissions (see Figure 1, published in API RP 535). "Excess air" (oxygen) is added to assure more thorough combustion. For every molecule of oxygen added, almost 4 molecules of Nitrogen are along for the ride. The large amount of Nitrogen is responsible for the lowering of thermal efficiency and increase in NO_x emissions.

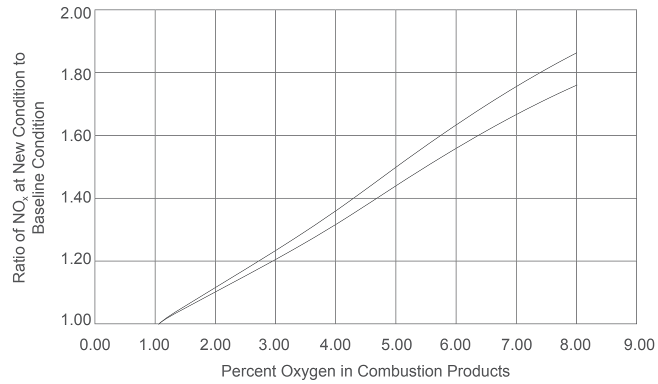


Figure 1: Percent O_2 in flue gas. Note that an increase 2% O_2 could cause an increase of 25%-30% in NO_x emissions

Running high levels of O_2 in the flue gas also results in decreased energy efficiency, through heating excess air. Conversely, enabling small reductions — even only 1% — of excess O_2 in the flue gas of fired heaters at an average-sized refinery or petrochemical plant can result in operational savings exceeding $1M/year.

On the other hand, operating with too low a level of O_2 in the flue gas creates the risk of sub-stoichiometric (insufficient oxygen) combustion, possibly tripping the heater, or in the extreme case, causing damage to the heater. Sub-stoichiometric conditions can result when the composition of the fuel feeding the combustion suddenly changes to a richer fuel that is higher in heating value, requiring more oxygen. If this could be anticipated (ie, feed-forward control), much of this challenge could be eliminated.

Reducing variability of the O_2 in the flue gas is the primary means of being able to lower the target O_2 setpoint and achieve the desired balance for safe, efficient, and environmentally friendly operation.

In the traditional approach, the process outlet temperature controller and/or the $\%O_2$ trim controller give feedback to the flow controller. These are lagging indicators. A cascade control loop is implemented using either pressure or volumetric flow of the fuel gas. This method of control can lead to problematic operation when there are rapid changes in the fuel composition.

The Solution

The root cause of heating value variability, leading to variability in $\%O_2$ in the flue gas, is the fact that the gross heating value of fuel gas and natural gas changes during operation since the components can change. The table below, which is published in API RP 538, Industrial Fired Boilers for General Refinery and Petrochemical Service, shows the gross heating values, on a mass basis vs. a volumetric basis, for components normally found in fuel gas and natural gas. The table also shows the percent change from methane (CH_4) for all the components.

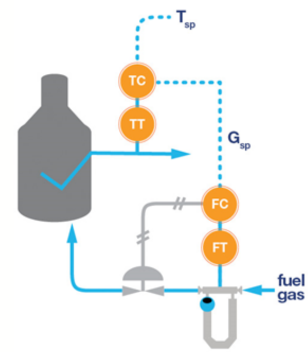


Figure 2. Flow schematic for a natural draft fired heater, using Coriolis for the flow control.

A simple flow schematic for a natural draft fired heater, using Coriolis for the flow control, is shown in Figure 2. Variability in inerts (non-combustibles) is the one condition that this control scheme cannot compensate for. Because they have a high molecular weight, but have no heating value, an analyzer for non-combustibles should be added to the control scheme.

Compound		Mass Flow Basis			Volume Flow Basis		
		BTU/lb	KJ/kg	%?from CH_4	BTU/scf	KJ/Nm³	%?from CH_4
Methane	CH_4	23.887	55.561	—	1012	37.706	—
Ethane	C_2H_6	22.323	51.923	-7%	1772	66.023	75%
Propane	C_3H_8	21.669	50.402	-9%	2522	93.967	149%
I-Butane	C_4H_{10}	21.186	49.279	-11%	3251	121.129	221%
n-Butane	C_4H_{10}	21.313	49.574	-11%	3270	121.837	223%
I-Pentane	C_5H_{12}	21.064	48.995	-12%	4012	149.483	297%
n-Pentane	C_5H_{12}	21.105	49.090	-12%	4020	149.781	297%
(n)Hexane+	C_6H_{14}	20.804	48.390	-13%	4733	176.347	368%
Hydrogen	H_2	51.900	120.719	117%	273	10.172	-73%

The table shows that the heating value correlates much more closely to mass flow than volumetric flow. By controlling the set point of fuel gas on a mass flow basis you can more closely control the energy feeding the combustion, and thus the air (oxygen) required. Hydrogen (H_2) is the exception to the relatively consistent energy value. On a mass basis, it has twice the energy content of methane. However, H_2 is so light compared to the hydrocarbons that it doesn't impact the overall heating value of the gas significantly on an energy/mass basis furthering the case for mass flow measurement.

Another option for enhancing this control scheme is to add a specific gravity analyzer on the fuel or natural gas. The relationship between the specific gravity of natural gas and its energy content is well established by AGA-5 in the following equation.

Heating Value (BTU/SCF) = 1150.1 (S.G) + 143.77 – (%CO2 x 25.38) – (%N2 x 16.639)

For fuel gas (RFG), the energy content cannot be defined in a general sense, but data can be collected for each site to establish and validate the relationship between the RFG and the specific gravity of the gas.

Combining the mass flow measurement from the Coriolis meter with the energy content of the gas allows you to control the energy for combustion and the heat release at the burner.

Operational Benefits

There are regulatory compliance benefits, in addition to the safety and efficiency benefits, to improving combustion control using Micro Motion Coriolis and Specific Gravity Meters on the fuel. The fuel that is consumed in combustion operations has to be reported to governing environmental regulatory agencies, such as the EPA. The meters controlling that process have requirements for accuracy and calibration or verification frequency.

Because Emerson's Micro Motion Coriolis meters feature Smart Meter Verification (SMV), the necessity to calibrate transmitters or pull orifice plates or other primary elements to verify measurement accuracy is eliminated. Most regulatory agencies and governing bodies recognize Emerson's recommended practice to verify accuracy. Simply running SMV while the meters are fully functional during normal operations meets the requirement.

To sum up, the benefits of the Micro Motion Coriolis solution for combustion control include:

- Improved fuel-to-air ratio control with changing composition
- Reduced O2 in the flue gas (reduced excess air fed to the combustion process)
- Reduced probability of insufficient air and heater trips
- Ability to select a %O2 setpoint acceptable from a safety, efficiency and environmental perspective
- More accurate and reliable emissions reporting
- Operational cost savings

Economic Benefit Study

A study was performed by members of an API RP556 subcommittee to evaluate various methods of fuel gas control for natural draft fired heaters. The objective was to calculate the net present value (NPV) for each of the following control methods:

- Pressure control
- Pressure corrected flow control
- Temperature, Pressure corrected flow control
- Uncorrected flow control
- Temperature, Pressure, Molecular Weight corrected flow control
- Mass flow control
- Mass flow with specific gravity analysis
- BTU control (assumed to be theoretical)

The study looked at the impact of changing fuel gas compositions on the indicated flow and the heat release to the burners under each control scheme.

The goal of the fuel control scheme is to be able to control the potential heat release to the burners. Whatever control method is used, the control valve responds to the actions from the controller to keep the process at its setpoint. For example, if the fired heater uses pressure control, regardless of upstream pressure, temperature, or composition of the fuel gas, the pressure controller will control the pressure. However, the amount of fuel and the potential heat release that it brings with it can change considerably with changing composition and changes to flowing temperature.

The aim of the study was to evaluate rapid changes in the fuel gas header conditions, conditions where the coil outlet temperature controller cannot adjust the fuel quickly enough to avoid an unstable condition in the heater. The study also assumed that the air flow control is manually operated, and the outside operator cannot adjust the air flow quickly enough, so a large step change in the $\%O_2$ may occur.

The study has two main parts. The first was evaluating how each control method would perform under changing temperature, pressure, and composition, and how that would impact the %O2 in the flue gas. The second part of the study used the data from the first part to perform an NPV calculation for each control method.

For the first part of the study, a Monte Carlo simulation (1,000 simulations per control type) was performed first to calculate a steady state condition, and then to evaluate an after step change condition.

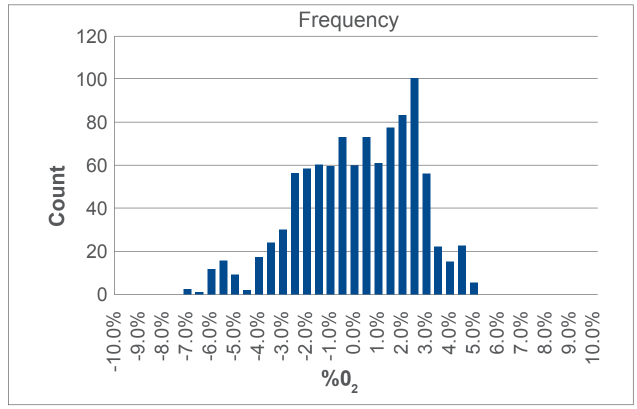
For each of the 1,000 simulations, a steady state condition was calculated using the following sequence:

1. Fix the fuel gas pressure at the burner tip
2. Randomly select fuel gas composition case
3. Run burner tip calculation to find the fuel gas mass flow
4. Assume fuel gas temperature and pressure are normally distributed
5. Calculate the reported fuel gas volumetric flow rate
6. Assume a normal distribution in the %O2 about a fixed target, and calculate the air flow rate

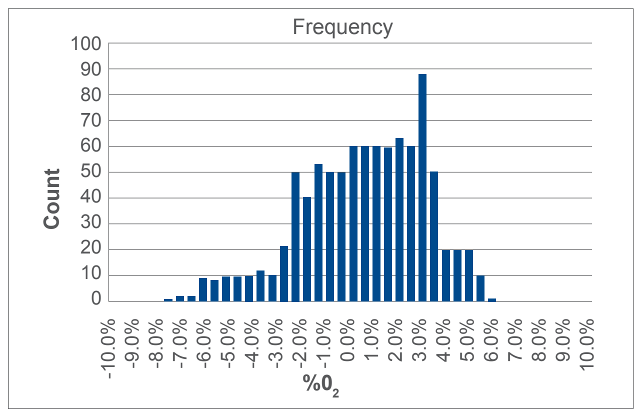
Next, a Monte Carlo simulation sequence was performed to calculate an after step change condition and determine the resulting deviation in the %O2 in the flue gas. The simulation steps were:

1. Randomly select new fuel gas composition
2. Calculate the fuel flow rate by equalizing one of the steady state conditions (depending on the control type being simulated, i.e. burner pressure, reported volumetric flow, etc.)
3. Using the steady state air flow rate, calculate the %O2 in the flue gas
4. Compare the calculated %O2 with the %O2 from steady state to evaluate the deviation

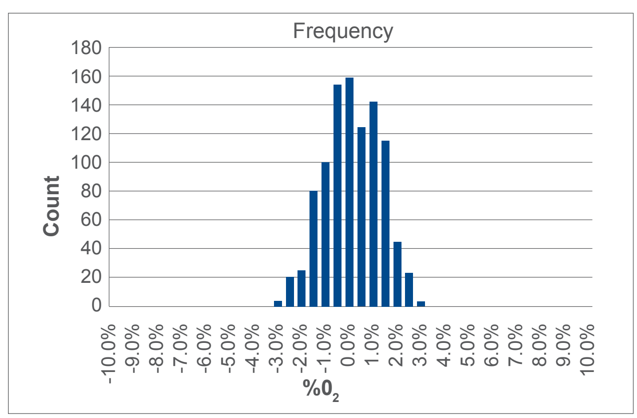
From a histogram of the results for each method of control, the target $\%O_2$ was chosen, and used in the second part of the study to calculate the NPV of each control method. The histograms below show example results from several methods of control.



Pressure Control



Volume Flow Control (Orifice dP)



Mass Flow Control

NPV calculation for the study was performed using a decision tree (see Figure 3). This approach to evaluating the NPV associates a cost with the consequence of each action being evaluated. In this case, the costs associated with running in that mode are evaluated.

One of the most important costs to evaluate is the firing cost, which depends upon the heater to be evaluated. For the specific absorbed duty of the heater chosen, the firing cost is calculated for the target O2 from the histogram results, subtracting the firing cost at 0%O2. A cost for the firing rate can then be plugged into the decision tree.

Costs were also assigned to the following events:

a) Safe shutdown

b) Minor explosion

c) Major explosion

Although the chances of having to shut down the heater are rare, and the chances of having a major or minor explosion even rarer still, it is a cost that can be evaluated by multiplying the cost by a very low probability of it occurring.

The decision tree is then populated with the following information:

a) Cost data

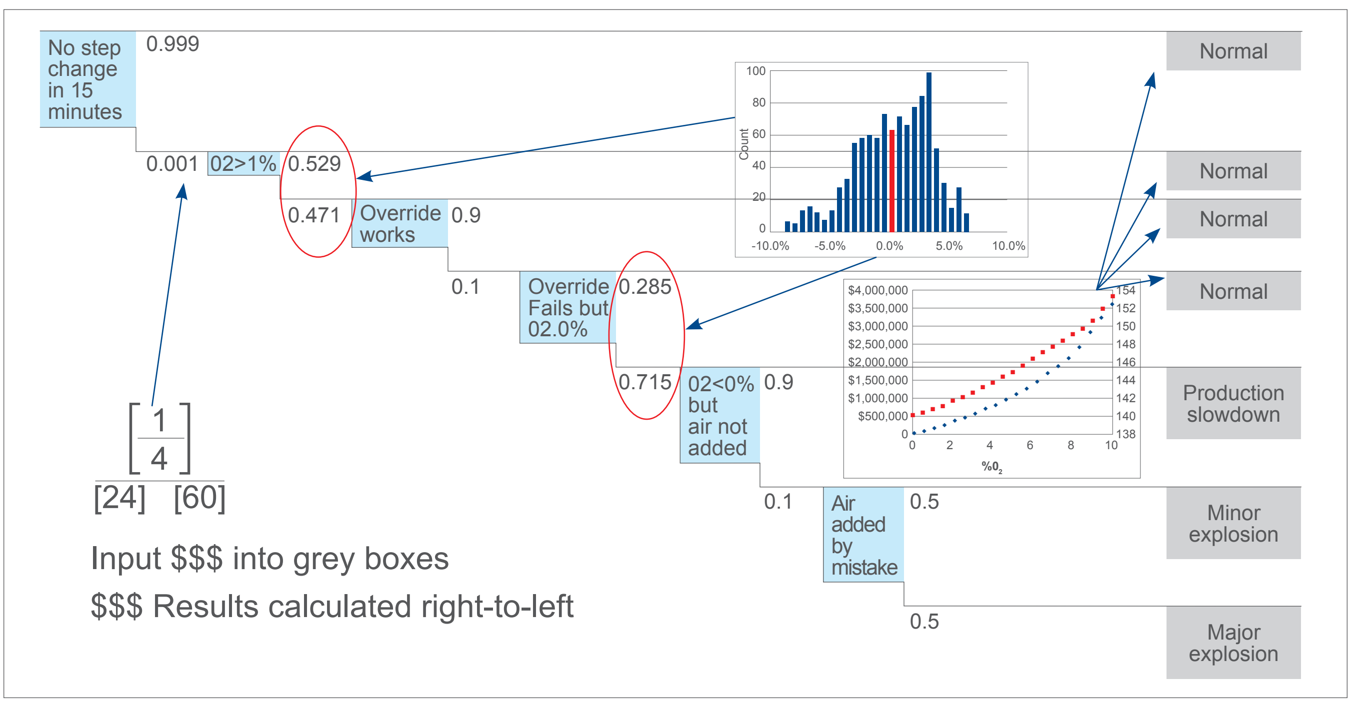
b) Probability of a fuel gas step change in a 15-minute period

c) A target $\%O_2$

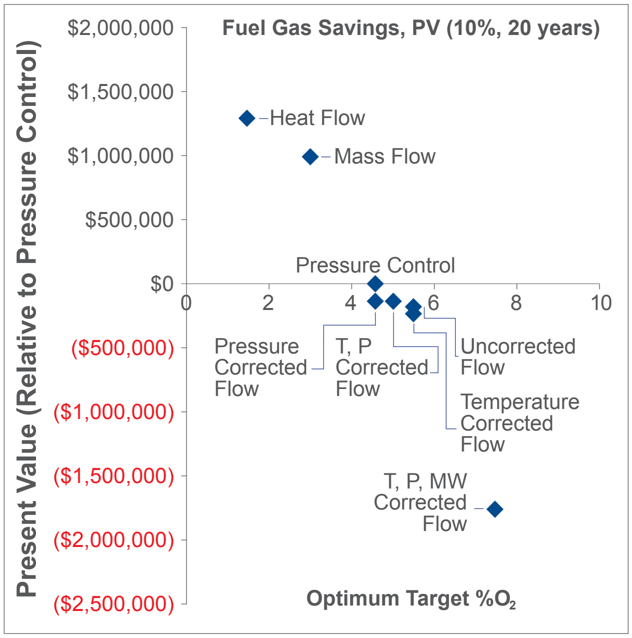
d) Monte Carlo simulation results for a specific control type

e) Probability of mitigation steps not working

An example decision tree is shown below. It is important to note that all the information that populates the decision tree can be changed based on experience with the heater under evaluation.



The results of the decision tree for a specific heater evaluated by the API group gave the following results for the various methods of control, seen in the chart below:



The NPV calculation uses a time period of 20 years, with a discount factor of 10%.

Conclusion

The fired heater study showed highly interesting results, and gave compelling reason for an evaluation to be performed for operators of natural draft (forced air heaters were not yet studied) fired heaters. The study found that controlling the fuel gas using Coriolis mass flow meters had a NPV of approximately $1,000,000, whereas temperature, pressure, or molecular weight corrected volumetric flow showed no benefit over pressure control. The only method of control that had a higher NPV was actual energy flow, but this was assumed to be a theoretical method of control because the response time for most composition analyzers is too slow for control purposes with rapidly changing composition.

The study results were based on data from a specific crude charge heater. Using data from an operator's specific furnace will give the confidence to make decisions about whether to invest in and implement a different method of control for their furnace.

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