DETECTING LOSS OF FLAME IN OIL REFINERY FIRED HEATERS USING ADVANCED PRESSURE DIAGNOSTICS

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Biography

John Miller is a principal engineer of pressure technology for the Rosemount business unit of Emerson Process Management. John works in developing and promoting applications for Rosemount Advanced Diagnostics pressure transmitters and in the research and development of new products. John has a BS in Mechanical Engineering and an MS in Electrical Engineering both from the University of Minnesota. He is inventor on 24 patents and other pending applications.

Randy Stier is a fired heater engineer with a strong track record of improving oil refinery profits through reliability, availability and energy related projects. A chemical engineer by training, Randy earned a BSChE degree from The University of Michigan and an MSChE degree from the Illinois Institute of Technology. Randy is currently Valero's Director of Refinery Heater Best Practices and Chairman of the API Subcommittee on Heat Transfer Equipment.

Abstract

Maintaining stable combustion is critical to the safe operation of fired heaters. When the ratio of air flow to fuel flow to a burner transitions from a point inside the burner's operating envelope to a point outside the burner's operating envelope, the combustion process becomes unstable and then stops. If this loss of flame is not recognized and acted upon properly, an explosion may occur.

One possible way to detect loss of flame may be to monitor pulsations in the difference between the flue gas pressure inside a fired heater and atmospheric pressure at a given elevation (commonly referred to as "draft"). During stable combustion, the draft will pulsate slightly (see Figure 1). This is commonly referred to as combustion rumble. As a burner's air/fuel ratio transitions from inside to outside the burner's operating envelope, the draft

pulsations may exhibit a sharp increase in amplitude and frequency, caused by instability in the burner flames. Flame instability is often a precursor to flame out.

Draft transmitters with Advanced Diagnostics Statistical Process Monitoring (SPM) capability monitor the pulsations in the draft measurement and detect the increase in amplitude or frequency associated with flame instability. SPM data may be integrated with heater operations. An alarm limit on the SPM standard deviation may be configured to alert a heater operator to potential combustion problems or flame out.

Valero has worked with Rosemount to evaluate the use of SPM technology for detection of flame instability or flame out. Recent testing was performed on five different burners at three different burner vendors. The technology was also evaluated on a heater at the Valero Texas City Refinery.

Experience gained from these tests may be used to determine where to set the alarm limit for detecting flame instability. There is a correlation between the volumetric firing rate of a burner/heater system and the draft standard deviation. This correlation can be exploited for selecting an appropriate alarm limit in an operating fired heater. Burner vendor tests indicate that a draft standard deviation alarm limit of 30 thousandths inches of water column (m-inWC) may be appropriate.

Additional work is required to validate these observations but initial results indicate the use of advanced pressure diagnostics may be an effective way to detect loss of flame.

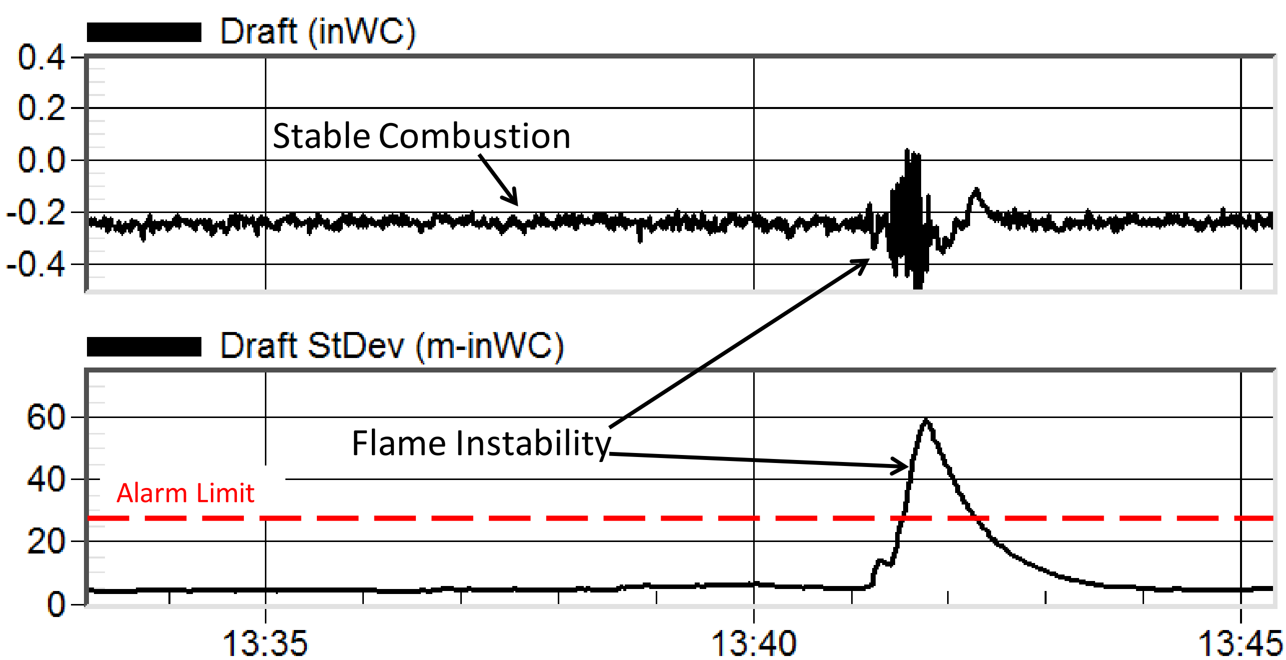

Figure 1 – Detection of Flame Instability with Advanced Pressure Diagnostics

Fired Heaters and Proper Combustion

Fired heaters are a class of indirect-fired equipment used to heat process fluids in oil refineries and other process industries. Many refineries burn fuel gas in their fired heaters in order to get the energy needed to heat the process fluids. These process fluids flow through tubes mounted throughout the fired heaters. Energy is transferred to the process fluids flowing through the heater tubes by conduction, convection, and radiant heat transfer. Process fluids can enter and exit the tubes as a gas, a liquid, or both. Fired heaters account for 2/3 to 3/4 of the energy consumed in a refinery.

Fired heater burners are designed to operate with more combustion air than needed in order to react all of the fuel gas. They are designed this way because burners are not perfect mixing devices. If a burner is only fed the amount of air theoretically required, not all of the fuel gas will find the available oxygen. The fuel gas without oxygen will not burn and combustion will be incomplete.

Maintaining stable combustion is critical to the safe operation of fired heaters. When the ratio of air flow to fuel flow to a burner transitions from a point inside the burner's operating envelope to a point outside the burner's operating envelope, the combustion process will become unstable and then stop. The transition of a burner's air/fuel ratio from inside to outside the burner's operating envelope may be caused by a number of different initiating events including a significant change in fuel gas composition, a sudden decrease in air flow, a sudden increase in fuel flow or a shift in the boundaries of the burner operating envelope.

Incomplete combustion (also known as substoichiometric combustion), caused by too little combustion air, is undesirable in a fired heater for the following reasons:

- A low oxygen-to-fuel gas ratio causes long flames which may touch the tubes. The term for this is flame impingement. If there is flame impingement, it may cause the tubes and other heater parts, such as the tube supports and refractory, to overheat.
- Energy is wasted when unburned fuel gas leaves the heater via the stack.
- Unburned fuel gas has the potential to ignite elsewhere in the fired heater if a source of oxygen is found. This is called "afterburning" and can result in damage to components in the fired heater.
- A low oxygen-to-fuel gas ratio may cause flame instability and potentially flame out.

Refinery fired heaters often use waste gas (hydrocarbon gas produced as a bi-products of other refining processes) as the fuel gas source. Burning waste gas is advantageous because it costs only a fraction per BTU as other fuel sources. The disadvantage of waste gas is that there can be significant variability in the composition, and therefore, a large variability in BTU per standard cubic foot. If the fuel gas BTU content suddenly increases, the heater may go into a state where there is not enough available oxygen for all the fuel. Figure 2 shows an example sequence of events that may result.

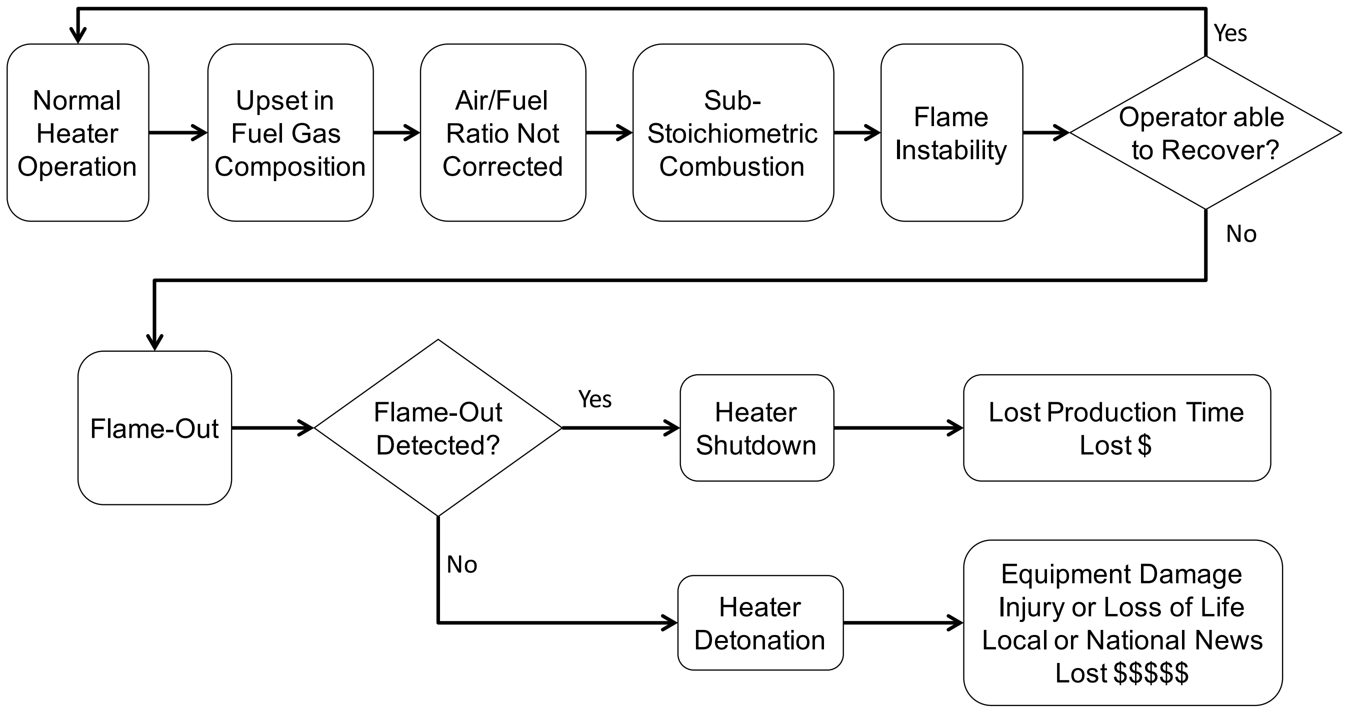

Figure 2 – Example Sequence of Events before and after a Flame out

If a heater experiences an upset in the fuel gas composition (e.g. a surge in the BTU content of the fuel gas or waste gas) and if the air/fuel ratio controller is not able to keep up, the burners may begin operating in substoichiometric, or incomplete, combustion. Depending upon the type of burner, the flames may start going unstable (Flame Instability). If the air/fuel ratio is not corrected (either manually by an operator, by via automatic O_2 control), the burner's flame may be extinguished shortly thereafter. After a flame out, a heater must be shut down to purge out the unburned fuel gas, resulting in lost production time for that operating unit. If a flame out is not detected, it is an especially dangerous situation because unburned fuel and air continues to be fed into the firebox. The slightest spark or ignition source could light this air/fuel mixture, causing a detonation of the heater, resulting in major equipment damage, and possibly, injury or loss of life.

Some refinery fired heaters with are equipped with flame scanners that can detect a loss of flame. However, flame scanners become problematic in multi-burner heaters because a flame scanner cannot detect if just a single burner is extinguished. Thus, most multi-burner heaters do not use flame scanners. For these heaters, current industry practice is to train operators to manually recognize loss of flame via operational variables, such as a sudden drop in firebox temperature and a sudden increase in O_2 or combustibles in the flue gas.

Draft Measurement and Flame Instability

The industry best practice calls for fired heaters to have a draft measurement. Draft is defined as the pressure difference between the ambient atmosphere outside of the heater and the inside of the heater firebox where combustion occurs ($Draft = P_{atmosphere} - P_{firebox}$). Figure 3 illustrates draft measurement on a fired heater. The red line shows the absolute pressure inside the heater at various elevations ($P_{firebox}$), while the blue line shows the corresponding ambient pressure ($P_{atmosphere}$).

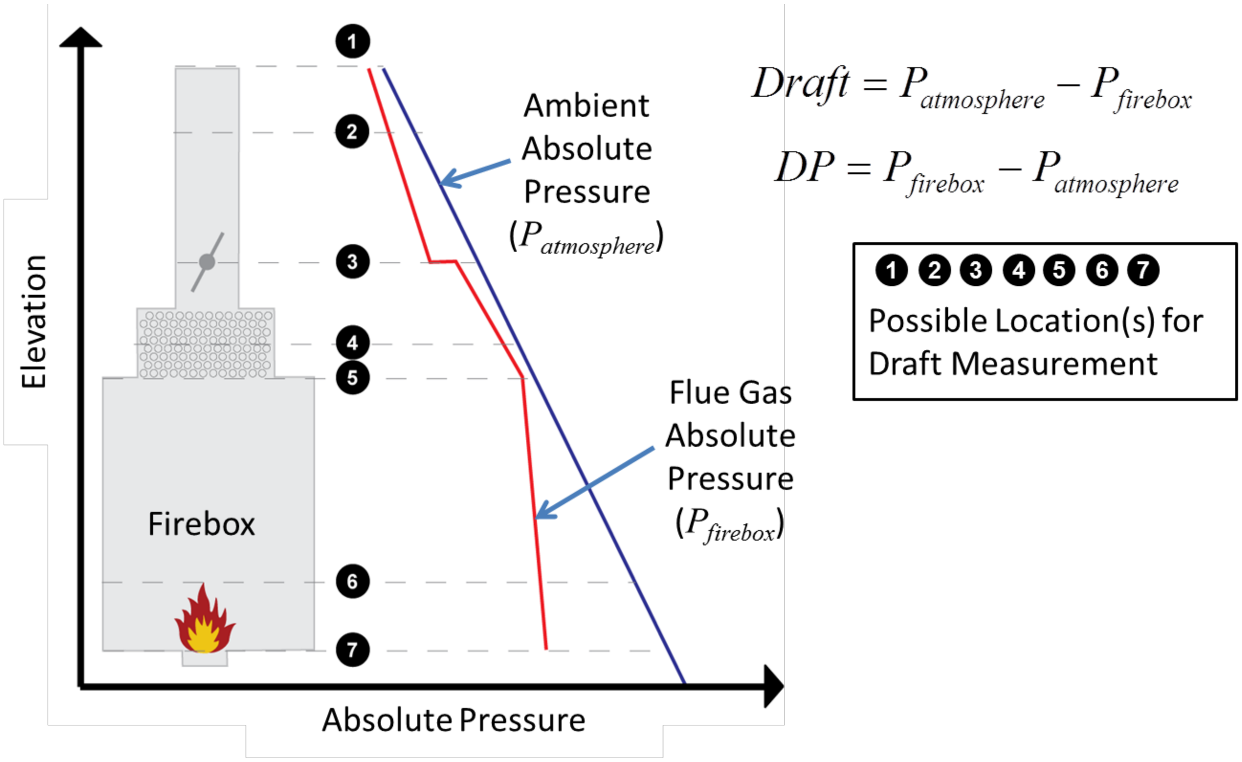

Figure 3 – Draft Measurement on a Fired Heater

Draft can be measured at any one of multiple elevations on the heater including at the stack (1 and 2), near the stack damper (3), at the convection section (4), at the bridgewall (5), near the burner (6), and at the floor of the heater (7). Typically, draft is measured at only one of these elevations. During normal operation, the firebox pressure is less than atmospheric pressure. If the firebox pressure goes higher, it is an indicator that there may be problems. Depending upon the elevation, heater design, and heater firing rate, the draft can be anywhere from 0.1 inWC (inches of water column) to 1.0 inWC. Within the industry, sometimes the draft measurement is expressed as a differential pressure ($DP = P_{firebox} - P_{atmosphere}$). Under this convention, the draft value is negative during normal combustion, and goes positive only if there are combustion problems (e.g. flame instability). Throughout the paper, we utilize this convention, showing a negative draft value in all of the trends.

As described previously, substoichiometric combustion may lead to instability in the burner flames. If someone is standing near the heater, flame instability can be heard audibly, as a "huffing" or "panting" in the heater. It is known in the industry that flame instability causes pulsations (or oscillations) in the firebox draft measurement. Sometimes flame instability is confirmed by an operator visually observing a draft gauge swinging between the positive and negative. Thermo acoustic coupling [1, 2, 3, and 4] is one mechanism that may contribute to flame instability and draft oscillations. Industry has investigated utilizing patterns in the draft oscillations for detecting flame instability [5].

Figure 4 shows an example of draft oscillations that occur under flame instability. Under normal heater combustion, the draft measurement is negative and relatively steady. However, when the flames go unstable, the draft starts oscillating, and may periodically go into positive. In the example below, during Healthy Combustion, the draft is approximately -0.2 inWC. But during Flame Instability the draft starts oscillating at a frequency of about 3 Hz, with a peak-to-peak amplitude of about 0.6 inWC. The draft even periodically goes as high as +0.2 inWC.

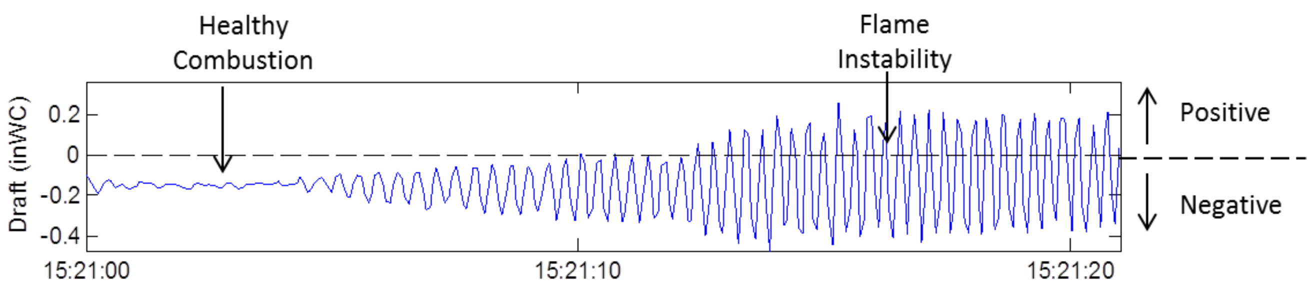

Figure 4 – Example Draft Measurement Signal during Flame Instability

However, the draft oscillations associated with flame instability are not normally seen in the draft measurement because of typical damping, filtering, or sampling, which may be implemented in the draft transmitter and/or in the Distributed Control System (DCS). Figure 5 shows the effect of transmitter damping (PV damping) on the flame instability draft oscillations. Many pressure transmitters are pre-configured with a PV damping of approximately 0.4 seconds. As shown in the middle trend, this damping flattens out the draft oscillations significantly. Sometimes a draft measurement is configured with a much higher damping (e.g. 5 seconds as shown in bottom trend) to smooth out the impact of combustion rumble on the signal, and make the draft steady when a heater is operating normally. A damping this high makes the flame instability draft pulsations impossible to see. With either the 0.4 second or 5 second PV damping, neither an operator nor an automatic control system can see the pulsations and positive differential pressure associated with flame instability.

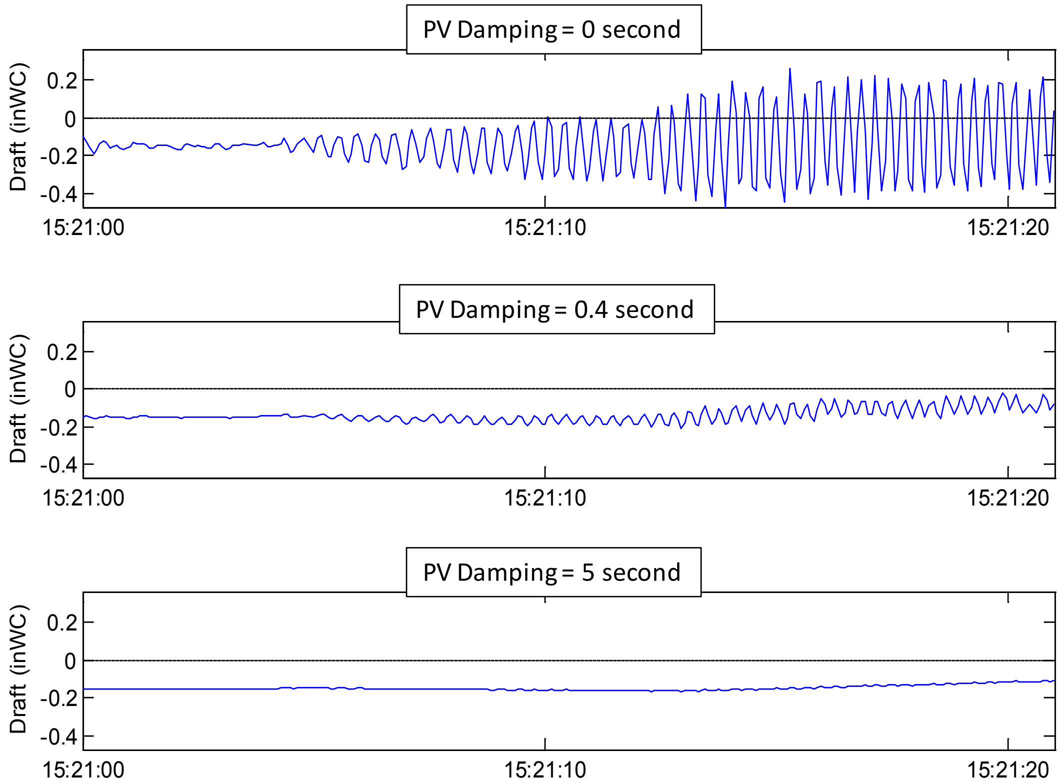

Figure 5 – Effect of Draft Transmitter Damping on Flame Instability Oscillations

The other limitation to observing the draft pulsations associated with flame instability is the damping and slow sampling rate of a typical DCS. A DCS may contain additional damping or filtering to further smooth out the draft measurement. A DCS also typically has a sampling rate too slow to see these draft oscillations. For example, a DCS may sample the pressure only once per second. Figure 6 illustrates a 1-second sampling of the draft measurement during flame instability. Because this is much slower than the 3 Hz oscillations of the draft, none of the positive pressure peaks are detected.

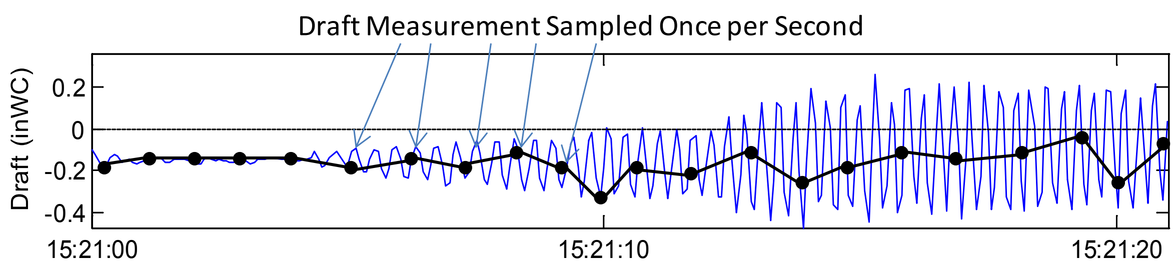

Figure 6 – Slower Sampling in the Distributed Control System (DCS)

Thus, because of limitations of transmitter PV damping, and DCS sampling rate, the draft oscillations associated with flame instability are normally not seen by a heater operator.

Advanced Pressure Diagnostics

Over the last twenty years, smart field devices have become increasingly more prevalent in the process industry. Smart field devices provide not just the basic process measurement (e.g. pressure, differential pressure, draft, temperature, or flow) but they provide a wide range of additional information, such as second and third process variables, device identification and health, and device diagnostics information. One example of such smart field devices is the Rosemount 3051S Advanced Diagnostics Pressure Transmitter with Statistical Process Monitoring (SPM) capability. SPM is available on most types of pressure measurements within the 3051S family, including absolute and gauge pressure, differential pressure (DP), DP flow, DP level, and draft. As used herein, the term “pressure transmitter” encompasses all of these pressure measurement types including fired heater draft measurement.

SPM technology allows a plant engineer or operator to see the variation (or noise) in a process that is normally filtered out when the variable is measured and displayed in the DCS. Because the pressure transmitter is closer to the process than the DCS, it can sample the pressure at a much faster rate, and turn any process variation into valuable information. The Rosemount 3051S pressure transmitter samples the pressure at 22 Hz, much faster than the typical DCS sampling rate of once every 1-2 seconds. The diagnostics transmitter calculates mean and standard deviation of the pressure and sends this information to the host system via digital communication protocol, such as HART or Foundation Fieldbus.

Figure 7 illustrates the architecture and implementation of a pressure transmitter with Advanced Diagnostics SPM capability.

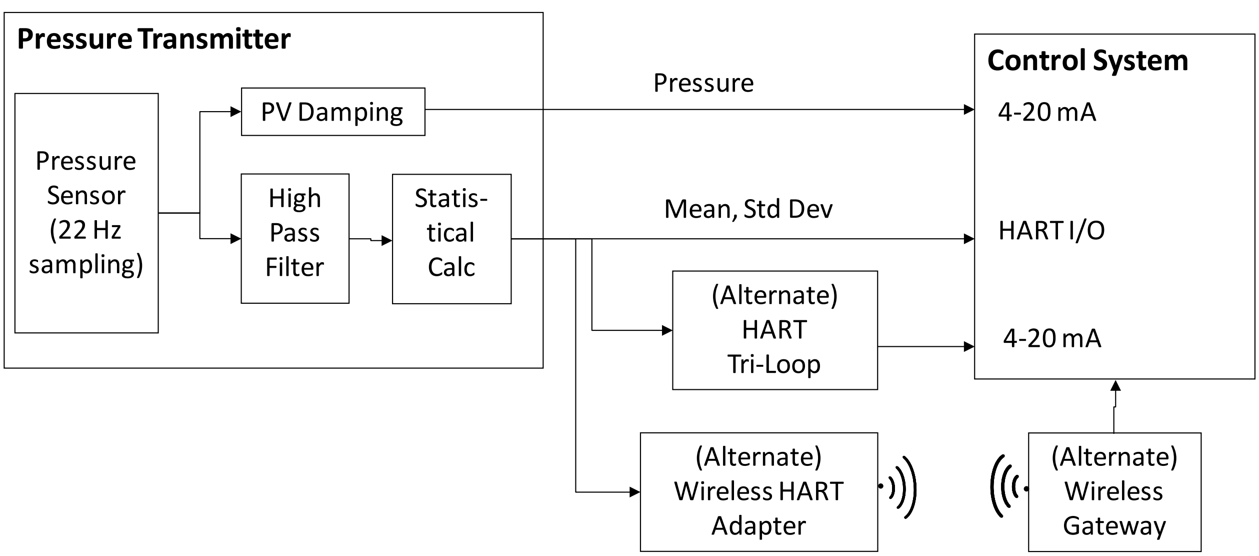

Figure 7 – Architecture and Implementation of Advanced Pressure Diagnostics

The pressure sensor measures the pressure at 22 Hz, applies the normal PV Damping, and then sends the measured pressure to the Control System via 4-20 mA. On a parallel path, a High Pass Filter and Statistical Calculations module takes the un-damped pressure and calculates mean and standard deviation. The statistical values are made available to the control system as secondary variables via HART I/O.

If a control system does not have HART I/O ability, the statistical values can still be accessed via a HART Tri-Loop (e.g. Rosemount 333) which converts the HART data to a 4-20 mA. Alternatively, a wireless HART adapter (e.g. 775 Smart Wireless THUM adapter) can be used to access the advanced diagnostics information, and transmit the information wirelessly to a gateway (e.g. 1420 Smart Wireless Gateway), which then integrates the diagnostics information with the Control System.

Figure 8 further illustrates Statistical Process Monitoring technology. On the left, is the process variable as measured by the pressure transmitter, with different amount of process variation (Normal, Noisy, and Quiet). On the right are the variables that the advanced diagnostics pressure transmitter sends to the control system.

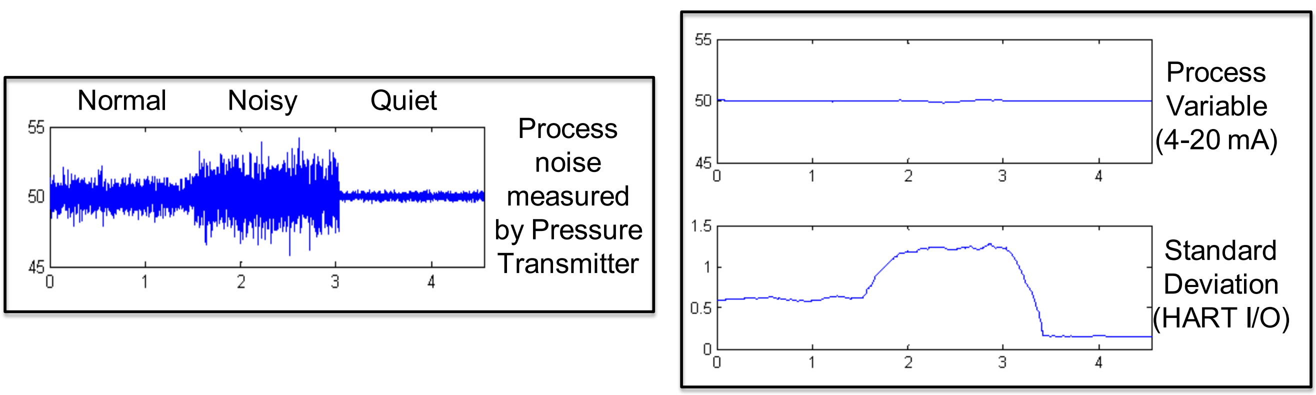

Figure 8 – Statistical Process Monitoring in a Pressure Transmitter

Note that the process variable (4-20 mA) is relatively flat, because the PV damping has removed all of the process variation. However, the standard deviation is a measure of how much process variation is in the original signal. The standard deviation is higher when the process is noisier, and it is smaller when the process is quieter.

As shown in Figure 7, a high-pass filter is used prior to the Statistical Calculations module. The purpose of the high-pass filter is to ensure that the SPM analyzes only the process variation at higher frequencies (approximately 1 Hz and higher). When there is just a slow change in the pressure measurement (such as the heater draft), this should not be interpreted as an increase in the process variation. Figure 9 illustrates the effect of using the high-pass filter. The top trend (a) represents the actual process behavior, including both a nominal (average) pressure, and random process noise. The middle trend (b) represents the pressure reading that is transmitted to the DCS via the 4-20 mA. The PV damping has smoothed out all the noise, and preserved the nominal pressure value. The bottom trend (c) represents the high-frequency noise that is analyzed by the SPM. The high-pass filter allows the SPM to analyze the pressure variation that is removed by the PV damping.

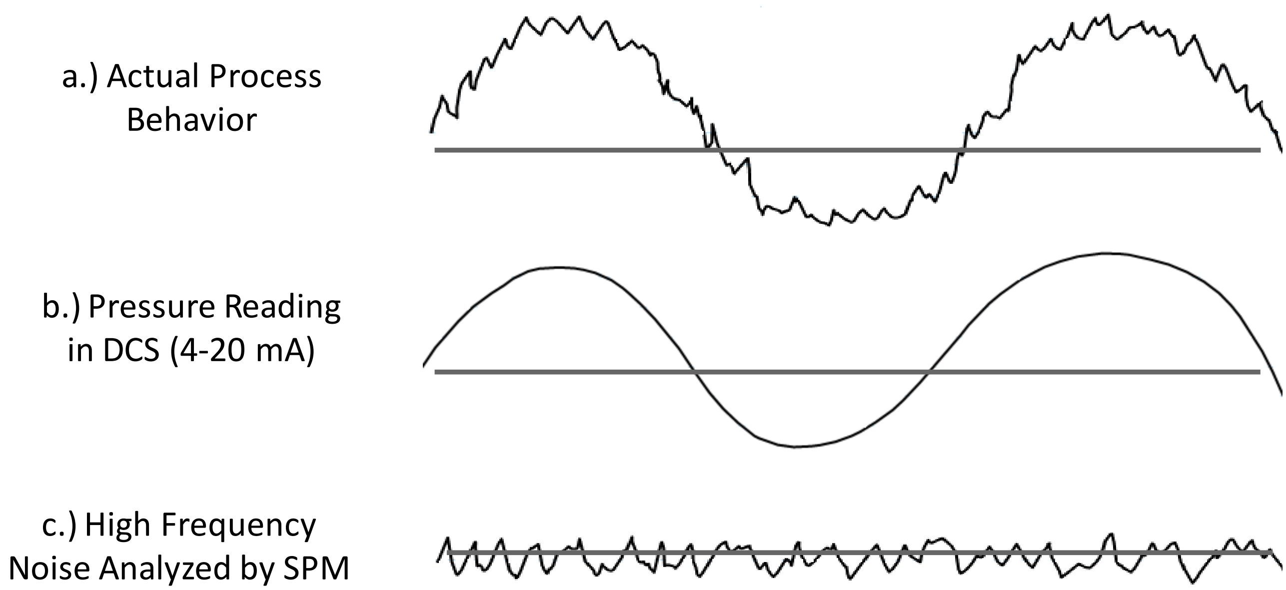

Figure 9 – Effect of High-Pass Filter on the SPM Algorithm

When the advanced diagnostics standard deviation is viewed in the control system, it is possible to detect abnormal conditions that would otherwise be unobservable using only the standard 4-20 mA pressure signal. Many different abnormal conditions have been shown to be detectable using advanced pressure diagnostics SPM technology, including plugged impulse lines [6, 7], entrained gas in liquid flows [8], increased liquid loading in natural gas wells [9], and distillation column flooding [10, 11].

Flame Instability Detection with SPM

As published previously [12, 13, 14, 15, 16], SPM technology can also be utilized to detect the draft oscillations associated with flame instability. Referring back to Figure 1, the increase in draft oscillations is detected as a change in the SPM standard deviation. This change in standard deviation occurs regardless of the transmitter PV damping (Figure 10). A heater operator, control system, or burner management system may utilize the SPM information as an indicator of instability in the burner flames either to make adjustments to prevent a flame out, or to recognize that the heater has flamed out and initiate a shut-down.

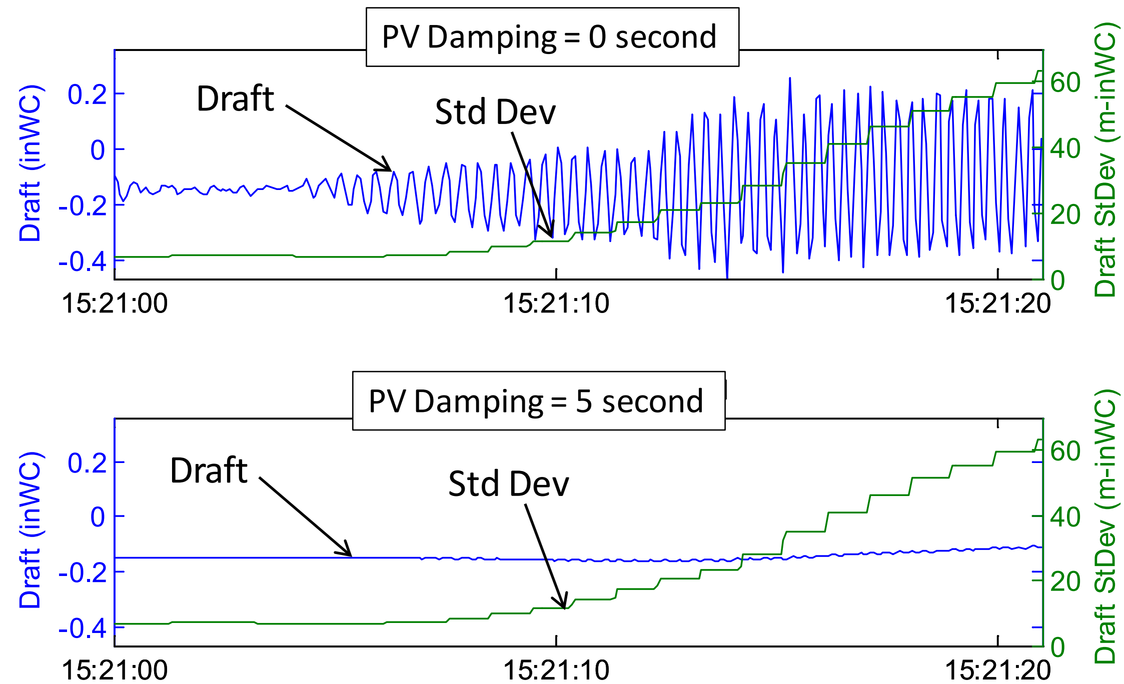

Figure 10 – SPM Standard Deviation is not affected by PV Damping

Implementing SPM technology to monitor an operating fired heater requires the following:

1. Measure draft using a draft transmitter with SPM
2. Trend SPM data into DCS process historian
3. Configure flame instability alarm

Item 1 requires simply replacing or upgrading the existing draft measurement with an advanced diagnostics draft transmitter with SPM. Referring back to Figure 3, the draft can be measured at any elevation on the heater. Previous work [13, 14, and 17] has shown that the SPM can detect flame instability regardless of the elevation of the draft measurement.

Item 2 requires first bringing the SPM data into the control system I/O via any of the interfaces shown in Figure 7, and then configuring the process historian to be trending the SPM data into the database. The SPM data may also be displayed to the heater operator so that they can use it together with other heater operational data.

Item 3 may take some additional effort. The flame instability alarm limit is the minimum value of the SPM standard deviation at which to notify a heater operator of combustion problems and/or flame instability. Obviously, in an operating fired heater, one cannot deliberately make the heater flame out, just to determine how much the standard deviation changes, in order to set the alarm limit. However, manufacturers of burners have test facilities that enable burners to be tested in a wide variety of conditions, including substoichiometric and flame instability conditions. It is possible that results from these tests at burner vendors may be utilized to gauge how much the SPM standard deviation changes under flame instability. The purpose of this joint effort between Rosemount and Valero was to evaluate the use of SPM technology for flame-instability detection, and to determine a method for setting the alarm limit on operating fired heaters.

Testing at Burner Vendors

Over two weeks in December of 2011, Valero tested five different burners at three different burner vendors. These tests were part of the standard Valero procedure for validating the suitability of each burner for various heater design or retrofit projects across the company. During these tests, each burner was evaluated on typical burner performance factors, such as range of firing rate and turn-down, flame size (length and diameter), emissions (CO, NOx, etc.), and acoustic noise levels. All five burners were the newest Ultra-low NOx burners made by each of the respective burner vendors. Four of the burners were round-flame burners, while one was flat-flame burner geometry.

Rosemount was also invited to participate in these burner tests to help evaluate the use of Advanced Pressure Diagnostics Statistical Process Monitoring technology for flame instability detection. On each test furnace, a Rosemount 3051S draft transmitter, with the Advanced Diagnostics (DA2 option), was installed. On all tests, the draft transmitter was installed at approximately the burner level (location 6 or 7 in Figure 3). Throughout the burner tests, both the un-damped draft measurement, and the draft standard deviation were recorded.

In addition to the regular burner tests, each burner was driven to various levels of substoichiometric combustion. Although burner vendors may have the capability of testing substoichiometric operation, this testing is usually not part of the standard burner test protocol, because heaters are not typically operated below stoichiometry. However, the refining industry recognizes that although they would never purposely operate a heater sub-stoked, unexpected events (e.g. a surge in the fuel gas composition) may occur periodically, and they want to be certain that their heaters will not flame out under such an event. Thus, substoichiometric testing at burner vendors is becoming more prevalent.

A typical substoichiometric / flame instability test would consist of the following:

1. Set the burner at a desired firing rate (e.g. minimum, normal, or design) and normal excess oxygen (e.g. 3% O_2, wet basis, in the flue gas)
2. While keeping the stack and burner air dampers at a constant position, gradually increase the firing rate, until the stoichiometric point (0% O_2 in flue gas) is reached. This normally coincides with the CO Break (the point where the concentration of carbon-monoxide in the flue gas exceeds 1000 parts per million).
3. While still keeping air dampers at a constant position, continue increasing the firing rate into the substoichiometric range. Because the % of stoichiometry cannot be measured directly, it must be estimated based on how much the fuel gas flow is increased.
4. Continue increasing the firing rate until either flame instability is observed (on a camera or through a test furnace viewport) or until the test furnace operators feel they cannot safety operate any further into the substoichiometric range.

Figure 11 shows an example of one of the flame-instability tests at a burner vendor. The top trend shows the un-damped draft measurement, while the bottom trend shows the draft standard deviation. Note that throughout this paper, the draft standard deviation is shown in units of thousandths inch of water column (m-inWC). For example 6 m-inWC = 0.006 inWC.

In this burner test, operation started at a baseline firing rate (3.6% O_2), and then the firing rate was gradually increased. The burner was still stable at both the stoichiometric point (3.15 MMBtu/hr) and at 90% of stoichiometry (3.47 MMBtu/hr). However, when trying to hold the burner at 85% of stoichiometry (3.6 MMBtu/hr) the burner flames would suddenly start becoming unstable. The flame instability could be seen both on a camera, visible in the control room, and in observing directly through a viewport on the test furnace. During flame instability, the sides of the burner flames could be described as "clapping hands together", and an audible "huffing" sound near the burner air intake.

Prior to the point of flame instability, the draft standard was approximately 4 to 7 m-inWC. However, at the point of flame instability, the standard deviation went up to between 60 and 70 m-inWC (about a 10 times increase). In all of the observed instances of flame instability, there was a similar large increase in standard deviation.

An alarm limit on the draft standard deviation could be defined for detecting flame instability. In this example, 30 m-inWC may be an appropriate alarm limit.

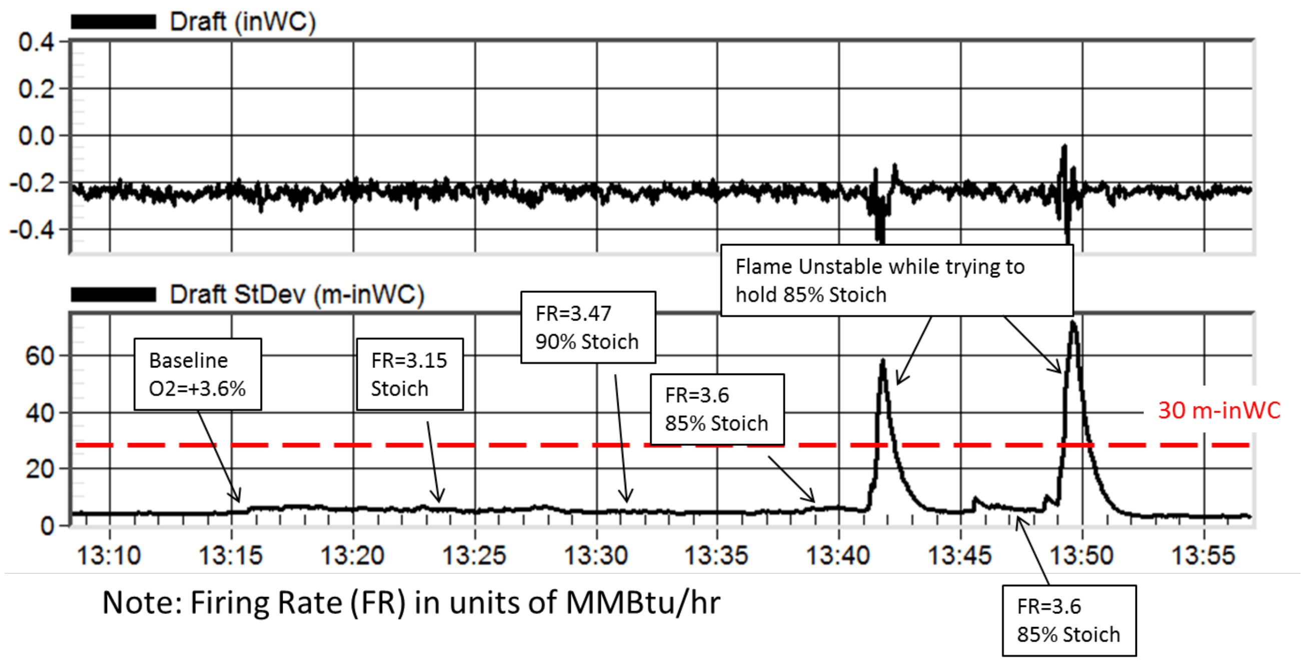

Figure 11 - Example Substoichiometric and Flame Instability Test at a Burner Vendor (Burner D-2 at Normal Firing Rate)

Table 1 shows a summary of all of the flame instability tests conducted at the burner vendors. Only burner vendor D was able to run the burners far enough into the sub-stoichiometric operating region to create flame instability. Burner vendors E and F showed their burners were stable down to 71% and 90% of stoichiometry respectively, but neither one had a test protocol that could take their burners to the point of flame instability.

Table 1 – Flame Instability Tests at Burner Vendors

Vendor	Burner	Geometry	Burner Firing Rate Conditions (MMBtu/hr)			Lowest % of Stoichiometry	Flame Instability in Burner	Flame Instability Detected with SPM
			Min	Norm	Max			
D	D-1	Round	1.12	5.05	6.72	57% (Norm FR) 70% (Max FR)	Yes *	Yes
	D-2	Flat	0.59	2.65	3.52	85% (Norm FR) 92% (Max FR)	Yes **	Yes
E	E-3	Round	2.29	7.96	9.15	71%	No	No
F	F-4	Round	1.96	6.26	7.83	90%	No	No
	F-5	Round	1.31	4.2	5.25	90%	No	No

* Burner D-1: When starting at the Normal Firing Rate, burner was stable down to 57% of Stoichiometry. Starting at the maximum firing rate, flame instability observed at 70% of Stoichiometry

** Burner D-2: Flame instability observed both when starting at the normal firing rate, and when starting at the maximum firing rate

It is interesting to note that of the two burners from vendor D, one of them was a round burner, while the other was a flat flame burner. The round flame burner (D-1) proved to be stable at as low as 57% of stoichiometry. (That is a, firing rate 43% higher than what would be needed to exactly match the available air.) However, the flat flame burner went unstable at as little as 92% of stoichiometry. Based on just a single test, one cannot make the conclusion that flat-flame burners are universally more unstable than round-flame burners. However, it appears that there may be a correlation between the geometry and stability of burners. It is recommended that more work be done in the industry to further explore this relationship.

Note in Table 1 that in the two burners where flame instability was created, it was detected by the draft transmitter with SPM. In the three burners that were not driven to the point of flame instability, the SPM standard deviation did not show the same large increase.

Figure 12 shows an example trend from a burner test at vendor F. This figure shows the values of draft and draft standard deviation that were observed over the full day of burner tests. Note that although there were a few periods when the burner operation was taken to the point of 90% of stoichiometry, the burner flames never went unstable. There were small changes in the draft standard deviation over the day of the tests, but it never went higher than 9 to 10 m-inWC. Using the same flame instability alarm limit of 30 m-inWC, we can see that this limit was not exceeded during the full day of the burner tests. Thus, the SPM did not give any false alarms.

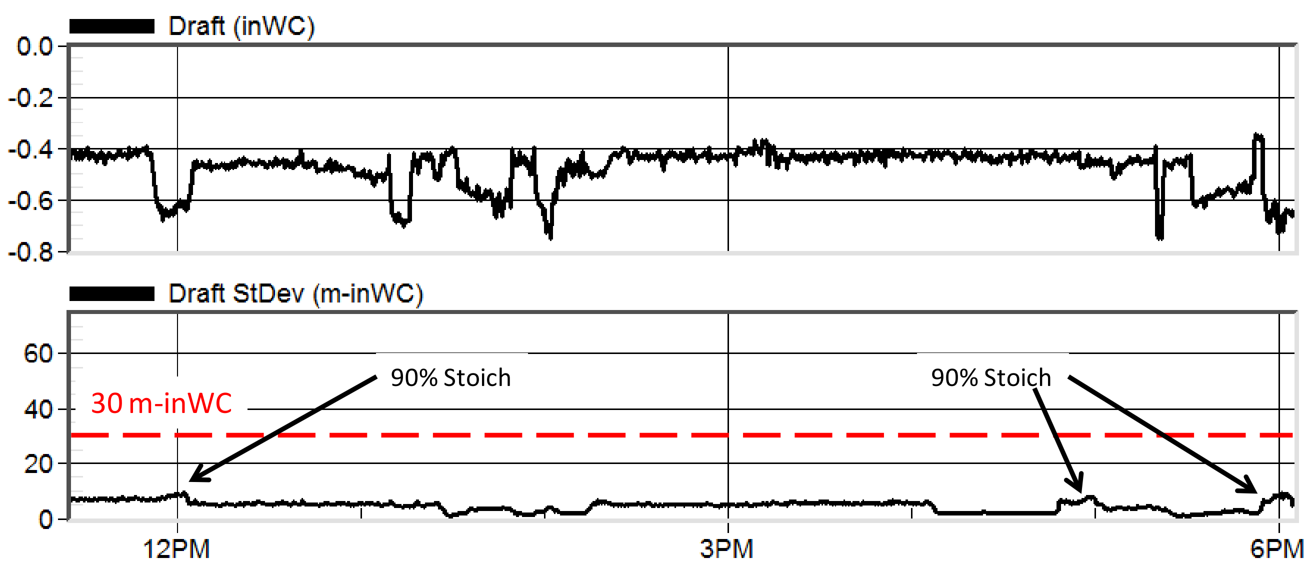

Figure 12 - Example Sub-stoichiometric test - Flame Instability Not Observed (Burner F-4)

Figure 13 shows one data point from a later test run on the same burner F-4. This data point was found rather opportunistically, as it occurred under a circumstance that typically doesn't happen in burner tests. In this case, the test furnace operators opened the stack damper to increase draft in the test furnace instead of keeping the damper partially closed and using steam injection to the base of the stack to increase draft in the firebox. Once the firebox was given line-of-sight to the sky, the burner flames started pulsating, and soon flamed out. A view of the trend of the draft standard deviation (Figure 13) shows that just prior to the flame out, there was a large increase in the standard deviation. In this case, the alarm limit of 30 m-inWC would be appropriate for detecting flame instability. There was also a point during light-off where the standard deviation exceeded 30 m-inWC. However, an implementation in an operating firing heater (such as in the Burner Management System) could have logic to ensure that a flame instability alarm is not generated during light-off.

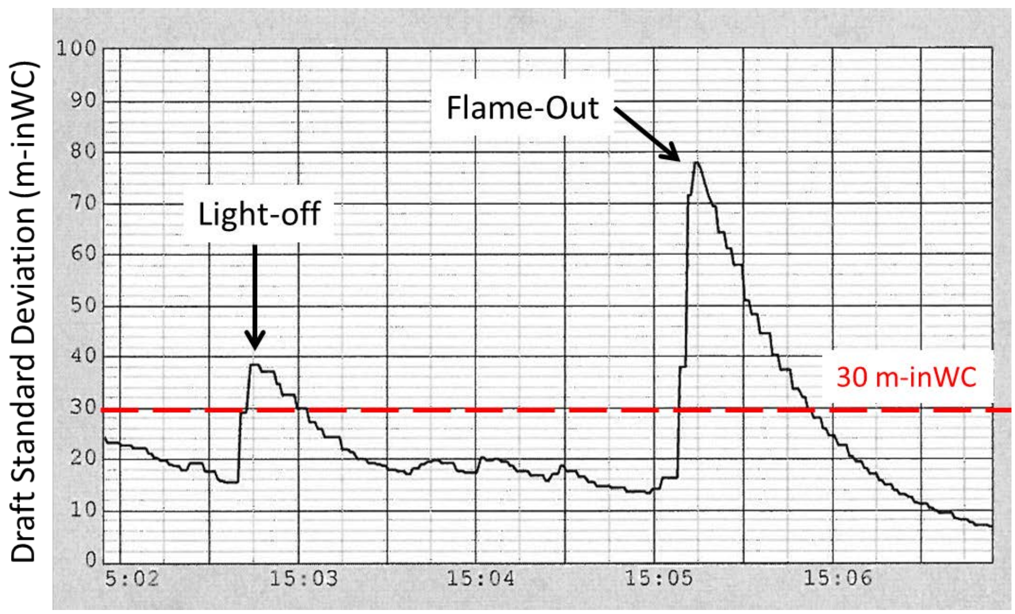

Figure 13 - Flame out Event Observed during a Later Test of Burner F-4

Refer to Appendix A for additional tends of data from the tests at the burner vendors.

Test on Refinery Fired Heater

As a follow-up to the burner vendor tests, in May of 2012, heater tests were conducted on the H-31 fired heater at the Valero Texas City Refinery. This is a radiant/convective vertical cylindrical heater, with a single row of tubes along the radiant axis. The heater has four burners, two on each side of the radiant tube bank. The burners in this heater were raw gas burners. This is an older model burner, not designed for the same low NOx levels as the burners tested at the vendors. Figure 14 shows a view looking from the bottom up into the radiant section of heater H-31.

Figure 14 – Inside the Radiant Section of Heater H-31

This test was a follow-up to the December 2011 burner vendor tests. The purpose of this test was to characterize changes in the draft standard deviation and to compare with the data that was taken at the burner vendors. Since this is an operating heater, the test team could not purposely flame out the heater, nor could the team create the same extreme substoichiometric conditions as were simulated in the test furnaces. However, it was determined that limited manipulation of firing rates, fuel pressures, and individual burners could be performed safely. During the tests, the team would be looking for characteristics of flame instability in the burner flames, and monitoring for any corresponding change in the SPM standard deviation.

Specifically, four tests were performed on this heater:

1. Low Burner Pressure on a single burner – Gradually close off the fuel supply valve to a single burner. See if as the burner is starved of fuel, it becomes "lazy" and affects the draft standard deviation.
2. High Fuel Gas Pressure – Increase the fuel gas pressure to feed more fuel to the burners (and reducing the O_2). See if burner flames go unstable.
3. Low O_2 – Increase fuel flow to drive the O_2 lower. Keep going until excess O_2 reaches 0.5%. (Typical O_2 on this heater is 3-4%). See if burner flames become unstable at low O_2.

4. Starve Single Burner – Close off the air register of a single burner to starve it of air. See if the burner flame goes unstable and affects the draft standard deviation.

Table 2 below summarizes the results from these heater tests. Flame instability could not be created in any of the tests. On the Low Burner Pressure test, the flame was completely extinguished before any change in draft standard deviation was observed. On both the High Fuel Gas Pressure and Low O_2 tests, there were small changes in standard deviation as the firing rate changed. However, these changes were significantly smaller compared to what is typically seen under flame instability. As seen looking through the furnace viewport, the burner flames remained in a stable, healthy combustion in both tests.

Table 2 - Heater Tests performed at Valero Texas City

Test	Lowest Recorded O_2	Flame Instability in Heater	Flame Instability Detected with SPM	Note
Low Burner Pressure on Single Burner	3.8%	No	No	Burner Completely Extinguished before any Change in Std Dev
High Fuel Gas Pressure	1.6%	No	No	Small increase in Std Dev with Firing Rate. Burner flames never went unstable.
Low O_2	0.3%	No	No	Small increase in Std Dev with Firing Rate. Lowest safe O_2 level reached. Burner flames never went unstable.
Starved Single Burner	2.1%	No	No	Single burner starved of air. Substoichiometric combustion observed through viewport.

The last test involved starving a single burner of air. There were small changes in the SPM standard deviation, but not of the magnitude that would indicate flame instability. A view of a starved burner through the heater viewport (Figure 15) showed very bad combustion (a bright orange flame that would jump up and down, as opposed to the stable blue flame of the normal operating burner). However, it was not the same as flame instability in the whole heater. Consequently, there was a small change in the draft standard deviation, but within the range of standard deviation changes that would be seen under normal heater operation.

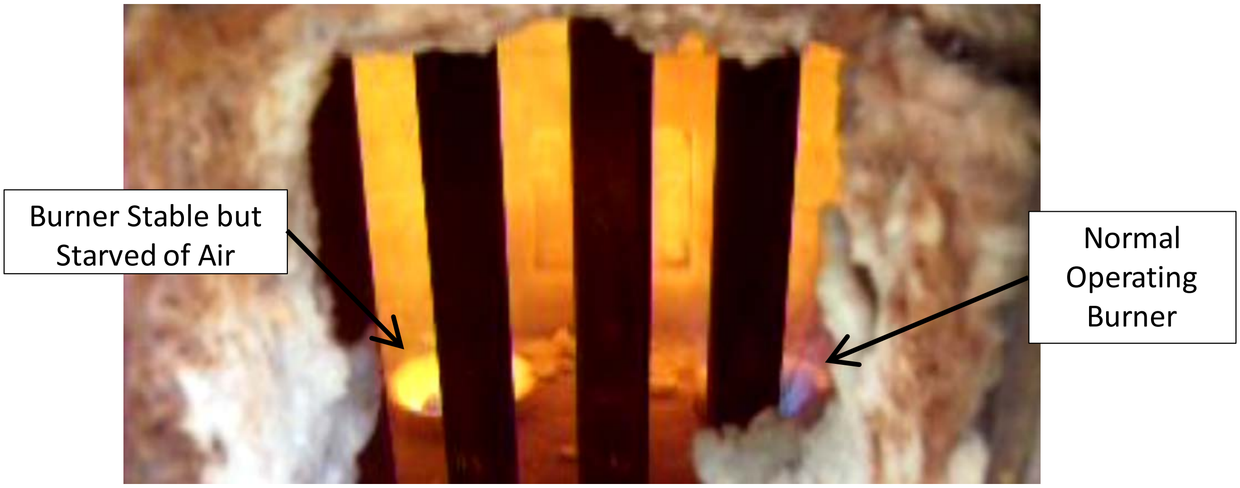

Figure 15 - Starved Burner seen in Heater Viewport

Figure 16 shows the trend of SPM Standard Deviation over the day of the heater tests. Although there were small changes in standard deviation with the different heater tests, these changes were all substantially less than what would be expected under flame instability. The alarm limit of 30 m-inWC was not tripped during the test.

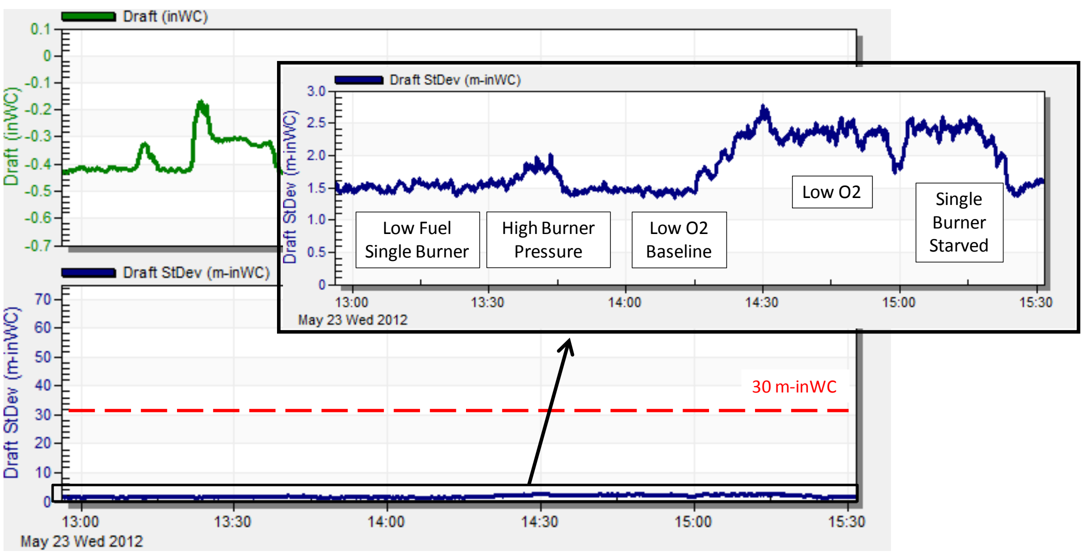

Figure 16 - Trend of Draft Standard Deviation during H-31 Heater Tests

Following the H-31 heater tests, the SPM standard deviation was monitored over five weeks of normal heater operation. During that time, the standard deviation did not go any higher than 2 m-inWC, always significantly less than the alarm detection limit of 30 m-inWC. Although no false alarm occurred during this time, we still don't know how high the standard deviation would go if flame instability and/or flame out actually did occur on this heater. It is possible that a much lower alarm limit (anywhere from 5 to 10 m-inWC) could be selected, which would not be tripped during normal heater operation. Additional heater operational experience is needed to confirm this.

Effect of Firing Rate and Comparison of Among Different Burners

During the burner and heater tests, it was observed that there was a correspondence between firing rate and draft standard deviation. In general, a higher firing rate of the burner(s) leads to a higher draft standard deviation. This makes sense because a higher firing rates means that there is more fuel and more combustion, thus more turbulence or combustion rumble. Figure 17 shows a comparison of the standard deviation values observed under normal operating conditions (e.g. minimum, normal, or maximum firing rate at 3% O_2), on each of the five burners tested at the vendors. The figure also shows standard deviation values observed during the H-31 heater tests.

For every burner, one can see that the standard deviation is the highest at the maximum firing rate, and the lowest at the minimum firing rate. This should be taken into account when setting the standard deviation alarm limit for detecting flame instability. The alarm limit must be chosen such that it would not be exceeded when the heater/burners are at the maximum firing rate. Note that the standard deviation values when burners D-1, D-2, and F-4 were unstable were in the range of 60 to 100 m-inWC and would be off this chart.

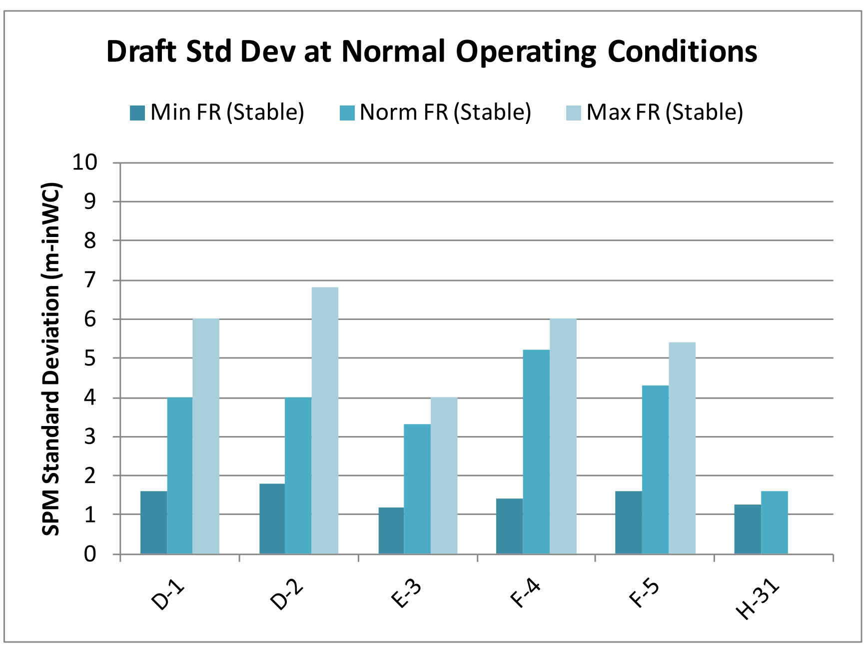

Figure 17 – Comparison of Draft Standard Deviation at Nominal Operating Conditions

Figure 18 shows a comparison of Total Firing Rate (MMBtu/hr) versus standard deviation for all five test furnace burners, and the four-burner heater H-31. All of these data points are from normal (stable) burner operation. For any single burner, there is the general relationship that standard deviation increases with firing rate. However, there is a large degree of separation between the different burners. In particular, note that on H-31, at higher firing rates, the draft standard deviation was substantially lower than that observed in all of the test furnaces.

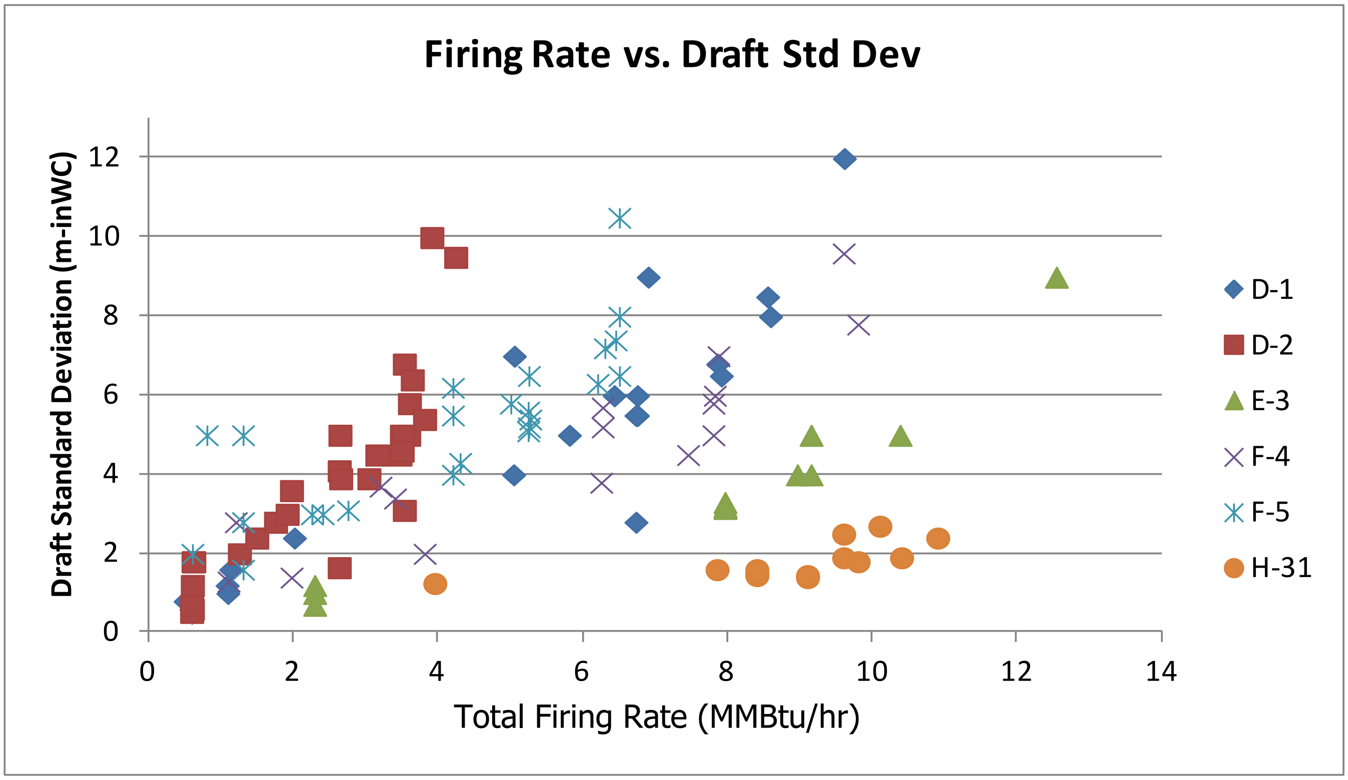

Figure 18 – Correlation of Firing Rate and Draft Standard Deviation

One factor that may explain the difference in draft standard deviation values among the different tests is the volumes of the fireboxes of the test furnaces and heater. A larger volume of the firebox means that the energy and turbulence of combustion is spread out more widely, and therefore the pulsations measured by the draft transmitter may not be as large.

Table 3 shows the approximate firebox volume on each of the test furnaces, and the calculated volumetric heat release at the Minimum, Normal, and Maximum firing rates.

Table 3 – Volumetric Heat Release for Each Test Furnace or Heater

Burner or Heater	# of Burners	Firebox Volume (ft^3)	Total Firing Rate (MMBtu/hr)			Volumetric Heat Release (Btu/hr/ft^3)		
			Min	Norm	Max	Min	Norm	Max
D-1	1	1215	1.12	5.05	6.72	922	4156	5531
D-2	1	792	0.59	2.65	3.52	745	3346	4444
E-3	1	1440	2.29	7.96	9.15	1590	5528	6354
F-4	1	2500	1.96	6.26	7.83	784	2504	3130
F-5	1	1000	1.31	4.2	5.25	1310	4200	5250
H-31	4	3049			12.5			3411

Figure 19 shows the same draft standard deviation values plotted against volumetric heat release. There appears to be a very definite correlation between draft standard deviation and volumetric heat release that is even consistent across different burners and fireboxes. Using volumetric heat release may be a way to predict the draft standard deviation values in a heater, using test data from a different furnace or heater. However, more work is required to validate this.

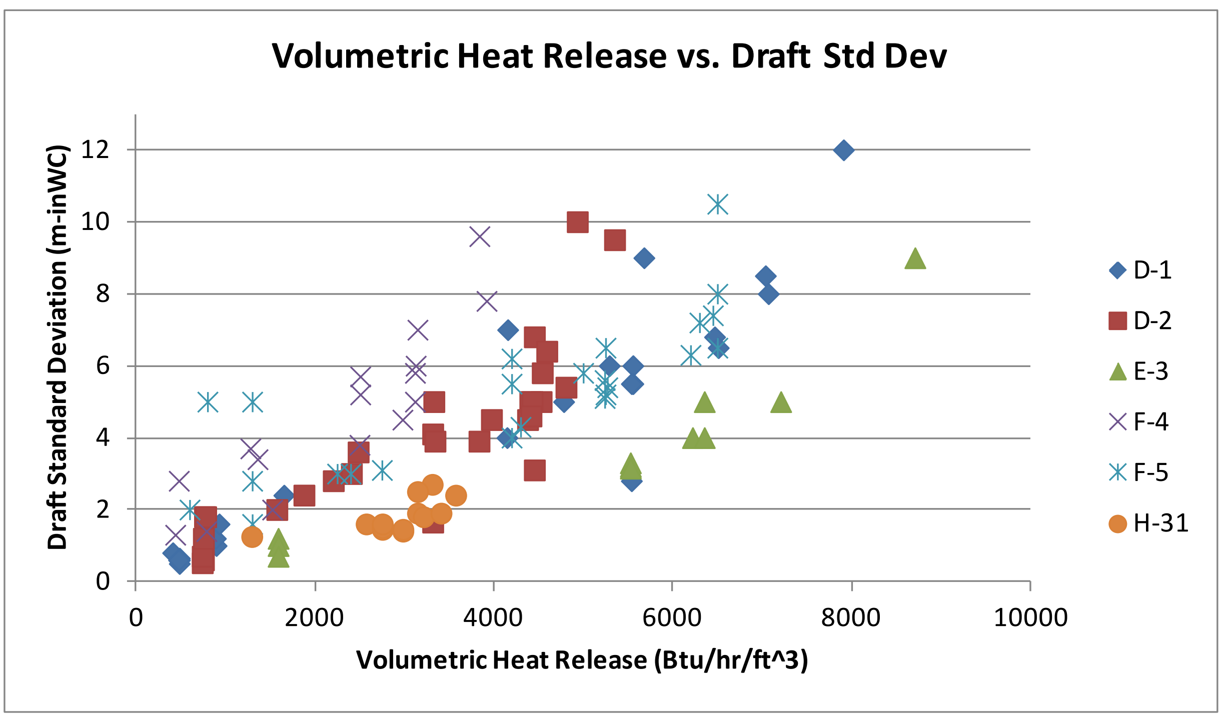

Figure 19 – Correlation of Volumetric Heat Release and Draft Standard Deviation

It may be possible to use operational data from a heater running in normal operation to set an alarm limit for flame instability detection. Figure 20 shows the draft standard deviation versus volumetric heat release for just the H-31 heater at the Texas City Refinery. Remember that during the tests on this heater, and in the weeks following, flame instability never occurred.

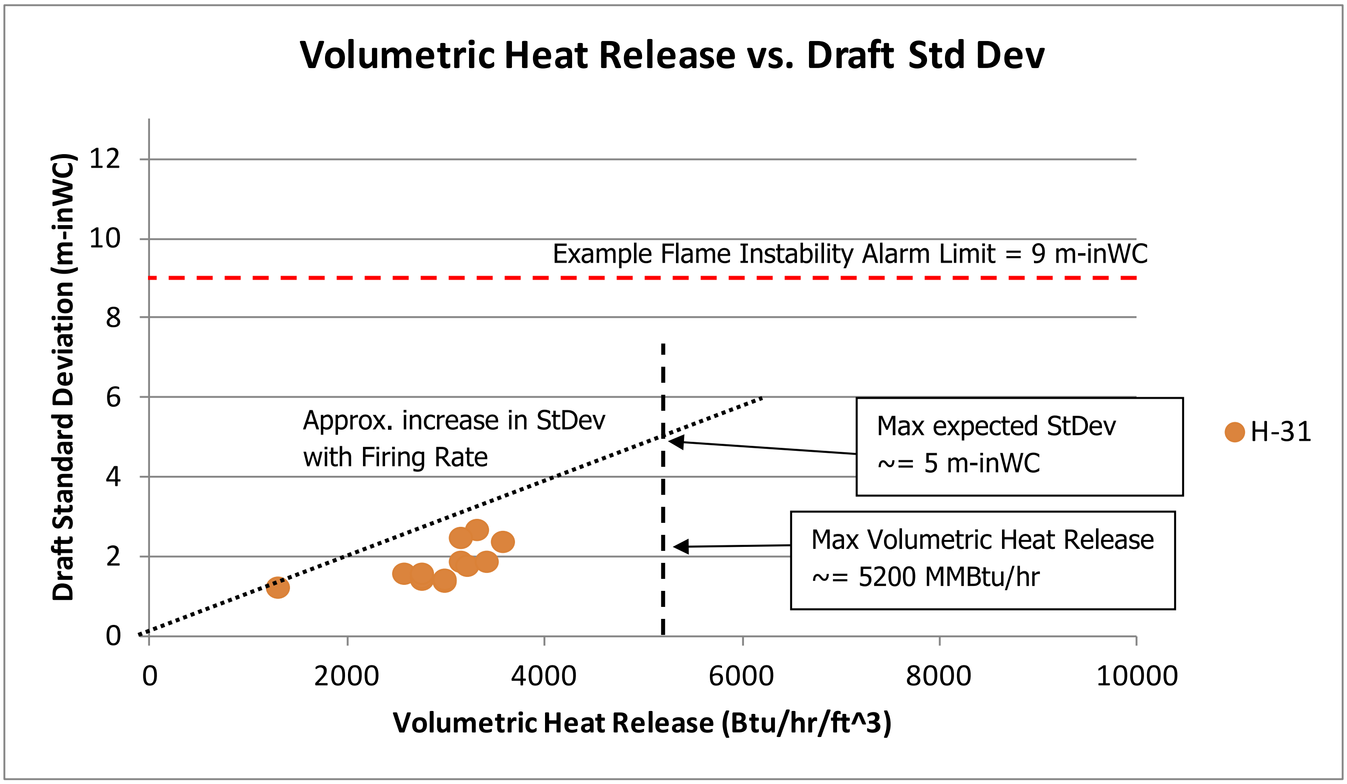

Figure 20 – Using Normal Heater Operational Data for Determining Flame Instability Alarm Limit

The H-31 heater has a maximum firing rate of 16 MMBtu/hr, corresponding to a maximum volumetric heat release of about 5200 Btu/hr/ft^3. This is marked with the vertical dashed line. The approximate increase in standard deviation with firing rate is marked by the diagonal dotted line. The point where these lines cross may correspond to the largest standard deviation value that would be expected in normal heater operation (approximately 5 m-inWC in this example). One could choose the flame instability alarm limit to be some multiple of this value. In the example, we have selected an alarm limit at 9 m-inWC. There would have to be substantial changes in the combustion conditions to make the draft standard deviation go higher than this limit.

The advantage to choosing a smaller alarm limit (e.g. as opposed to the 30 m-inWC from the burner vendor test data), is that, in this heater, we really don't know how high the standard deviation will go during substoichiometric combustion or flame instability. A smaller detection limit gives greater possibility that the alarm will occur under some future, but unknown magnitude, increase in draft oscillations.

The method shown in Figure 20 could be used to set the flame instability alarm limit on any operating fired heater. However, this method is based on only a limited set of test data. A linear relationship between standard deviation and firing rate may not necessarily exist on every burner/heater/furnace system. Furthermore, the actual magnitude of increase of the standard deviation during flame instability may vary between different heaters or burners. In addition to substoichiometric combustion, there may be other mechanisms that cause flame instability and/or flame out. As additional industry experience is gained using SPM technology for heater monitoring, it is expected these other factors will be better understood, and that new guidelines and best practices may be determined for setting the alarm limit, and integrating SPM technology with fired heater operation.

Considerations for Industry

Statistical Process Monitoring technology has been shown to have significant promise for monitoring heaters and detecting flame instability and flame out. However, more data is needed to fully evaluate the potential of this approach. Whenever adding a new draft transmitter to an oil refinery fired heater, owner/operators may wish to purchase a pressure transmitter with SPM technology. The SPM Standard Deviation could be integrated with the other heater operational data either via direct HART I/O, with a HART to analog converter, or with a wireless interface. Heater operators could monitor the Standard Deviation along with other heater measurement points, and use it as an indicator of combustion problems or flame out. An initial flame instability alarm limit could be set based on the standard deviation during normal heater operation and/or standard deviation values observed under flame instability in a test furnace. This alarm limit could be adjusted as experience is gained with a given heater.

SPM is a relatively new technology for monitoring fired heaters. If one chooses to implement SPM for monitoring heaters, the technology should be utilized in addition to (not as a replacement for) industry recommended best practices. Refer to API Recommended Practice 556 [18] for best practices in the instrumentation, control, and protective systems for fired heaters.

It is recommended that purchasers request burner vendors to monitor and trend the SPM standard deviation during burner tests. This data can be utilized during substoichiometric testing as an indicator of the stability of the burners. The SPM data can be used as a means to compare the stability of different burners at various levels of sub-stoichiometry. The SPM data can also be given to a heater designer or an end-user owner-operator, and used by the industry to further understand the application of SPM technology for heater monitoring.

Summary and Conclusion

Advanced pressure diagnostics Statistical Process Monitoring is a promising technology for detecting flame instability and/or flame out in fired heaters. The draft pulsations associated with flame instability can be detected by a draft transmitter with SPM. An increase in the draft standard deviation may be indicative of flame instability. A heater operator may be able to use the draft standard deviation together with other heater operational data to gain insight into the health of the burner combustion. An alarm may be configured to generate an indicator of flame instability when the draft standard deviation exceeds the alarm limit. Initial results show that for some heater/furnace/burner systems, an alarm limit of 30 m-inWC may be suitable for detecting flame instability. On other systems, a limit of 5 to 10 m-inWC may be appropriate. There is a general relationship between volumetric heat release and draft standard deviation. This relationship may be exploited to select an initial flame instability alarm limit on an operating fired heater. Although additional work may allow more precise determination of the optimal alarm limit for a given heater, current experience suggests that all fired heaters would benefit by utilizing pressure transmitters with SPM technology for the draft measurement.

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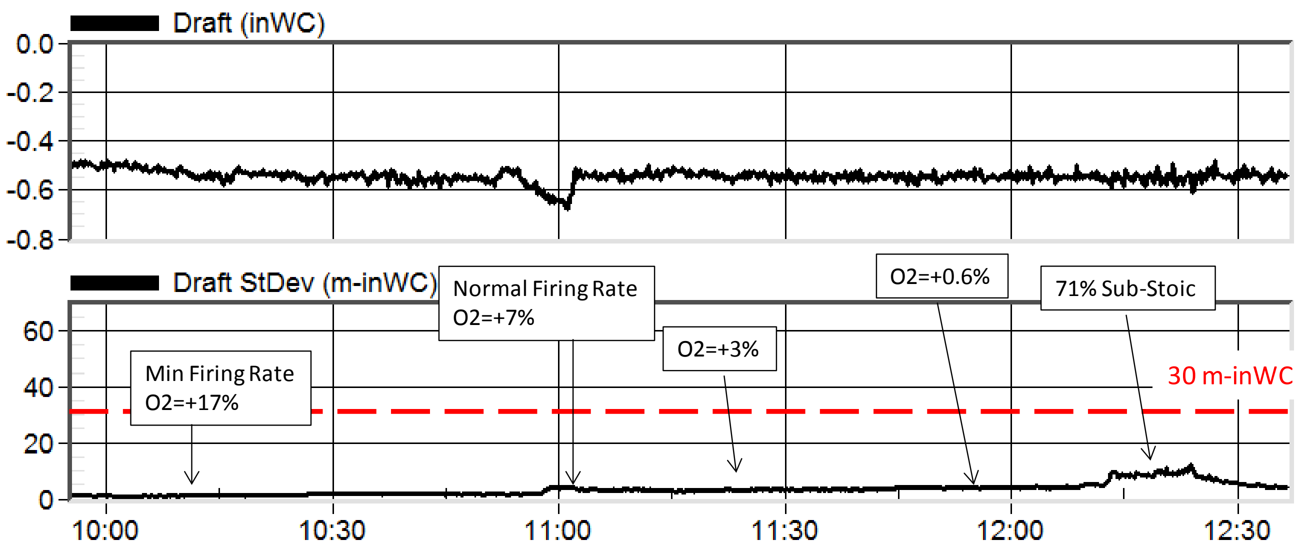
Appendix A

This appendix shows the trends of draft and SPM Standard Deviation for all of the burner vendor tests that were performed in December 2011. All labels of Firing Rate (FR) are in units of MMBtu/hr.

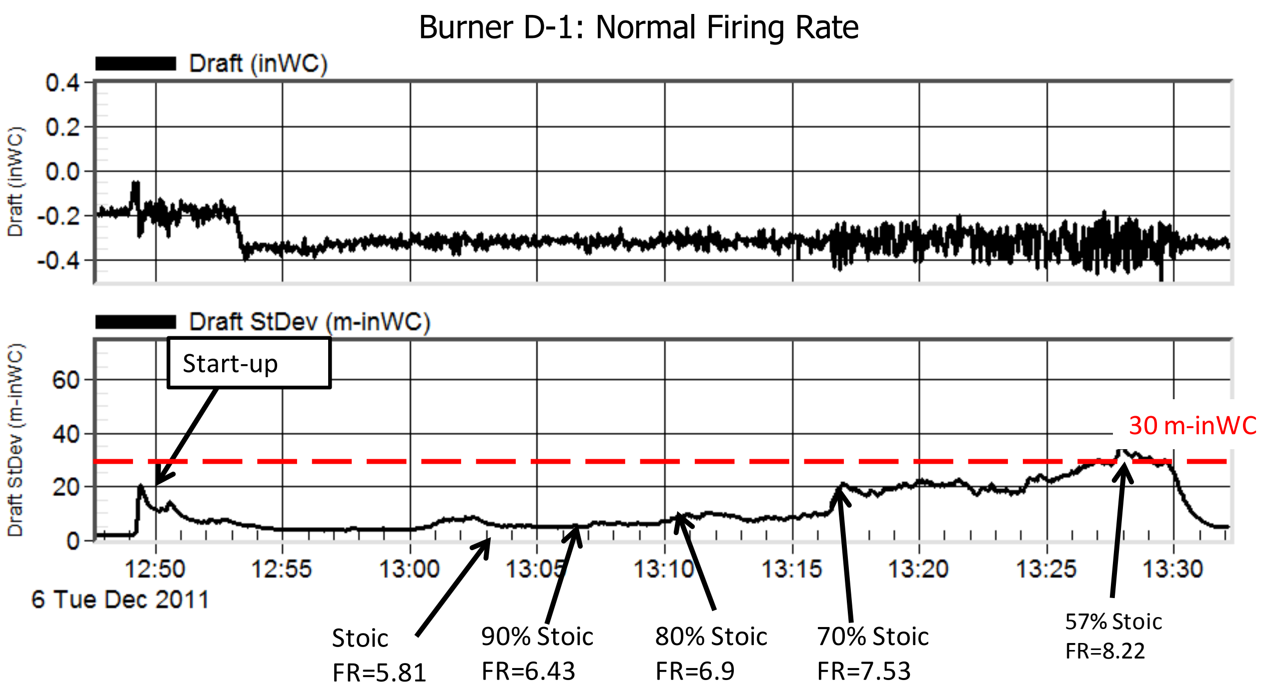
Burner E-3

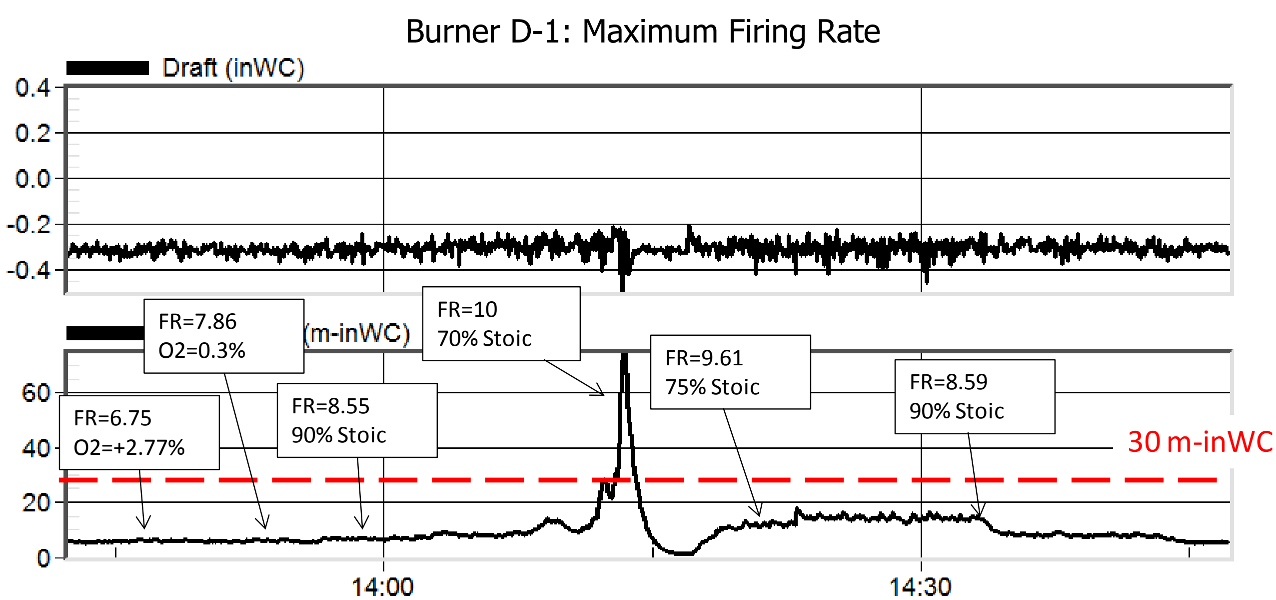
Vendor	Burner	Geometry	Burner Firing Rate Conditions (MMBtu/hr)			Lowest % of Stoichiometry	Flame Instability Observed
			Min	Norm	Max		
E	E-3	Round	2.29	7.96	9.15	71%	No



Burner D-1

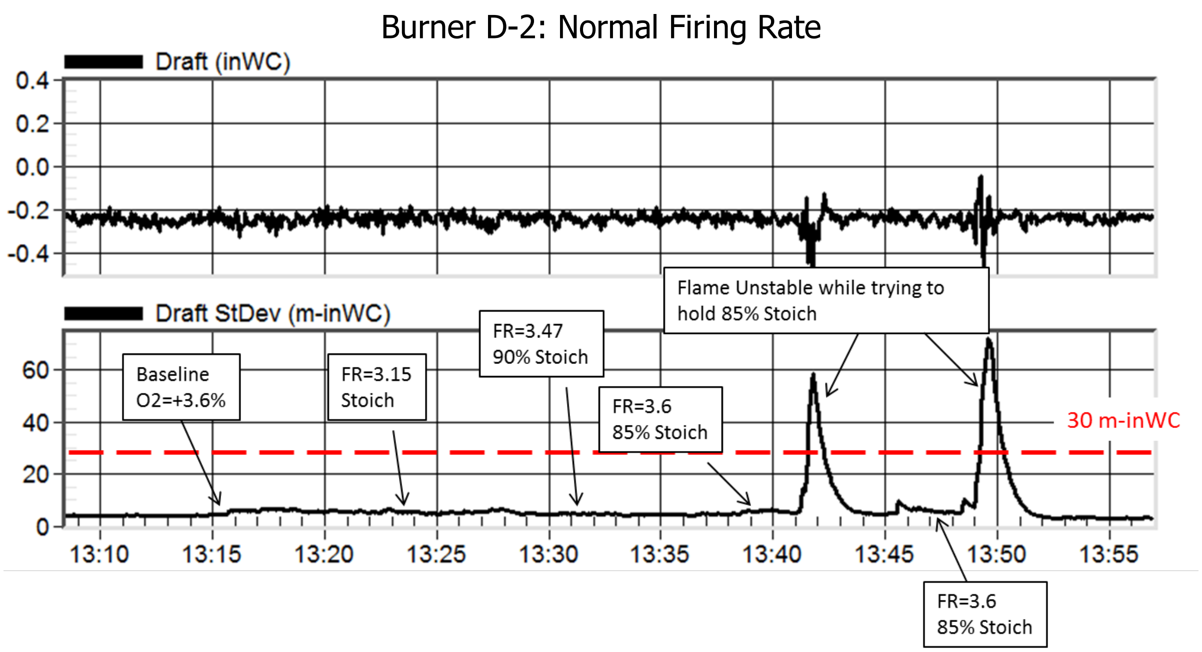
Vendor	Burner	Geometry	Burner Firing Rate Conditions (MMBtu/hr)			Lowest % of Stoichiometry	Flame Instability Observed
			Min	Norm	Max		
D	D-1	Round	1.12	5.05	6.72	57% (Norm FR) 70% (Max FR)	Yes (Max FR only)

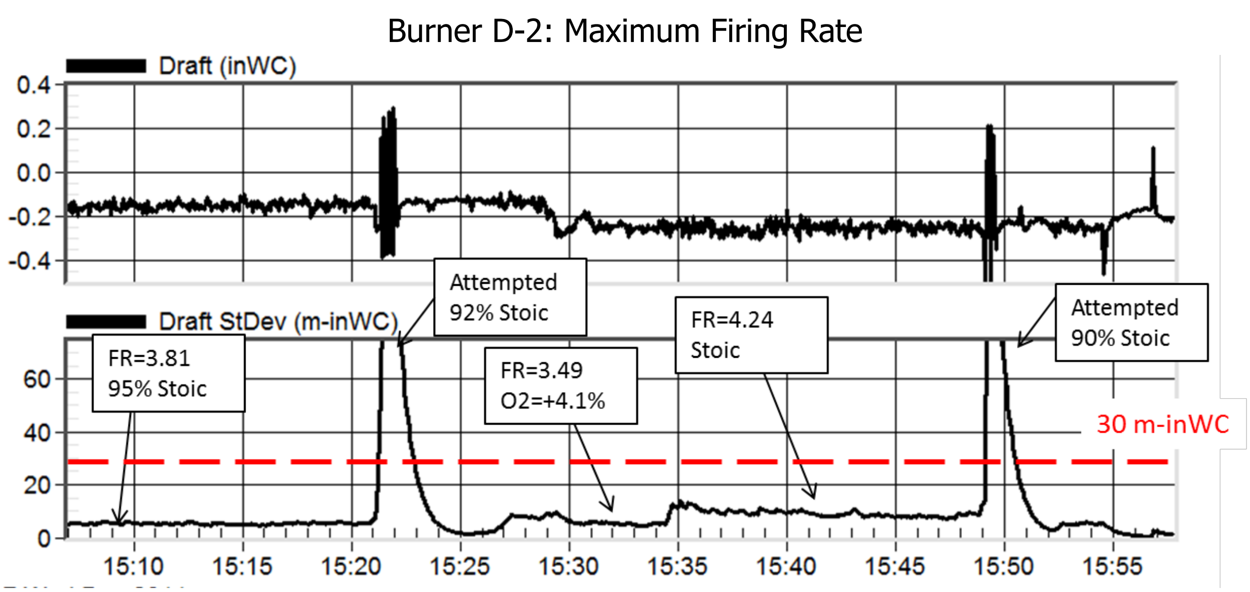




Burner D-2

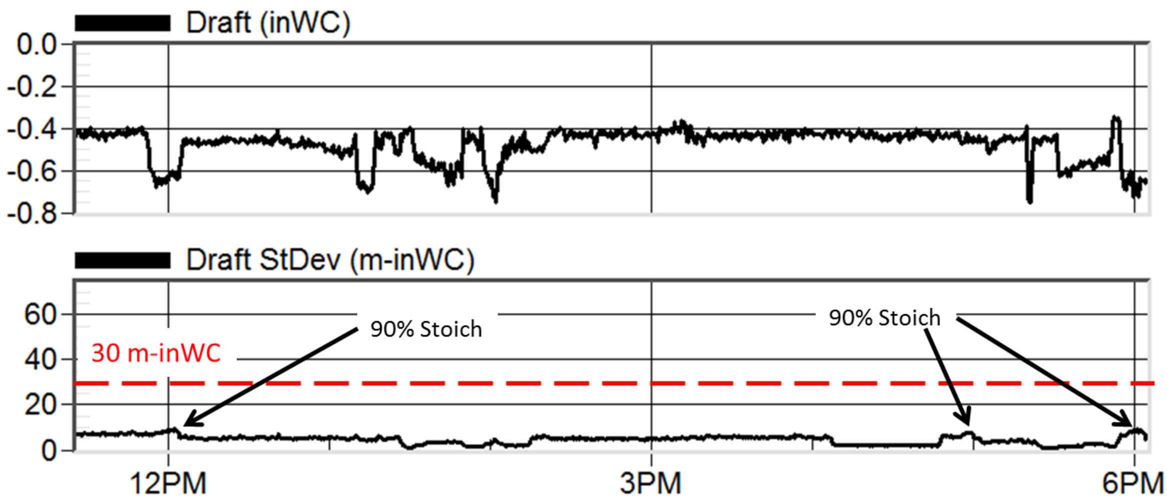
Vendor	Burner	Geometry	Burner Firing Rate Conditions (MMBtu/hr)			Lowest % of Stoichiometry	Flame Instability Observed
			Min	Norm	Max		
D	D-2	Flat	0.59	2.65	3.52	85% (Norm FR) 92% (Max FR)	Yes





Burner F-4

Vendor	Burner	Geometry	Burner Firing Rate Conditions (MMBtu/hr)			Lowest % of Stoichiometry	Flame Instability Observed
			Min	Norm	Max		
F	F-4	Round	1.96	6.26	7.83	90%	No



Burner F-5

Vendor	Burner	Geometry	Burner Firing Rate Conditions (MMBtu/hr)			Lowest % of Stoichiometry	Flame Instability Observed
			Min	Norm	Max		
F	F-5	Round	1.31	4.2	5.25	90%	No