A SAGE METERING White Paper

SAGE METERING
8 Harris Court, Building D1, Monterey, CA 93940
Telephone: (831) 242-2030
www.SageMetering.com

Combustion Efficiency and Thermal Mass Flow Meters

By Bob Steinberg, President, CEO

November 13, 2012

Table of Contents

Introduction

A significant way to reduce energy consumption in a manufacturing environment is to optimize the combustion control on industrial boilers, steam generators, furnaces, ovens, smelters and process heaters. Combustion efficiency and energy management is achieved through accurate and repeatable measurement of gases.

Combustion Control

By monitoring the air and fuel rates to burners, optimal air-to-fuel ratios are achieved, resulting in significant reductions in fuel gas cost, improved process efficiency, enhanced product quality, better yields, while simultaneously lowering combustibles. Many local and state-wide jurisdictions have environmental regulations requiring flow meters on all medium and large heating units to measure plant wide emissions. Common applications for combustion control monitoring are found in a variety of industries including: textile, glass manufacturing, automotive, aluminum & steel, food & beverage, pulp & paper, power, chemical and refining.

Stoichiometric Combustion

The purpose of combustion is to efficiently consume fuel to produce heat. There are three components of combustion: fuel, oxygen and heat. The most common fuel sources in a combustion process are fossil fuels; natural gas, oil and coal. Fossil fuels are hydrocarbons; organic compounds containing carbon and hydrogen. To maximize the efficiency of combustion, it is important to consume (or burn) all the fuel, which is known as *complete combustion*.

To achieve complete combustion it is critical to introduce air into the combustion chamber. Without it, the fuel will have partial or *incomplete combustion* and the exhaust gases will contain some unburnt and partially burnt fuel. Assuming we are evaluating a natural gas fed combustion process, the unburnt fuel components will be carbon monoxide (CO), hydrogen (H_2) as well as methane (CH_4).

Combustion efficiency is dependent upon using the right amount of air to consume the fuel.

Fuel Consumption
The presence of uncombusted or partially burnt fuel is indicative of incomplete combustion which greatly reduces efficiency. Therefore, burning the fuel in the presence of excess oxygen ensures that the fuel will achieve complete combustion.

Minimize Excess Oxygen
In the combustion process all excess air is heated in the combustion chamber and this energy is lost out the exhaust. For this reason, the second governing factor of combustion control is to minimize the extra oxygen used to reduce the loss of energy from heat going up the stack.

Stoichiometric combustion is a theoretical point in which the optimum amount of oxygen and fuel mix generates the most heat possible and maximum combustion efficiency is achieved. There are no unburnt combustibles and no excess air. It is something to strive for, though in reality it does not occur. It is theoretical and in a real combustion process, the mixing between the air and fuel does not provide the perfect conversion.

Excess Air and Air-to-Fuel Ratio

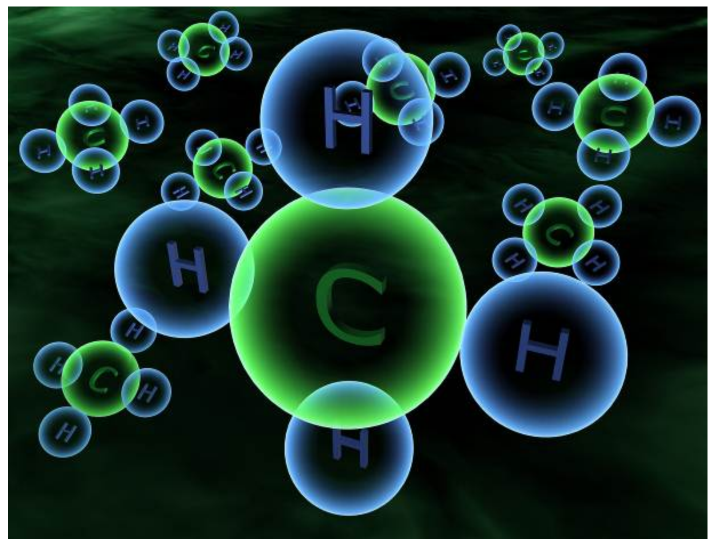
In fuel-fired process heating the largest source of energy loss is through the exhaust stack, which is why managing air flow is critical to combustion efficiency. When fuel burns in the presence of oxygen it is converted to carbon dioxide, water and heat. Consider the combustion of methane (CH_4).

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + \text{Heat } (1{,}013\ \text{Btu/ft.}^3)$$

Air contains approximately 21% oxygen and 79% nitrogen. In this case the reaction for complete combustion becomes:

$$CH_4 + 2O_2 + 7.53N_2 \rightarrow CO_2 + 2H_2O + 7.53\ N_2 + \text{Heat } (1{,}013\ \text{Btu/ft.}^3)$$

The amount of air required will vary depending on the type of fuel. Ideally you would want to add enough oxygen to consume all the fuel so that little or no combustibles are exhausted, while minimizing the excess air to prevent energy loss out of the stack.



Air-to-fuel ratio defines the amount of air needed to burn a specific fuel. The common fuels used in combustion process are: oil (#2, 4 and 6), diesel oil, gasoline, natural gas, propane, and wood. Ratios for common gases, liquid and solid fuels are noted on Table 1.1 and 1.2.

Table 1.1 Combustion ranges for common gases

Fuel	*Stoichiometric Air/Fuel Ratio (air ft.^{3} / fuel ft.^{3})*	*Heat of Combustion (BTU/ft.^{3})*
Methane (CH_4)	9.53	1013
Propane (C_3H_8)	23.82	2590
Natural Gas	9.4-11.0	950-1150
Coke Oven Gas	3.5-5.5	400-600

Table 1.2 Combustion ranges for Oil and Coal

Fuel	*Stoichiometric Air/Fuel Ratio (air ft.^{3} /fuel lb.)*	*Heat of Combustion (BTU/lb.)*
No. 2 Oil	180-195	18,500-19,800
No. 6 Oil	170-185	17,500-19,000
Bituminous Coal	120-140	12,000-14,000

Optimizing Air-to-Fuel Ratio

For any combustion process there is a balance sought between losing energy from using too much air, and wasting energy from running too rich. The optimum combustion efficiency occurs at the optimum air-to-fuel ratio and controlling this provides the best efficiency. In most scenarios, a liquid and gas fuel burner achieves this desired balance by operating at 105% to 120% of the optimum theoretical air. For natural gas fired burners the stoichiometric air required is 9.4-11 ft.^{3} / 1.0 ft.^{3} of natural gas, or approximately an air-to-gas ratio of approximately 10:1. This results in an excess oxygen level of 2%.

In the combustion zone it is difficult to measure excess air. In the stack however, it can be easily measured using Oxygen analyzers. When operating with 5%-20% excess air, it would correlate to a 1% to 3% oxygen measurement in the stack.

The optimum air-to-fuel ratio will vary at different operating loads. *Tuning* is the act of establishing the desired air-to-fuel relationship under different operating conditions. This can be accomplished when evaluating specifics in the stack: temperature, oxygen concentration as well as carbon monoxide and NO_x emissions.

Measuring Flue Gases

By understanding the delicate balance of excess air-and-fuel usage, we can measure both the concentrations of the oxygen and combustibles in exhaust gas to develop air-to-fuel control strategy. The measurement of both O_2 and CO are critical measurements here. To maintain the highest combustion efficiency continuously, measurements of both flue gas oxygen and combustibles are required.

When determining the carbon monoxide content from the flue gas we are able to make adjustments to the process operation because the CO content represents the unburnt fuel which is wasted because of insufficient air. Alternatively, by measuring the O_2 in the stack gas we are able to monitor the loss of energy from too much excess air

Oxygen and combustible analyzers can provide continuous sampling and analysis of flue gases, making analyzing oxygen and combustibles in the stack gases a way to maximize combustion efficiency. Optimum combustion can be achieved at various air-to-fuel ratios to correspond with different operating loads. This makes it challenging to use oxygen analyzers alone to control excess air. Additionally, an uneven distribution of oxygen in the flue gas could result in oxygen level variations.

Measuring Air and Fuel Flow

In the previous section we explored using flue gas measurements to control the air-to-fuel ratio, here we investigate varying air and fuel pre-combustion flows to improve efficiency. Burner control systems optimize the air-to-fuel ratio for maximum efficiency and minimal unburnt combustibles. A ratio flow strategy is pivotal in safe and cost effective operation of fired heaters, furnaces, boilers and similar combustion processes. The first requirement is to establish process variable signals by measuring the *mass flow* of the fuel flow and combustion air flow rate. Since combustion is dictated by mass it is optimal to measure *mass flow* rather than *volumetric flow*.

Mass flow measurement of natural gas and combustion air flow provides essential information for a facility to operate at maximum efficiency and minimal emissions.

Air Flow Monitoring

Measuring combustion air flow can be challenging because it is typical to have high flow rates at low pressures through irregular and large ducts. Swirls and turbulence in combination with insufficient straight runs make it difficult to obtain the desired flow profiles which can change with different operating loads.

Calibration accuracy needs to be good, and repeatability is critical. Tuning the boiler optimizes the combustion efficiency. During combustion tuning the air-to-gas fuel rates are optimized at different boiler loads. Tuning includes measuring air and gas mass flow rates along with O_2 and CO concentration, NO_X concentration (if appropriate), outlet temperature, and flue gas recirculation flow settings (if appropriate). In air flow monitoring, when setting the fuel flow the combustion air flow is tuned to match the gas flow to achieve the desired air-to-gas ratio. The meter must provide repeatable flow measurement when operating at the same parameters on a different day.

Natural Gas Measurement

Measuring natural gas flow to the combustion source can be used to improve overall combustion efficiency.

There is also a need to measure greenhouse gas emissions to comply with EPA requirements. Facilities emitting 25,000 metric tons of CO_2e annually are required by the EPA to report annual emissions per EPA mandate 40 CFR Part 98. Additionally, local environmental authorities frequently require reporting natural gas consumption to determine emissions.

Flow Technologies

There are many flow technologies that can be used to measure gas flow and the main ones are noted below. While these meters are suitable for measuring natural gas flow, because of the higher volumes typical for combustion air and the larger duct sizes, most of these technologies are not suitable for combustion air flow measurement.

Flow Meters

Coriolis flow meters provide a direct mass flow measurement based upon the deflection force of the fluid moving through a vibrating tube. These meters are very accurate with high turndown capabilities and are independent of fluid properties. They are also very expensive to purchase and install, and are not suitable for larger pipe sizes.

Positive Displacement meters require fluid to mechanically displace components and measure *volumetric flow* at the operating pressure and temperature. While they have good accuracy, pressure and temperature compensation would be required to obtain mass flow and since they have moving parts gas cleanliness needs to be considered.

Thermal Mass flow meters measure the mass flow based on heat transfer from a heated element. The measurement is in mass flow and additional pressure and temperature correction is not required. They also provide excellent accuracy and repeatability and are easy to install.

Turbine Flow meters measure *volumetric flow* based on fluid flowing passed a free-spinning rotor; each revolution corresponding to a specific volume of fluid. The meters have high turndown and accuracy. Unfortunately, because of the moving parts the meter's use is limited to clean dry gases only, and pressure and temperature compensation would be required.

Ultrasonic Flow meters measure the difference in transit time of pulses that travel from a downstream transducer to the upstream transducer, compared to the time from the upstream transducer back to the downstream transducer. This style of meter is extremely accurate, but very expensive and pressure and temperature measurement would be required.

Vortex Flow meter has a bluff object or shedder bar that is placed in the flow path and as gas flows around the shedder bar, vortices are cyclically generated from opposite sides of the bar. The frequency of vortex generation is a function of the gas velocity. The frequency of vortex shedding is independent of fluid composition. The meter however requires pressure and temperature compensation and requires a minimum flow rate to generate vortices.

Differential Pressure Meters

Differential pressure flow meters calculate flow by measuring pressure drop over an obstruction inserted in the flow path. Common types of flow elements are: orifice plates, flow nozzles, venturi tubes and averaging pitot tube. This technology can be used for both natural gas flow and combustion air flow.

Orifice Plate is a differential pressure meter commonly used for natural gas measurement. It measures *volumetric flow* not mass flow. Limitations of this meter include: poor low flow sensitivity, limited turndown, creates pressure drop which impacts operating costs, and requires correction of pressure and temperature to obtain mass flow.

Averaging Pitot Tube is a differential pressure flow measurement device commonly used for combustion air measurement. The instrument has limitations with gas flow; especially low flow sensitivity and turndown. The measurement is contingent upon achieving velocity pressure, and it is possible to not have sufficient velocity to obtain a suitable signal at low flow rates.

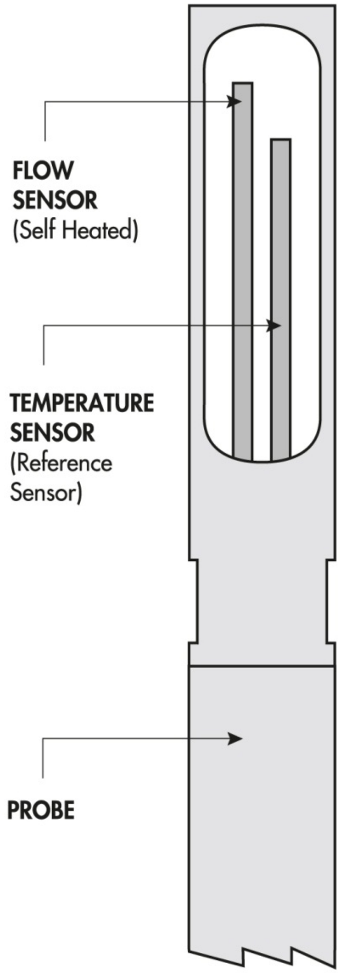
For combustion air flow measurements, other flow elements or obstructions have been used; these include measuring the pressure drop across an elbow in the duct work, across a venturi built into the duct or even across turning vanes in the duct.

Thermal Mass Flow Meters

Thermal mass flow meters (TMFM) are ideally suited for measuring both natural gas flow and combustion air flow in combustion processes.

Principals of TMFM Operation

Thermal mass flow meters (TMFMs) measure gas flow based upon the principal of convective heat transfer. Either insertion style probes or in-line flow bodies support two sensors that are in contact with gas. The sensors are resistance temperature detectors (RTDs), and the SAGE METERING (SAGE) sensors consist of highly stable reference-grade precision matched platinum windings that are clad in a protective 316 SS sheath for industrial environments.



One of the sensors is heated by the circuitry and serves as the flow sensor, while a second RTD acts as a reference sensor, and measures the gas temperature. The SAGE proprietary sensor drive circuitry maintains a constant overheat between the flow sensor and the reference sensor. As gas flows by the heated sensor (flow sensor), molecules of the flowing gas transport heat away from this sensor, the sensor cools and energy is lost. The circuit equilibrium is disturbed, and the temperature difference (ΔT) between the heated sensor and the reference sensor has changed. Within one second the circuit will replace the lost energy by heating the flow sensor so the overheat temperature is restored.

The electrical power required to maintain this overheat represents the mass flow signal. There is no need for external temperature or pressure devices.

One of the advantages of TMFMs is that they have no moving parts which reduce maintenance and permit their use in difficult application areas including wet (saturated) gas. They also do not require temperature or pressure corrections and provide good overall accuracy and repeatability over a wide range of flow rates. This style of meter measures mass flow rather than volume and is one of the few categories of meters that can measure flow in large pipes and ducts.

SAGE provides TMFMs that are factory calibrated and configured for easy installation. They are ready to be installed direct into the pipe or duct without any need for field set up and calibration. SAGE offers insertion as well as in-line TMFMs, with built-in flow conditioners that monitor the air and fuel flow rates to the burner. These direct mass flow meters are highly accurate and repeatable, and have negligible pressure drop.

Sage Metering Prime 1/4” to 4” flow body with flow conditioner (NPT standard, flange optional)

The SAGE meter has extraordinary rangeability of at least 100 to 1, and has the fast response necessary for proper combustion control. Because of its low-end sensitivity, the SAGE TMFM can accurately measure extremely low velocity, down to 5 SFPM, making it extremely effective for measuring the low flow rates of air and natural gas which can occur at low boiler operating loads. In addition to the 4 – 20 mA control output of flow rate, the meters also provide pulsed outputs of consumption, and Modbus compliant RS485 RTU communications. The meters feature bright graphical displays of flow rate, totalized flow and gas temperature, plus, continuous diagnostics. For difficult to reach burner lines, or for locations with extreme radiant heat, SAGE also offers a remote style flow meter, with up to 1000 feet of lead length compensated cable – all electronics and powering are done at the transmitter – thus, the probe or flow body simply has a terminal junction box.

Sage Metering Prime (SIP) with Insertion Probe

Measuring Greenhouse Gas Emissions

MFMs offer a reliable solution to measure gas mass flow for various environmental applications. As previously stated, the EPA requires reporting greenhouse gas emissions from many stationary combustion sources. When burning natural gas, bio gas or other gaseous fuels, the simplest method of determining Greenhouse Gas emissions is to measure the amount of fuel consumed and then using EPA formulas convert the fuel consumption to emissions of the various greenhouse gases. The SAGE meter fully complies with EPA reporting requirements using the built in totalizer as well as meeting EPA calibration requirements.

Calibration Verification

The SAGE TMFM comes from the factory fully calibrated and can easily verify that it maintains its original factory calibration through an in-situ calibration verification.

All SAGE meters are able to perform the in-situ calibration check as long as a "no flow" (0 SCFM) condition can be created. "No flow" is easily created using an isolation valve assembly with the insertion meter style. Unlike other TMFMs, the SAGE In-Situ Calibration not only verifies that the unit is accurate; it also indicates that the sensor is clean. If the meter does not pass the calibration check the first time, in most cases simply cleaning the sensor, and re-testing will verify that the meter is accurate and hasn't drifted or shifted.

Conclusion

By assessing stoichiometric combustion, we understand the parameters needed to achieve optimum combustion to save energy, increase efficiency and reduce pollutants. Combustion efficiency and energy management is achieved by optimizing air-to-fuel ratios which are attained through accurate and repeatable gas flow measurement. Direct measurement of combustion air flow and fuel flow provide the criteria needed to reach peak efficiency. Thermal mass flow meters are ideal to measure the mass flow of combustion air and fuel gas, outperforming traditional flow meters in these applications.