
9 Burner Testing

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9.1 INTRODUCTION

Burner testing provides an opportunity to gather and verify valuable information such as operating parameters, pollutant emissions, flame dimensions, heat flux profile, safety limitations, and noise data. Information from test data is often essential for performance verification of customer applications as well as being vital to research and development efforts. Empirical data collected from burner testing is a valuable source of information that can be used to improve the predictive capabilities of CFD models (see Chapter 5 and Reference 1), which are becoming more prevalent tools used in the research, development, and design of combustion equipment at the forefront of technology in the industry. At state-of-the-art test facilities as shown in Figure 9.1, testing is done year-round to provide customers the data they need to improve heater designs and operate their heaters and furnaces more efficiently and to develop new technology to meet the ever-increasing demands of customer processes and environmental regulation.

While designing a burner appears to involve relatively simple calculations, it is difficult to predict how a burner will operate over a broad range of operating conditions. Consider the multitude of heater and furnace applications, the wide range of available fuels and oxidants, the required pollutant levels to be met, and the different furnace operating conditions. The variations between burner designs are numerous. Through full-scale testing, specific conditions can be simulated and the actual operational performance of a burner can be measured accurately. Testing allows a burner manufacturer to optimize a burner design to closely meet the requirements of a specific application.

An important operating parameter that can be obtained through testing includes the heat release range of the burner. Burners are sized for a maximum heat release with a specified turndown, or the minimum rate at which a burner can be safely operated. Turndown is defined as the ratio of maximum heat release to minimum heat release:

$$\text{turndown} = \frac{\text{maximum firing rate}}{\text{minimum firing rate}} \quad (9.1)$$

For example, if the maximum heat release of a burner is 5×10^6 Btu/hr and the minimum heat release of that burner is 1×10^6 Btu/hr, then the turndown is 5:1. Another variable that operators and engineers may need to know is what happens to a burner if it is fired beyond its maximum designed heat release. With this performance information, a customer can set a target oxygen level in the flue gas to stay above or set an upper pressure limit for a given fuel to stay below to ensure that the burner does not exceed the designed parameters. More important, test data can determine the upper heat release value at which a burner can be safely operated for short durations until a process upset can be corrected.

An operator also needs to know the point at which a burner will become unstable if fired below the minimum heat release. The rate at which a burner can be fired below the designed minimum heat release is defined as the absolute minimum. A lower pressure limit can be set as a safety limit for the fuel gas to ensure safe heater operation. This information is especially useful in determining how many burners should be fired, and at what heat release, for special operations.

Along with defining the firing envelope of a burner, the combustion air settings can be determined through testing to ensure the efficient operation of a heater or furnace by controlling the excess oxygen in the flue gas. By running at lower oxygen concentrations, fuel savings can be realized, thus leading to higher heater efficiency. In complex furnaces such as ethylene heaters, which may have hundreds of burners in operation at once, advanced knowledge of air door settings for various operating conditions can save valuable time in trimming the excess air during actual operation.

Other information that can be collected during a burner test or demonstration is the emissions of pollutants such as NO_x, CO, and unburned hydrocarbons (UHC). While it is easy to predict emissions for a single fuel, modern burners are often expected to operate acceptably on a wide



FIGURE 9.1 John Zink Co. LLC. R&D Test Center, Tulsa, Oklahoma. (Courtesy of John Zink Co., LLC.²¹)

range of fuels. As a result, some fuels may not be fired at their optimum pressures, and variables such as fuel pressure can significantly affect the emission performance of a burner. By testing a burner in an operating furnace prior to final installation, the expected emissions for different operating conditions can be predicted and anticipated with a greater degree of accuracy.

When firing burners on a wide variety of fuels, flame dimensions can change, depending on the fuel fired, the operating fuel pressure, and the heat release, because the mixing energy available can significantly affect the volume or shape of a flame. By conducting a burner test over the normal operating envelope of a burner, the dimensions of the flame can be determined for all conditions. The flame dimensions are important to ensure that there is proper heat distribution in the combustor and that the flames do not impinge undesirably on anything in the combustor.

Another valuable piece of data that can be collected is noise. New and existing plants are being more strictly regulated and are required to reduce noise levels. Depending on the severity of the requirement, mufflers can be designed to attenuate the burner noise to acceptable levels (see Chapter 7).

Some burners are designed to heat a furnace wall. For these burners, heat flux profiles can be determined through testing to provide heater manufacturers with information about the transfer of heat radiated from the wall to the process tubes. By optimizing the heat flux profile, the heat transfer to the load can be optimized to maximize the overall system thermal efficiency.

Testing can provide a variety of data concerning a burner's performance. But without a proper setup, the correct instrumentation and measurement methods, and a well-defined test procedure (test matrix), the data collected during a test may have little or no meaning. This chapter discusses the proper elements required for conducting a test. Items discussed include identifying the application of the burner, selecting the correct test environment, and determining the test fuels to be utilized during testing.

This chapter also discusses the instrumentation necessary to record consistent and accurate data. This includes the concentration of NO_x, CO, O₂ (wet and dry), unburned hydrocarbons (UHC), and particulates in the flue gas; heat flux; and noise emissions from the burner. Fuel flow metering and flame measurement are also discussed.

With input from the furnace manufacturer and end user, a meaningful test procedure can be put together that will yield valuable data in determining a burner's performance under different operating conditions. The test procedure is designed to answer a specific set of questions regarding the performance of the burner. By closely matching the conditions of operation expected in the field, data can be collected that will aid operators in running their furnaces.

Finally, this chapter discusses data analysis. Once a test is run, it must be determined if the burner has met the criteria outlined in the test procedure. The criteria include performance guarantees and operating parameters. With the data collected, the test engineer can optimize the burner to improve emissions, flame dimensions, stability, and air flow distribution.

Armed with the knowledge described above, customers will have a greater understanding of what to expect from a burner test, as well as what goes into setting up and conducting a test that will provide meaningful data. API 535 gives some good guidelines for specifications and data required for burners used in fired heaters.²

Several excellent general references have been published concerning combustion diagnostics. An early book by Beér and Chigier (1972)³ gives detailed descriptions and diagrams of different probes used to make measurements in industrial-scale flames. The report by Okoh and Brown (1988)⁴ reviews and compares many techniques for the measurement of a wide range of variables in combustion systems. It also includes equipment specifications and suppliers. The books edited by Durão et al. (1992)⁵ and Taylor (1993)⁶ contain chapters on the use of both physical probes and optical techniques. Fristrom (1995)⁷ has several chapters devoted to probe and optical measurements in flames. The books by Eckbreth (1988)⁸ and Chigier (1991)⁹ focus specifically on optical techniques for diagnosing flames. The articles by Fristrom (1976),¹⁰ Bowman (1977),¹¹ Gouldin (1980),¹² and Becker (1993)¹³ review probe measurements in flames. Newbold et al. (1996)¹⁴ gave a good example of making probe measurements of velocity, species, radiation, and gas temperature in an

industrial, gas-fired, flat-glass furnace. Solomon et al. (1986)¹⁵ reviewed Fourier transform infrared (FTIR) optical techniques for measuring particles, species concentrations, and temperature in combustion processes. Articles are available on the use of laser diagnostics in combustion systems.^{16–20} Lewallen et al. (2001)²¹ have written a book chapter on burner testing for the hydrocarbon and petrochemical industries.

9.2 THERMAL ENVIRONMENT

There are three common thermal environments used to test burners: open air testing, a test or pilot furnace test (usually a single burner test), or testing in the actual application or furnace. Each method offers its own set of advantages and disadvantages.

9.2.1 OPEN AIR

While testing in open air can provide a stunning visual observation of the burner's flame and its characteristics, open air testing provides very limited information required to evaluate a burner's suitability for its intended operation. In essentially all industrial combustion applications, the burners are fired in some type of combustor. As an example, burners designed for petrochemical and refining industries operate under vessel pressures that are slightly less than atmospheric pressure or are fired into pressurized vessels. In both cases, the equipment is fired into a controlled volume so that the heat generated can be transferred to the heat load. Therefore, an important limitation of open air firing is the lack of an enclosure. As government agencies continue to work on the problem of clean air, the demand for burner equipment that produces lower and lower levels of NO_x, CO, unburned hydrocarbons (UHCs or VOCs), and particulate emissions continually pushes equipment manufacturers to come up with innovative ways to reduce emissions. As a result, burner testing must be conducted in a combustor that allows the firing of fuel mixed with an oxidant (ambient air, preheated air, turbine exhaust gas, oxygen-enriched air, or pure oxygen) through the burner and out of an exit to pass the flue products out.

The stack of a furnace is sampled to measure the pollutants mentioned earlier (NO_x, CO, UHC, etc.) in order to determine if the equipment is meeting the permitted levels required by the local environmental agency. To test burner equipment, most manufacturers have testing facilities that allow the burner equipment to be tested so that emission data can be collected.

9.2.2 PILOT FURNACE

Pilot furnaces provide an enclosure for burners to be fired in. Burner manufacturers are interested in testing the equipment for a number of reasons. These include confirming capacity (heat release rate), ensuring air and fuel metering is at the desired pressure drop, verifying flame shape (or heat flux profile), and analyzing the pollutants produced by the burner. Pilot or test furnaces are typically sized to handle a limited range of heat input and burner configurations (up-fired, down-fired, fired adjacent to a wall, or fired radially against a wall). The test furnace gives accurate information on how a single burner operates, whereas many industrial furnaces use multiple burners.

This pilot-scale furnace data is then used to predict the performance in a given application. Due to the wide range of commercial applications, single burner pilot furnaces are attractive for their flexibility. Test setups can be implemented and dismantled for a relatively low cost compared to testing multiple pieces of equipment at the same time. Depending on the application, testing more than one burner can create problems for adequately cooling the furnace to the desired operating conditions. Most test furnaces are water cooled, either by passing water (or other heat-absorbing media) through tubes or encapsulating the furnace with a water jacket. Most of the heat generated during pilot testing is waste heat as no product is being processed during testing.

Another significant limitation to pilot testing or single-burner testing is the impact of the proximity of multiple burners in an actual application, or the furnace fluid dynamics. Depending on the configuration of the actual furnace, the circulation of flue products within the furnace can be dramatically different than the circulation pattern in a test furnace. This can result in poor flame quality, higher emissions, and the added risk of improper heat transfer in the actual application. To compensate for the differences in pilot furnaces compared to operating furnaces, other tools must be used in conjunction with a burner test to gain insight into and a predictive capability of how a burner or multiple burners will perform. Additional avenues include computational fluid dynamics or CFD (see Chapter 5), physical testing (see Chapter 10), and field-testing (discussed below).

9.2.3 FIELD TESTING

Simply put, field testing is collecting available data from furnaces in operation to evaluate the performance of burners. There are many advantages to field testing. Here, this refers to testing in actual furnaces that are test sites designed to demonstrate feasibility. These test sites may or may not be eventual end users. Field test furnaces are generally representative of typical furnaces for a given application, including multiple burner operation. The data collected is extremely valuable as it validates the calculations that burner manufacturers use to predict burner performance. The impact of burner-to-burner proximity (or spacing) can be evaluated as can the effect of the flue gas currents within the furnace on the flame envelope.

There are also some disadvantages to field testing. One is the confidentiality of the data collected. Most industries are extremely competitive and rival companies are reluctant to share data that may or may not be giving them a competitive edge in the market. Also, furnaces, with the passage of time, begin to “leak.” Leaks are, by definition, any area in a furnace where air is allowed to enter the vessel other than through the air entry of the burner. This problem is often not easily detected. Most furnaces are outfitted with an oxygen analyzer that monitors the percentage of oxygen in the flue gases exiting the stack. For most applications this is approximately 2 to 3% oxygen (volume, dry) in the flue gas. With excessive leakage of an air source, the uncontrolled air may negate the pollutant-reducing technology employed by the burners. Another limitation is often a lack of instrumentation. Outfitting an actual operating furnace with analytical equipment to measure emissions, fuel and air flow, and process conditions can be very expensive. Due to the limitations of economics, furnaces are typically fitted with the minimum amount of required instruments to safely operate and produce products. Finally, the sole reason for the existence of furnaces is for generating product and producing a profit. Supply and demand dictates at what condition the heater is operating and it is difficult to coordinate a time that the heater will be operating at design conditions for a period of time sufficiently long enough to record a complete set of data that gives an accurate representation of the burner’s performance.

9.3 BURNER TEST SETUP

One of the most important aspects of a burner test is the setup. This includes the selection of a test combustor, which is determined by the type of burner to be tested and its installation configuration. Typically, test furnaces are built with one of two common methods of cooling: a water-cooled jacket or a series of water-cooled tubes. A water jacket is simply a furnace surrounded by two shells (an inner and outer) of carbon steel that contains circulating water between the shells. This keeps cooling water on the four vertical surfaces to transfer heat. The other method utilizes cooling tubes that run either horizontally or vertically along one or two of the furnace walls.

Burners are designed to cover a wide range of applications. They are vertically up-fired, vertically down-fired, or horizontally fired. They can have round or rectangular flames and can be free-standing (away from the walls) or fired along a refractory wall. The criteria for selecting a burner normally includes the fuel to be fired, oxidant (typically air) supply method, emission

requirements, and heater configuration. Fuels can be gas, oil, waste gas, or some combination of the three. The combustion air supply can be either natural (induced) draft, forced draft, turbine exhaust gas, or other sources of oxygen. Emission requirements are primarily based on NO_x but can include unburned hydrocarbons, carbon monoxide, SO_x, and particulates.

The test fuel blend is an important component of a successful test, particularly those for burners used in petrochemical applications. Without the proper blend, a simulated fuel may or may not provide data that will aide engineers and operators when starting up new units or evaluating the performance of new burners installed in an existing unit. Test fuels are typically blended to closely simulate the heating value, flame temperature, specific gravity, and major components of the fuels to be used in the actual application. Another example of the importance of the test fuel is the case where fuel oil is used. The nitrogen content in heavy fuel oils is very important in determining NO_x emissions. In some cases, chemicals such as pyridine may need to be added to the test fuel to match the nitrogen content in the actual fuel.

9.3.1 APPLICATION

Although any fuel (solid, liquid, or gas) can be used in a burner designed for a specified fuel type, this chapter is limited to gas and liquid fuel firing because they are, by far, the most common found in most industrial applications. When firing a fuel, the normal products of combustion are CO₂, H₂O, N₂, O₂, and the energy or heat released during a combustion process. Unfortunately, there are also other less desirable products that can be released. These commonly include unburned hydrocarbons (UHCs), particulates, NO_x, SO_x, and CO.

9.3.2 TEST FURNACE SELECTION CRITERIA

The selection of a test furnace is important. The furnace should be big enough to contain the flame without impingement on the walls or ceiling of the furnace. Also, it is important to select the proper furnace to keep the furnace temperature close to the customer's expected furnace temperature. The following figures show some typical furnaces used for burner testing.

The furnace shown in [Figure 9.2](#) can be tested in a variety of configurations. Wall-fired burners can be tested at the floor level and radiant wall burners can be tested at higher elevations in the furnace to match the end-use configuration. The number of burners can be changed to simulate the setup in the field as well as to achieve a certain furnace temperature.

The furnaces shown in [Figure 9.3](#) can be tested in the down-fired configuration to simulate certain types of reformers in the petrochemical industry where the burners are installed on the roof of the furnace and fired down in between the process tubes. Another type of furnace is a vertical cylindrical water-jacketed furnace as shown in [Figure 9.4](#).

Because test facilities are not built for the purpose of heating an actual load (e.g., a hydrocarbon fluid in a petrochemical application) to a desired temperature or creating products, the heat released from the burners must be absorbed by some method. The furnace shown in [Figure 9.4](#) is surrounded by a shell filled with water. [Figure 9.5](#) shows a test furnace used to demonstrate burners for terrace wall reformers.

9.3.3 SELECTION OF TEST FUELS

The main criteria for fuel selection include the similarity in combustion characteristics with the actual fuel specified for the application, economics, availability, and compatibility with the systems, operations, and equipment. [Figure 9.6](#) shows both permanent and portable fuel storage tanks. Portable tanks can be used when testing is required on specialty fuels.

Probably the most critical component of successfully testing a burner is the selection of the test fuel. Without matching key components in the customer's fuel, the emissions, stability, and flame shape shown during a burner test may vary greatly when compared to the field results.



FIGURE 9.2 Test furnace for simulation of ethylene furnaces. (Courtesy of John Zink Co., LLC.²¹)

Fuel can be blended to the heating value or molecular weight as specified or as mutually agreed upon with the customer. Fuel and the diluent content of the fuel gas blend should be similar in volumetric proportion as in the specified actual service fuel gas if these proportions significantly impact burner performance. The Wobbe index is often used when reviewing a test blend that will be used to simulate a fuel. The Wobbe index is the higher heating value (HHV) of a fuel, divided by the square root of its specific gravity (SG):

$$\text{Wobbe index} = \frac{HHV}{\sqrt{SG}} \quad (9.2)$$

The specific gravity (SG) for a gas is the ratio of the molecular weight of a gaseous fluid to the molecular weight of air. The specific gravity for a liquid is the ratio of the density of a liquid to the density of water. It is important to note that the two fluids must be compared at the same temperature. Two fuels will provide the same heat release from a gas tip at a given supply pressure if the Wobbe index is the same.



FIGURE 9.3 Test furnace for simulation of downfired tests. (Courtesy of John Zink Co., LLC.²¹)



FIGURE 9.4 Test furnace for simulation of upfired tests. (Courtesy of John Zink Co., LLC.²¹)

While the Wobbe index is a good indicator to see if a fuel is similar, it is important to try and match the lower heating value (LHV), molecular weight, and adiabatic flame temperature to ensure a good simulation. Commonly available gaseous fuels for blending at well-equipped test facilities include natural gas, propane, propylene, butane, hydrogen, nitrogen, and carbon dioxide. The composition of natural gas varies by geographic location. As an example, Tulsa natural gas has a typical composition as shown in [Table 9.1](#).

[Table 9.2](#) illustrates a typical refinery gas and the points of interest in determining a test blend that will effectively simulate the fuel handling properties, burning characteristics (tendency of a fuel to coke, etc.), and emission levels of the customer's fuel composition.

Based on the available fuels for blending, the hydrogen content is matched, propylene is used to substitute the ethylene content, and Tulsa natural gas (TNG) is used to simulate the methane content. By holding the hydrogen content fixed at 38%, TNG and propylene are balanced to obtain a match of the lower heat value (LHV) and molecular weight. By attempting to balance the LHV, molecular weight, and adiabatic flame temperature, a test fuel blend of 34% TNG, 28% C_3H_6 , and 38% H_2 would be acceptable to simulate the refinery fuel gas illustrated in [Table 9.2](#). [Table 9.3](#) gives a side-by-side comparison of the fuel properties.

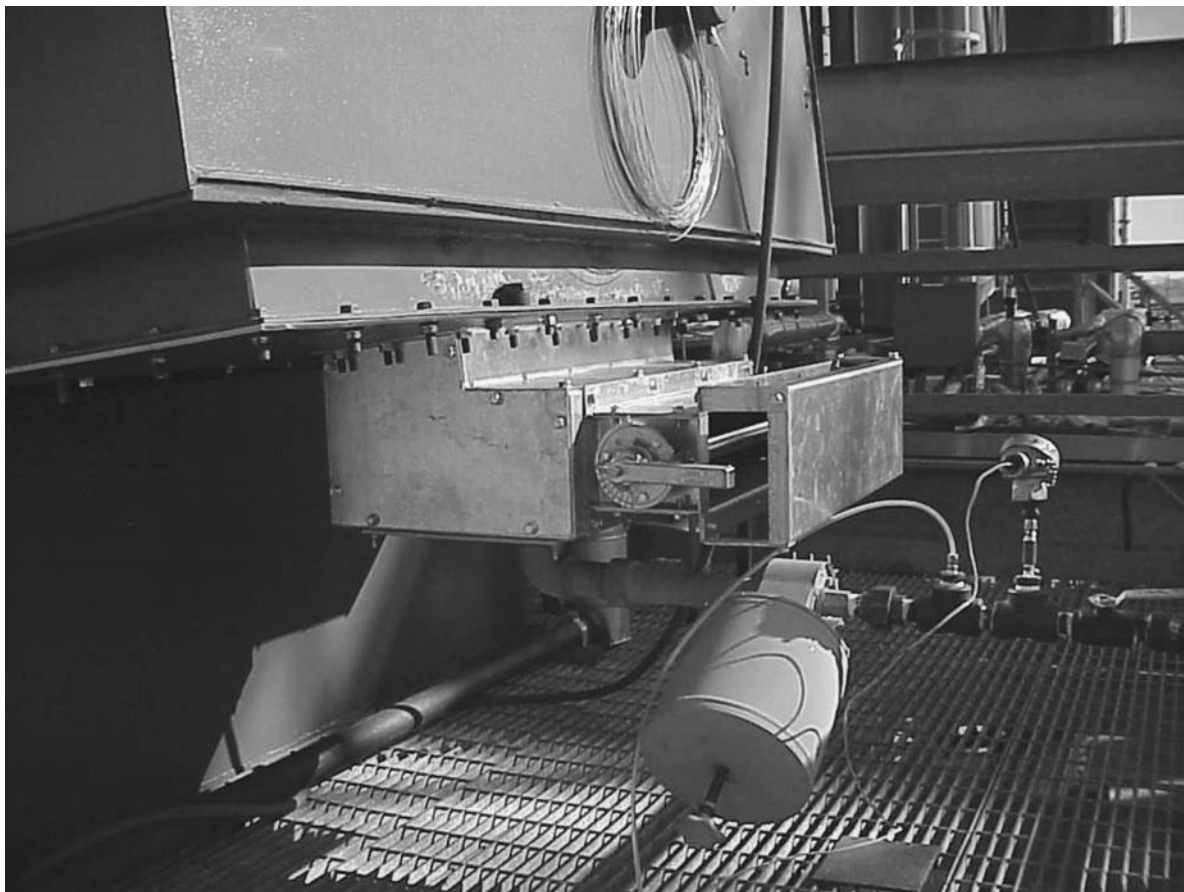


FIGURE 9.5 Test furnace for simulation of terrace wall reformers. (Courtesy of John Zink Co., LLC.²¹)



FIGURE 9.6 Test fuel storage tanks. (Courtesy of John Zink Co., LLC.²¹)

TABLE 9.1**Tulsa Natural Gas Nominal Composition and Properties²¹**

CH ₄ (volume%)	93.4	C ₄ H ₁₀ (volume%)	0.20
C ₂ H ₄ (volume%)	2.70	CO ₂ (volume%)	0.70
C ₃ H ₈ (volume%)	0.60	N ₂ (volume%)	2.40
LHV (Btu/scf)	913	HHV(Btu/scf)	1012
Molecular weight	17.16	Specific heat ratio @ 60°F	1.3
Adiabatic flame temperature (°F)	3452		

TABLE 9.2**Typical Refinery Gas²¹**

Fuel Component			
Name	Formula	volume %	
Methane	CH ₄	8.13	Balance of fuel is primarily methane and ethane.
Ethane	C ₂ H ₆	19.9	
Propane	C ₃ H ₈	0.30	
Butane	C ₄ H ₁₀	0.06	
Ethylene	C ₂ H ₄	32.0	Note: level of olefins in the fuel.
Propylene	C ₃ H ₆	0.78	
Butylene	C ₄ H ₈	0.66	
1-Pentene	C ₅ H ₁₀	0.07	
Benzene	C ₆ H ₆	0.12	Note: hydrogen content
Carbon Monoxide	CO	0.22	
Hydrogen	H ₂	37.8	

TABLE 9.3**Comparison of Refinery Gas to Test Blend²¹**

	Refinery Fuel	Test Fuel
LHV (Btu/sch)	1031	1026
HHV (Btu/scf)	1124	1121
Molecular Weight	18.09	18.38
Specific heat ratio @ 60°F	1.27	1.26
Adiabatic flame temperature (°F)	3481	3452
Wobbe Index	1422	1407

With the test fuel(s) established, it is time to determine what measurements will need to be taken and what instruments will be required.

9.4 INSTRUMENTATION AND MEASUREMENTS

Measurements generally required during testing include (but not limited to) fuel pressure and temperature, air pressure drop and temperature, fuel flow rates, flame dimensions, and emissions measurements.

9.4.1 COMBUSTION INPUTS

Combustion is the mixing of fuel and air to generate a reaction that produces energy. To conduct a successful test, many variables have to be measured throughout testing. The properties of the air and fuel must be measured, as well as the flue gas products resulting from combustion. In addition,

the operating conditions of the furnace must be measured in order to use the data collected. All test data must be corrected to the actual conditions that will be seen in the actual customer furnace.

9.4.1.1 Fuel Flow Rate

One of the most important aspects of burner testing is fuel metering. When firing a natural-draft burner, it is difficult to measure the flow rate of combustion air. Therefore, accurately metering the flow rate of each individual component used to make up a fuel blend is necessary to measure the heat release of the burner and its performance. There are many ways to measure flow, including differential pressure, magnetic, mass, oscillatory, turbine, and insertion flow meters just to name a few. For purposes of burner testing, the differential pressure flow meter will be discussed. Even limiting this discussion to differential flow meters, there are still several different methods of measurement available. Measuring the differential pressure across a known orifice plate is a common method to measure the gaseous fuel and steam flow. For liquid fuel firing, a coriolis meter is often used.

The orifice plate is the most commonly applied method of measuring flow.²² The advantage of using orifice plates (see Figure 9.7) is that they are versatile and can be changed to match a flow rate and fuel to be metered. Also, there is a significant amount of data concerning measuring fuel flow via an orifice plate. Finally, there are no moving parts to wear out. The drawbacks to orifice plates are that they are precision instruments and the following must be considered: the flatness of the plate, smoothness of the plate surface, cleanliness of the plate surface, sharpness of the upstream orifice edge, diameter of the orifice bore, and the thickness of the orifice edge. The critical inaccuracies due to these items can be alleviated by the purchase of ASTM-approved plates, rather than machining the plates. Another drawback is loss of accuracy when measuring flow rates of dirty



FIGURE 9.7 Orifice plate flow meter.

fuels. While dirty fuels are a way of life for the refining industry, test fuels are clean (no liquid or solid particles in the gaseous fuels) and such concern is minimized. Two items that should be verified when testing with orifice plates are that they are installed in the right direction (the paddle usually indicates the inlet side) and that the correct orifice bore is in the correct flow run.

While orifice plates can be used to meter liquids, coriolis meters are often preferred for measuring liquid fuel flow such as no. 6 oil or diesel oil. The coriolis meter operates on the basic principle of motion mechanics.²² The coriolis meter is able to measure the mass by measuring the amount of vibration the tube carrying the fluid is undergoing. The coriolis meter is a more expensive means of measurement, but this is often offset by its degree of accuracy and its low maintenance requirements.

9.4.1.2 Combustion Air Flow Rate

Combustion air flow rates are probably the most difficult measurements to make. Most applications are natural-draft applications where the differential pressure between the furnace and the external (or atmospheric air) to the combustion chamber creates air flow. This differential is usually less than an inch of water column. Because so little energy is available for metering and mixing the air flow, devices for measuring air are not practical due to their intrusive nature and energy requirements. In forced-draft (air supplied by a blower or fan) testing and turbine exhaust gas (TEG) testing, the combustion air is supplied via ducting to the burner. With this type of testing, air flow can be measured using devices such as venturi meters, the use of a Pitot tube, or a hot wire anemometer. Usually, the air flow is a calculated variable based on the fuel flow, which is measured, the fuel composition and the percentage of oxygen in the flue products. Due to the difficulties in air flow measurement, it is critical to ensure proper metering and measurement of the flue products and fuel properties.

9.4.2 COMBUSTOR CONDITIONS

The conditions within the combustor or furnace also provide critical information in determining the performance of a burner. Some of the information collected from the combustor includes the furnace gas temperatures at different locations. Typically, it is good practice to collect the furnace gas temperatures at the elevation of the burner, midway through the combustion chamber, and at the exit of the fired chamber. This is usually measured with a velocity thermocouple.

9.4.2.1 Furnace Temperature

A suction pyrometer (also known as a suction thermocouple or velocity thermocouple) is widely considered the preferred method for obtaining gas temperature measurements in the harsh environment of an operating furnace. If a bare thermocouple is introduced into a hot furnace environment for the measurement of gas temperature, measurement errors can arise due to the radiative exchange between the thermocouple and its surroundings. A suction pyrometer (see [Figure 9.8](#)) is typically comprised of a thermocouple recessed inside a radiation shield. An eductor rapidly aspirates the hot gas across the thermocouple. This configuration maximizes the convective heat transfer to the thermocouple while minimizing radiation exchange between thermocouple and its surroundings, ensuring that the equilibrium temperature is nearly that of the true gas temperature.

9.4.2.2 Burner Conditions

There are several burner conditions that should be recorded during testing. These mainly concern the configuration of the burner, such as the position of the combustion air inlet damper and the fuel injectors. The burner tile or quarl geometry should be recorded. Pressures and temperatures inside the burner at one or more locations are often of interest.



FIGURE 9.8 Suction pyrometer with noise muffler.

9.4.2.3 Draft

The combustion air for natural-draft burners (see Chapter 16) is induced through the burner, either by the negative pressure inside the firebox or by fuel gas pressure that educts the air through a venturi. Natural-draft burners are the simplest and least expensive burners, and most commonly found in the hydrocarbon and petrochemical industries. Because the energy available to draw air into the burner is relatively low, it is difficult to measure the air flow through the burner. As a result, the temperature of the air, the ambient air pressure, the fuel flow, and the excess air measurements are critical in accurately calculating the air flow through a natural-draft burner.

Forced-draft burners are supplied with combustion air at a positive pressure. The air is supplied by mechanical means (air fans/blowers). These burners normally operate at an air-side delivery pressure that can be in excess of 2 inches of water column (0.5 kPa). They utilize the air pressure to provide a superior degree of mixing between fuel and air. Also, with forced-draft systems, air control can be better maintained, thus allowing furnaces to operate at lower excess air rates over a wide firing range and allowing the operator to realize economic savings. [Figure 9.9](#) shows an example of a mobile air preheater used during forced draft testing.

With the use of an air delivery system, the air flow can be measured to provide a secondary method of measuring the air flow to validate the primary measurement. Fuel flow metering is still used to regulate the air flow. By knowing the amount of fuel burned and the excess air exiting the furnace, the amount of air consumed by the burner can be calculated.

9.4.2.4 Flame Characteristics

The flame shape and dimensions are determined by the burner tile, the drilling of the gas tip, the fuel, and the aerodynamics of the burner. Round burner tiles are used to produce a conical or cylindrical shape. Flat flame burners are designed with rectangular burner tiles and produce fishtail-shaped flames. Many of the liquid fuel burners are designed with round burner tiles and produce a conical



FIGURE 9.9 Forced-draft air preheater. (Courtesy of John Zink Co., LLC.²¹)

flame. The drilling of the oil tip determines the shape and length of the flame. Reducing the angle produces a longer, narrower flame. Increasing the angle produces a shorter, bushier flame. Forced-draft burners produce a shorter flame because of the better mixing between the fuel and the air. Firing in combination with both liquid and gas fuels will increase the length and volume of the flame and can cause coking of the oil and gas burner nozzles.

Another characteristic of a burner flame is its stability. Stability is a controversial and subjective measurement. Stability can be defined as erratic motion at the flame front (point of ignition), by vibrations in the furnace, or by CO measurements within and around the flame envelope. Industry practice defines flame shape as the envelope that is in the visual spectrum. As can be imagined, two people viewing a flame will arrive at different dimensions, thus making flame shape very subjective. To compensate for this inaccuracy, testing has fallen back to measuring the CO to determine the point at which combustion is nearly complete. It is widely debated as to whether the CO measurement for defining a flame shape is 500, 1000, 2000 ppm, or some other level. Flame intensity is how bright a flame is to the naked eye. Oil-fired burner equipment typically produces an intense flame that is bright yellow and opaque. Gas-fired equipment typically produces a blue, less intense translucent flame.

9.4.2.5 Heat Flux

Several techniques have been developed to measure heat flux levels at different locations within a furnace. The instruments designed to successfully obtain heat flux data in the hostile environment of a full-scale furnace are typically water-cooled probes inserted through a furnace port at the location of interest. The probes may utilize pyrometers that measure radiant or total (radiant + convective) heat flux levels. The sensing element is typically composed of a thermopile-type sensor that outputs a voltage proportional to the temperature difference between the area of the element exposed to heat transfer from the furnace and the area that is cooled and kept at a relatively constant temperature per the element design. Sensor element designs differ chiefly between the geometry

and configuration of the thermopile-type sensing element. Common designs utilize a plug-shaped thermopile element with the exposed face at one end and the opposite end cooled by contact with a heat sink (see Figure 9.10). Others use a disk-shaped sensor with the temperature gradient existing between the center of the disk receiving radiant energy and the radial edge that is cooled by contact with a heat sink. A sensor designed to measure only the radiant component of heat flux (radiometer) may utilize a crystal window, gas screen, or a mirrored ellipsoidal cavity (see Figure 9.11) to negate convective heat transfer to the sensor. A radiometer is also often equipped with a gas purge in an effort to keep the crystal window or mirrored ellipsoidal cavity clean and free from fouling. Critical parameters to consider when using a heat flux meter include the ruggedness, sensitivity, calibration method, and view angle of the instrument.

9.4.3 EMISSIONS MEASUREMENTS

Emissions analysis is an important criterion for burner testing. The main pollutants in the combustion products are NO_x, CO, unburned hydrocarbons, and particulates. There are several parameters that are typically measured to determine the pollution emission rate. These are discussed in this section. A more comprehensive discussion is given elsewhere.²³

There are two methods for obtaining gas samples: extractive and *in situ*. In extractive sampling, the exhaust gas is withdrawn from the sample point and conveyed to a gas sampling system (see Figure 9.12) typically located in a conditioned building. The extracted sample must be conveyed in such a way as to preclude any changes in the composition prior to reaching the analysis equipment. This typically involves heat traced sample lines to prevent water from condensing out of the sample, which could cause a scrubbing effect on some of the other components. Extractive systems can have a significant time delay between extracting a given sample and determining its composition, depending on how far the sample is being transported.

In situ sampling means that the sample probe is located directly in the exhaust gas stream. *In situ* sampling involves analyzing the exhaust gases in the exhaust stack without extracting them. *In situ* analyzers are available for SO₂, CO, O₂, NO_x, and CO₂. They are also available for measuring opacity and particulates. There is essentially no time delay in getting an analysis. However, the sensor is often subjected to high exhaust gas temperatures and any particulates in the stream that could cause plugging. The electronics are also typically subject to the weather conditions which can increase maintenance costs. The physical location of the equipment, typically on the side of an exhaust stack, may make maintenance more difficult.

9.4.3.1 Exhaust Gas Flow Rate

The exhaust gas flow is usually not directly measured but is often determined through a combination of measurements, calculations, and assumptions. For example, the gas velocity is measured at one or more points across the exhaust duct. Because it is not known *a priori*, if the gas sample is homogeneous, it must be assumed, until proven otherwise, that there is some variation across the exhaust gas duct. This is done by making multiple traverses across the duct. The cross-sectional area of the duct is subdivided into smaller areas for the purpose of making measurements. The gas velocity in each sub-area is assumed to be constant. Then the gas flow rate through that sub-area is simply:

$$Q_i = \frac{v_i}{A_i} \quad (9.3)$$

where Q_i is the gas flow rate through sub-area i , v_i is the gas velocity through the sub-area, and A_i is the area. The sum of all the sub-areas equals the total cross-sectional area of the duct:

$$A = \sum_{i=1}^n A_i \quad (9.4)$$

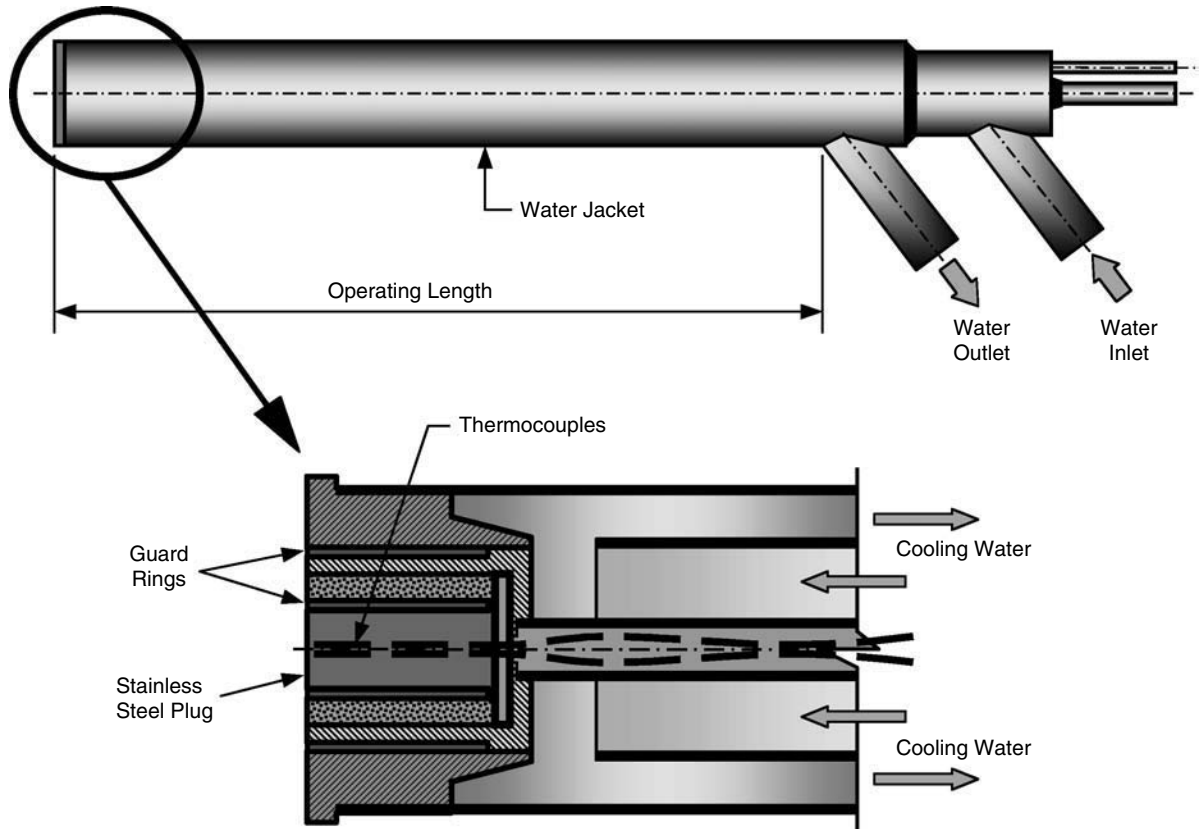


FIGURE 9.10 Schematic of a heat flux probe. (Courtesy of John Zink Co., LLC.²¹)

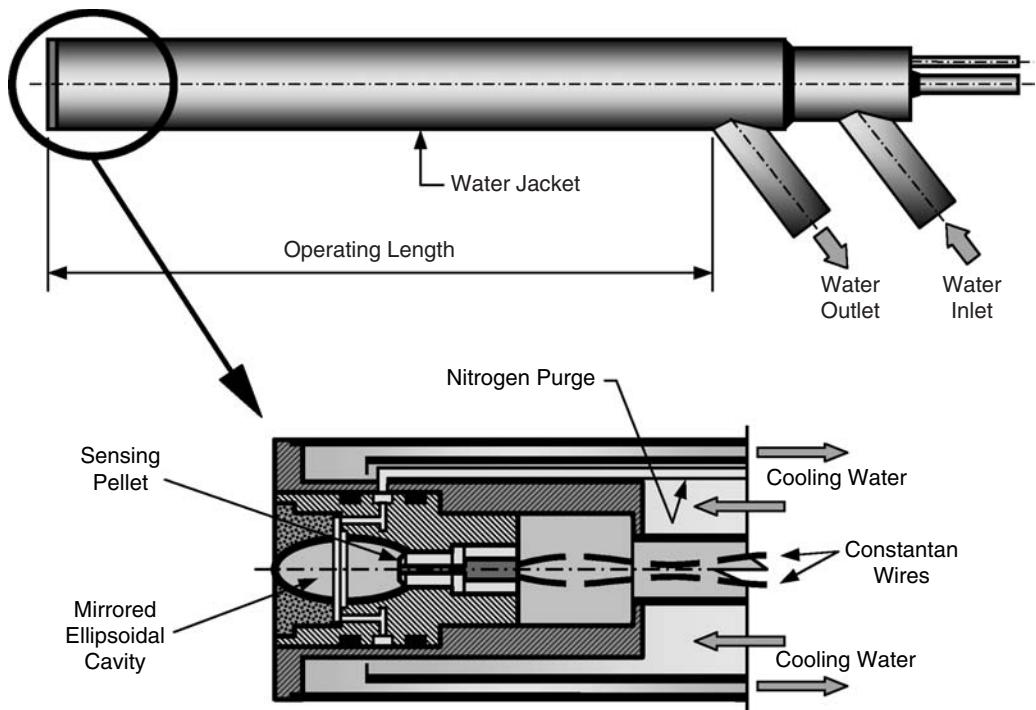


FIGURE 9.11 Schematic of an ellipsoidal radiometer. (Courtesy of John Zink Co., LLC.²¹)



FIGURE 9.12 Gas sample analysis system.

where A is the total duct cross-sectional area and n is the total number of sub-areas. Then, the total exhaust gas flow rate equals the sum of the individual gas flow rates:

$$Q = \sum_{i=1}^n Q_i \quad (9.5)$$

EPA Method 2 discusses how to determine the volumetric stack gas flow rate using an S-type Pitot tube that includes a temperature sensor (see Figure 9.13).²⁴ The method only applies to flows that are not swirling or cyclonic. This method combines measurements and calculations to determine the gas flow rate. Specific guidelines are given for what materials should be used and that dimensions are critical. Each Pitot probe must be calibrated with a known coefficient that should be engraved on the probe. The static and dynamic measuring holes on the probe must not be plugged; that might be a problem in particulate-laden flows. The pressure “head” or difference between the static and dynamic measurements is typically very small and can be measured with an inclined manometer (see Figure 9.14) or a similar device such as a magnehelic gage. Both of these need to be calibrated to ensure accuracy.

According to EPA Method 2, the average stack gas velocity can be calculated for an S-type Pitot tube using:

$$v_s = K_p C_p \sqrt{\frac{(p_t - p_{st})T_s}{P_s M_s}} \quad (9.6)$$

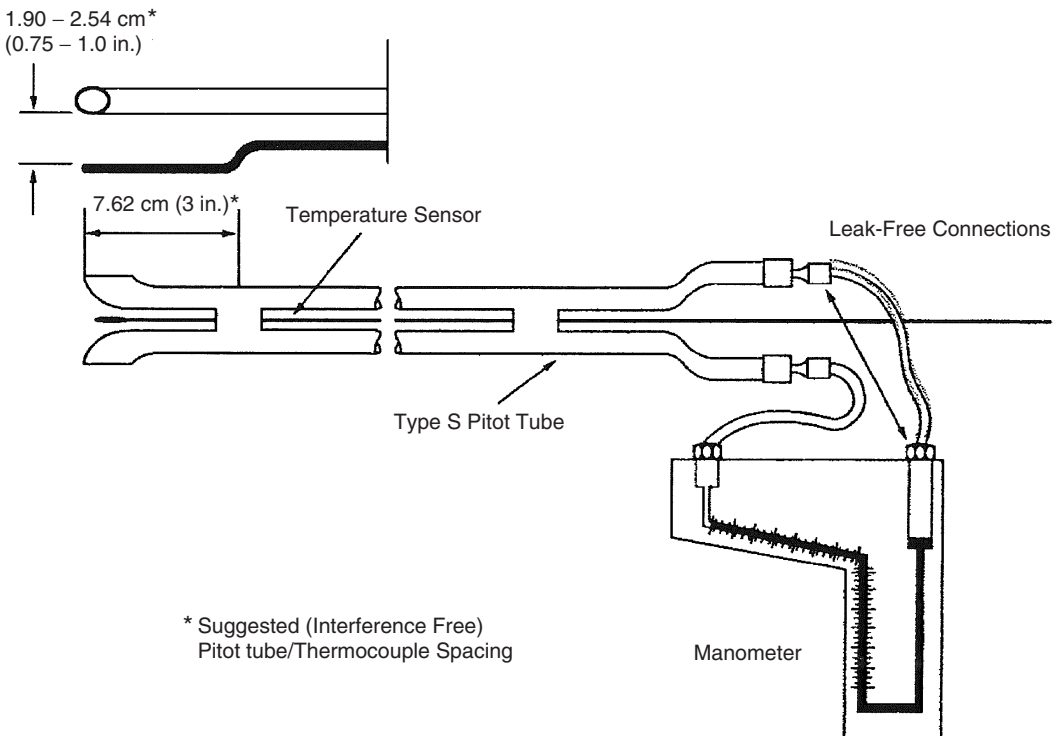


FIGURE 9.13 S-type Pitot tube manometer assembly for measuring gas velocity. (From U.S. EPA.²⁴)

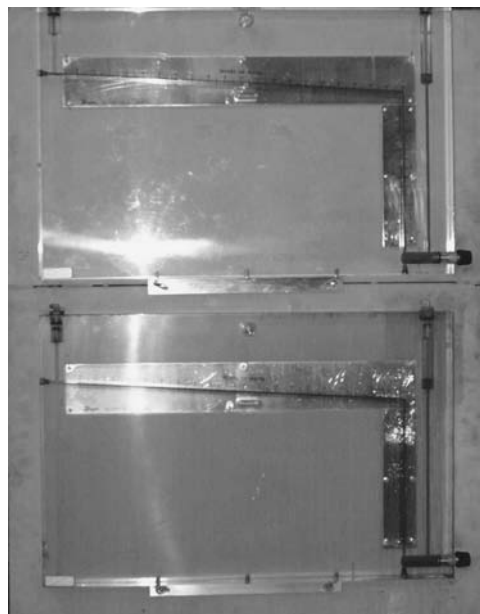


FIGURE 9.14 Inclined manometers for measuring differential pressure.

where

- v_s = average stack gas velocity (ft/s)
- K_p = velocity equation constant
- C_p = Pitot tube probe constant
- $p_t - p_{st}$ = difference between total and static pressures measured with Pitot tube (in. H₂O)
- T_s = absolute stack temperature (°R)
- P_s = absolute stack pressure (in. Hg)

$$M_s = M_d(1 - B_{ws}) + 18B_{ws} \quad (9.7)$$

where

- M_s = molecular weight of wet stack gas (lb/lb-mole)
- M_d = molecular weight of dry stack gas (lb/lb-mole)
- B_{ws} = fraction by volume of water in the gas stream (determined by Methods 4 or 5)

According to EPA Method 2, the average dry stack gas volumetric flow rate is calculated as follows:

$$Q = 3600(1 - B_{ws})v_s A \left[\frac{T_{std} P_s}{T_s P_{std}} \right] \quad (9.8)$$

where

- Q = volumetric flow rate in dry standard cubic feet per hour (dscf/hr)
- B_{ws} = fraction by volume of water in the gas stream (determined by Methods 4 or 5)
- v_s = average stack gas velocity (ft/s)
- A = cross-sectional area of the stack (ft²)

T_{std} = standard absolute temperature = 528°R
 P_s = absolute stack pressure (in. Hg)
 T_s = absolute stack temperature (°R)
 P_{std} = standard absolute pressure (29.92 in. Hg)

EPA Method 2A discusses the direct measurement of the gas volume flow rate through pipes and small ducts. These devices include, for example, positive displacement meters and turbine meters. This is a much simpler and faster technique than measuring multiple traverse points in the exhaust gas stack and then computing the flow rate based on several different types of measurements (e.g., pressure difference, gas temperature, barometric conditions, and moisture in the stack gases). Direct measuring devices must also be properly calibrated to ensure accuracy. These usually cost much more than the using Pitot tubes and manometers but require far less labor to operate. They can also mitigate the problem of varying conditions across the exhaust duct. However, they are typically used only on smaller diameter ducts and they may introduce a significant pressure drop in the exhaust system that may require either additional fan power or a reduction in the exhaust gas volume flow rate, which is usually not desirable.

In some cases, the simplest and most straightforward method to determine the exhaust gas flow rate is to calculate it based on the incoming fuel and combustion air flows and measured exhaust gas composition. This is often of sufficient accuracy for many situations. This method uses a combination of measurements, assumptions, and calculations to determine the gas flow rate. There are also some variations of the technique. However, in general, the technique involves calculating the gas flow rate based on either the measured input flow rates, the measured stack gas composition, or a combination of the two as a check to make sure the results make sense.

9.4.3.2 Exhaust Gas Temperature

A common method for measuring the exhaust gas temperature is with a suction pyrometer (see [Figure 9.8](#)). At the desired measurement location, gases are extracted from the flame through a sampling tube. A thermocouple is positioned just inside this tube, typically made of a ceramic or high-temperature metal, which acts as a radiation shield. This technique is particularly useful when measuring gas temperatures in hot-surfaced enclosures. Surface radiation from the walls to an unshielded thermocouple may introduce large errors in the gas temperature measurement. Chedaille and Braud (1972)²⁵ and Goldman (1987)²⁶ specifically discuss the use of a suction pyrometer to measure gas temperatures in combustors. This device has been successfully used to measure gas temperatures in excess of 2200K (3500°F).

The use of a thermocouple that is not shielded from radiation effects is not recommended unless appropriate corrective calculations are applied (see Reference 27). These corrections can be on the order of 200°F (110°C), or even more in certain cases. Unshielded thermocouples tend to underestimate the actual gas temperature because of radiant and conductive losses from the thermocouple junction. This is significant because NOx emission guarantees are often based on the measured combustor temperature. If the measured temperature is 200°F (110°C) less than the actual temperature, then the NOx may be significantly higher than expected because of its exponential dependence on gas temperature. Therefore, it is important to have a reasonably accurate furnace gas temperature.

9.4.3.3 NOx

The chemiluminescent method is most widely used for NOx analysis.²⁸ The method is capable of measuring oxides of nitrogen from sub-parts per million to more than 5000 ppm. Newer detector models are free from disadvantages inherent in analog systems and provide for increased stability,

accuracy, and flexibility. The principle of operation of these analyzers is based on the reaction of nitric oxide (NO) with ozone:



The sample, after it is drawn in the reaction chamber, reacts with the ozone generated by the internal ozonator. The above reaction produces a characteristic luminescence with an intensity proportional to the concentration of NO. Specifically, light emission results when electronically excited NO₂ molecules decay to lower energy states. The light emission is detected by a photomultiplier tube, which, in turn, generates a proportional electronic signal. The electronic signal is processed by the microcomputer into an NO concentration reading. To measure the NO_x (NO + NO₂) concentration, NO₂ is transformed to NO before reaching the reaction chamber. This transformation takes place in a converter heated to about 625°C (1160°F). Upon reaching the reaction chamber, the converted molecules along with the original NO molecules react with ozone. The resulting signal represents the NO_x. Further details of the workings of a chemiluminescent gas analyzer can be found in any standard text.

9.4.3.4 Carbon Monoxide

The carbon monoxide (CO) exiting a burner will initially increase slowly as the excess air rate decreases. The increase will accelerate as excess air levels continue to decline to near zero. Typical control points range between 150 and 200 ppm CO. This range usually results in the best overall heater efficiency. Certain localities may require lower emission levels. The presence of unsaturated hydrocarbons can lead to pyrolysis and polymerization reactions, resulting in a greater possibility that CO will be produced. Burners with greater swirl and/or higher combustion air pressure drop (such as forced-draft burners) typically have lower CO emissions at equivalent excess air levels. The reason is that these burners provide a superior degree of mixing to allow improved combustion at lower excess air levels.

Although CO can be continuously monitored by chromatographic analysis using thermal conductivity detectors or by FTIR spectroscopic methods, individual analysis is best accomplished using a nondispersive infrared technique. The main advantages of this technique is that it is highly specific to CO, and has lower ranges with a wider dynamic range, increased sensitivity and stability, and easy operation because of microcomputer control diagnostics. An added advantage of the technique is that the changes in temperature and pressure of the sample gas are immediately compensated by the microcomputer and the results are thus not affected by fluctuations in the operating conditions. The basic principle of these analyzers is based on the radiation from an IR source passing through a gas filter alternating between CO and N₂ due to rotation of the filter wheel. The CO gas filter acts to produce a reference beam which cannot be further attenuated by CO in the sample cell. The N₂ side of the filter wheel is transparent to the IR radiation and therefore produces a measure beam that can be absorbed by CO in the cell. These analyzers can measure 0.1 to 1000 ppm CO under well-controlled conditions. The detailed working of an IR analyzer can be obtained from a standard text on the subject.

9.4.3.5 O₂ (Wet and Dry)

The oxygen concentration is also conveniently measured by chromatographic techniques using thermal conductivity detectors and also by low-resolution FTIR spectroscopy. Individual measurements of oxygen concentration are most widely done by analyzers based on standard paramagnetic analyzers. The detailed working of such analyzers can be found in related texts.

9.4.3.6 Unburned Hydrocarbons (UHCs)

The unburned hydrocarbons (UHCs) increase as the excess air rate decreases. The combustion of hydrogen and paraffin-rich fuel will produce a minimum of combustibles. The presence of unsaturated hydrocarbons leads to pyrolysis and polymerization reactions, resulting in more combustibles. Unsaturated hydrocarbons, chlorides, amines, and the like can plug or damage burner tips, disrupting the desired fuel/air mixing. This can cause a further increase in the combustibles level. Heavy oils are more likely to produce greater levels of combustibles than lighter oils. Heavier components are not as easily atomized and ignited and, therefore, polymerization and pyrolysis reactions are more likely to occur. Forced-draft burners provide better mixing of the fuel/air mixture and therefore produce reduced combustibles at equivalent excess air rates.

Chromatographic techniques are the most widely used for VOC determination in the refinery off-gases. Their use as a multi-component, completely automated, and continuous emissions monitor is not documented in the literature. Coleman et al.²⁹ (1996) have discussed the use of gas chromatography-based continuous emission monitoring system for the measurement of VOCs using a dual-column (with DB-5 and PoraPlot U, respectively) gas chromatograph equipped with thermal conductivity detectors, in which separation was optimized for fast chromatography. In this system, nine different VOCs plus methane and CO₂ were separated and analyzed every 2 minutes. Because the permits are issued to report emission in pounds or tons of pollutants emitted and not on the basis of parts per million (ppm), the setup was equipped with a continuous mass flow measurement device. The data thus collected can be converted to pounds or mass of VOCs emitted. The column DB-5 separates ethanol, isopropanol, n-propanol, methyl ethyl ketone, isopropyl acetate, heptane, n-propyl acetate, and toluene. The PoraPlot U separates methane and carbon dioxide. A chromatographic technique using two fused silica columns — one with Dura-Bond and the other with Gas Solid-Q-PLOT — equipped with flame ionization detector was used by Viswanath (1994) to measure VOCs in air.³⁰

A technique reported by Pleil et al. (1988)³¹ uses the fact that the compounds once identified by retention time in the chromatographic analysis can be confirmed by determining a second dimension, such as its mass fragmentation pattern or its IR absorption spectrum from a highly specific detector such as a mass selective detector (MSD) or a Fourier transform infrared (FTIR) system. Even with this combination, care should be taken to avoid occasional confusion among isomeric, co-eluting compounds with similar, strongly absorbing functional groups. Using this technique, Pleil et al.³¹ were able to identify and successfully determine more than 40 compounds in the VOCs. They used cross-linked methyl silicon megabore capillary columns with both flame ionization detector (FID) and electron capture detector (ECD) simultaneously. A similar study of VOCs was reported by Siegel et al. (1992).³² They used a DB-1 column with a flame ionization detector and a mass selective detector (GC/MSD).

The U.S. EPA guidelines as presented in “Compendium of Methods for the Determination of Toxic Organic Compounds in Ambient Air, Method TO-14” is slowly becoming the criterion for VOCs (Pleil et al., 1991).³³ The recommended method uses cryogenic pre-concentration of analytes with subsequent gas chromatographic separation and mass spectrometric detection. The methodology requires detecting nanogram and sub-nanogram quantities. To get this high sensitivity, the method TO-14 recommends the use of a selective ion monitoring (SIM) spectrometric technique. The details of the method were discussed by Pleil et al. (1991).³³ Evans et al. (1992)³⁴ have also discussed the use of a cryogenic GC/MSD system to measure the VOCs in air in different parts of the country. The sample first passes through a fused silica column to resolve the target compounds. The column exit flow splits, such that one third of the flow is directed to the chromatographic column (with flame ionization detector) and two thirds of the flow goes to the mass selective detection system (MSD). The method was found to effectively detect 0.1 ppb by volume of about 25 VOCs.

Larjava et al. (1997)³⁵ have recently reported a comprehensive technique for the determination of nitric oxide (NO), sulfur dioxide (SO₂), carbon monoxide (CO), carbon dioxide (CO₂), and total hydrocarbons (C_xH_y) in the air. The technique used single-component gas analyzers in parallel with a low-resolution Fourier transform infrared (FTIR) gas analyzer. The technique successfully demonstrated that the results obtained by single-component analyzers and the FT-IR were very close. Online analysis of stack gases with FTIR spectrometry has received considerable attention recently because of the multi-component analysis capability and sensitivity of the method (Larjava et al., 1997; Wübern, 1992;³⁶ and Demirgian and Erickson, 1990).³⁷ A typical low-resolution FTIR spectrometer uses spectral resolution, BaF₂ optics, a Peltier-cooled semiconductor detector, and a temperature-controlled multi-reflection gas cell. The advantages of low-resolution FTIR over conventional high-resolution FTIR are its rugged design, high signal-to-noise ratio without liquid nitrogen-cooled detectors, reduced data storage requirements, and increased dynamic range for quantitative analysis (Larjava et al., 1997).³⁵

Jayanti and Jay (1990)³⁸ have summarized studies on estimating VOCs by different techniques employed by different workers.

9.4.3.7 Particulates

Proper combustion of gaseous fuels does not generate significant quantities of combustion-generated particulates. Particulate emissions generally occur with the burner of heavy fuel oils. Burners with greater swirl and/or higher combustion air pressure (such as forced-draft burners) are less likely to produce particulates. They provide a superior degree of mixing to reduce the formation of particulates. Greater atomization of fuel oil into finer particles will reduce particulate emissions. High-intensity burners can considerably reduce particulates. The high degree of swirl, coupled with the high-temperature reaction zone, induces superior combustion of the particulates. However, these burners also emit an increased amount of NO_x.

The particulates from the hydrocarbon industries are the pollutants that are emitted by the effluent gases. The most important criterion for the evaluation of particulates is the particle size. It has been observed that different results are obtained using different techniques of collection and analysis.

The U.S. EPA (1971)³⁹ recommended procedures suggest that sampling ports be located at least eight duct diameters downstream and two diameters upstream from any flow disturbance. Flue gas should be drawn through the EPA sampling train. It is important to maintain isokinetic sampling conditions. The EPA defines isokinetic sampling as “sampling in which the linear velocity of the gas entering the sampling nozzle is equal to that of the undisturbed gas stream sample point.”⁴⁰ This is particularly important when measuring larger particulates, especially those greater than about 5 μm. A schematic of an isokinetic sample probe is shown in [Figure 9.15](#).

Particles can be collected by filtration, impaction, and impingement. Glass fiber and membrane filters are efficient for 0.3-μm particles. These filters can be used in an inline filter holder. The filter holder can be kept inside the sampling port such that the filter attains the temperature of the gas stream.

For particulates collection by impaction, an Anderson type in-stack sampler is used. In cases where the sampler cannot be accommodated inside the sampling port flange, it can be put outside, with an arrangement to heat it to prevent condensation within the sampler. In this type of sampler, the collecting plates are coated with a thin film of silicone grease formed by immersing them in a 1% solution of silicone grease dissolved in benzene and dried overnight at 100°C (212°F).

The collection of particulates by impingement consists of using a series of three or four liquid impingers. These impingers each contain 250 ml of distilled water. A common practice is to use impaction and impingement techniques followed by glass fiber back-up filters.

Sampling times also vary according to the technique employed. One- to five-minute samples are common for filters and Anderson-type units, while 20 minutes are needed for impingers.

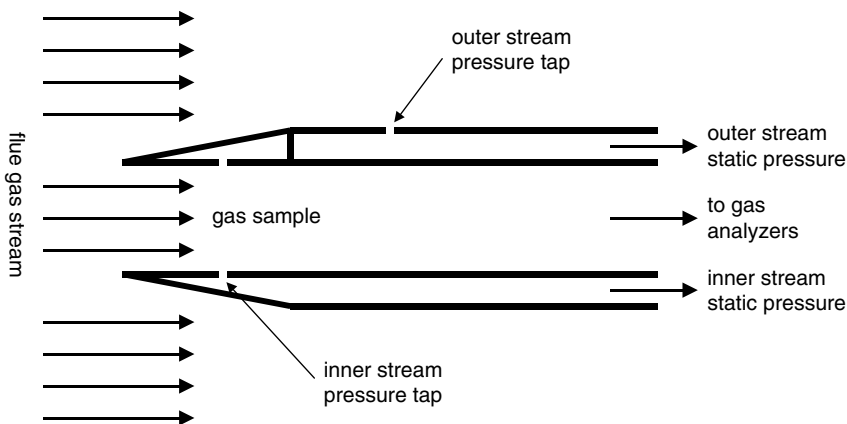


FIGURE 9.15 Nozzle for isokinetic sampling probe (not to scale).

Filter samples are analyzed by light microscopy and scanning electron microscopy (SEM). The liquid samples from the wet impingement device are filtered onto 0.2- μm membrane filters and examined by SEM. The samples from the Anderson sampler can be analyzed by the recommended procedure or by calculations based on Ranz and Wong equations. The Anderson plates can also be examined by SEM to determine the range of particles trapped on the plates. Particle counts can be determined by light microscopy using an oil-immersion lens system (Byers, 1973).⁴¹ Individual particles are compared on the basis of equal area to previously calibrated circle sizes contained on a size comparator. In an exhaustive study, Byers⁴¹ took data on particulates from a refinery effluent and suggested that membrane filters should be preferred when the gas being sampled is at a temperature less than 300°F (150°C). For higher temperatures, the Anderson sampler is suitable, provided the plates are suitably coated. Sampling techniques causing agglomeration, such as glass fiber filters, wet collection, bulk grab samples, and scrapping of deposits from collecting surfaces, should be avoided.

9.4.3.8 Noise

Noise is discussed in more detail in Chapter 7 and therefore will only be considered briefly here. Figure 9.16 shows a commonly used device for measuring industrial noise. A noise measurement system consists primarily of some type of microphone to receive the sound, some type of transducer to convert the sound waves into a usable signal typically digital, and a meter to convert the signals into the proper weighting system and to display and record the signals.



FIGURE 9.16 Bruel & Kjaer, sound level meter. (Courtesy of Bruel & Kjaer.)

The American Petroleum Institute Recommended Practice 531M gives information on measuring noise from process heaters.⁴² Recommendations are given for making field measurements, as well as procedures for sound-level measurement, including correcting for background noise. Measurements are suggested to be made at 1 m (3.3 ft) from the outside heater walls at various locations, depending on the configuration.

Hassall (1998)⁴³ lists the following procedural steps when making noise measurements:

1. Determine what quantities are to be measured.
2. Select the instruments, including the type of microphone to be used.
3. Determine the minimum number of microphone positions and their locations, including a diagram of the arrangement (multiple microphones are necessary to measure the sound field).
4. Check the system sensitivity.
5. Measure the acoustical and electrical noise level.
6. Measure the source sound levels.
7. Correct the measurements as appropriate (e.g., subtracting background noise).
8. Record the data.

Lang (1998)⁴⁴ discusses how to make sound power level measurements, typically used as a descriptor for stationary equipment. These measurements can be used to calculate the sound pressure level at a given distance from equipment, compare the noise radiated by equipment of the same type and size, compare the noise radiated by equipment of different types and sizes, determine whether equipment complies with a specified upper sound emission limit, determine the amount of noise reduction required for a particular circumstance, and develop quieter equipment. This type of measurement requires a three-dimensional array of microphones and therefore is not commonly used when measuring combustion noise.

Measuring sound intensity can be challenging as multiple types of probes are required to measure both the sound pressure and the particle velocity.⁴⁵ This is often done using two microphones and performing appropriate calculations to determine the particle velocity. This type of measurement is also not commonly done for industrial combustion systems.

There are a number of factors that can affect noise measurements and instrument performance, including temperature, humidity, atmospheric pressure, wind or dust, and even magnetic fields.⁴⁶ Instruments should be calibrated according to the manufacturer's instructions before and after each day of use and whenever the temperature or relative humidity changes significantly. Zahringer et al. (2000)⁴⁷ experimentally demonstrated the effectiveness of using microphones combined with an intensified camera system to measure acoustic oscillations in a boiler.

9.5 TEST MATRIX (TEST PROCEDURE)

9.5.1 HEATER OPERATION SPECIFICATIONS

Some of the parameters normally measured in burner testing are fuel pressure, air-side pressure drop, noise emissions, NO_x emissions, CO emissions, UHC emissions, particulate emissions, heat flux profiles, flame dimensions, and some subjective burner characteristics such as flame stability and color.

9.5.2 PERFORMANCE GUARANTEE SPECIFICATIONS

The primary reasons for conducting a burner test are to determine the operating envelope of the burner and the emissions performance. With this data collected, the burner's performance in the field will be more predictable and easier to operate.

9.5.2.1 Emissions Guarantees

It is important to identify which fuels are the operation or on-line fuels and which fuels are for start-up or emergency use only. By identifying which fuels the emissions guarantees apply to, the burner can be better optimized to run on the operation fuels.

9.5.2.2 Noise

Noise emissions are becoming as important as stack emissions. With some industrial plants located near populated areas, it is important to keep noise to a minimum. Burner testing is usually conducted on a single burner, and noise emissions are usually measured at 1 meter (3 ft) from the burner. Data collected during the test include an overall dBA measurement and an octave band measurement ranging from 31.5 to 8000 Hz. When collecting noise data, it is important to measure it with the burner operating, and without it operating, to obtain the background noise which may or may not be required to determine the noise contributed from the burner.

9.5.2.3 Fuel and Air-side Pressure Drop

The fuel and air-side pressure drop also need to be verified during the test. The test confirms that the burner will have the correct capacity for proper operation. The fuel-side pressure drop will be displayed during the test. It is important that the test engineer ensure that the customer's fuel will meet the design pressure requirement based on the data collected on the test fuels. When verifying the air-side pressure drop, the test engineer must determine the elevation and the range of the ambient air temperatures that the burners will be subjected to once installed in the field.

9.5.2.4 Flame Dimension Guarantees

Flame dimensions in a full-scale furnace are typically made by subjective measurement. The flame envelope is most often determined by visual observation. These visual observations will often vary somewhat, depending on the observer and also on the operating conditions. For example, in an outdoor test furnace, the reflection of the sun off the sight ports can make it difficult to determine an approximate flame length. The hotter the test furnace, the more difficult for the human eye to distinguish between the hot furnace walls and the flame.

This operating parameter is important in ensuring that the flame will not impinge on the furnace process tubes or interact with another burner's flame. Flame impingement on the tubes can damage the process tubes and cause the furnace to prematurely shut down for repairs — at great expense to the operator. Flame interaction between two or more burners can result in longer, more uncontrollable flames and higher emissions. It is important to identify the burner spacing, the furnace dimensions, and the customer's desired flame dimensions. With this information, the test engineer can fine-tune the flame envelope to improve the burner's performance in the customer's heater.

9.5.3 DATA COLLECTION

Prior to installation and testing a burner, a test matrix (test procedure) must be developed. A sample fuel gas specification is shown in [Table 9.4](#). A typical test procedure might resemble that shown in [Table 9.5](#). With a well-developed test procedure, the data collected from a test will be meaningful and will assist the operator in running the furnace and predicting the performance from the furnace.

The data should be recorded in an orderly fashion, preferably with a computer data acquisition system or by hand on a well-conceived data entry form. It is important to record not only all the

TABLE 9.4
Test Procedure Gas Specification Sheet²¹

JOHN ZINK COMPANY TULSA, OK			BURNER PERFORMANCE DEMONSTRATION BURNER SPECIFICATION (GAS)			
Date:	2/4/00	Rev. No:	0	J.Z. Quote No:		
Customer:				Customer P.O. No:		
Burner:	PSFFG-45M			J.Z. Sales Order No:		
Drawing:				Capacity Curve No:		
User:				Project Engineer:		
Jobsite:				Test Engineer:		
CUSTOMER HEATER DATA						
Spec Reference:				Direction of Firing:		
Item No:				Setting Thickness:		
Quantity of Burners:	60			Burner Spacing:	39 inches (1 meter)	
Type of Heater	Ethylene			Pilot:	ST-1S manual pilot	
Firebox Dimensions:				Elevation:	<1000 feet ASL	
Draft Type	Induced					
SPECIFICATIONS						
Fuel Composition	LHV	MW	FUEL A	FUEL B	TMG	
Component:	Btu/scf	## mol	vol%	vol%	vol%	vol%
Tulsa natural gas	913.0	17.160	34.00	80.00	100.00	
Hydrogen	273.8	2.022	38.00	20.00		
Propane	2314.9	44.100				
Propylene	2181.8	42.080	28.00			
Carbon Dioxide		44.010				
Butane	3010.6	58.120				
Lower Heating Value:	Btu/scf					
Molecular Weight:	(## mol)		18.385	14.132	17.180	
Isentropic Coefficient:	(Cp/Cv)		1.2600			
Temperature:	(degF)		60	60	60	
Pressure Available:	usig		20.0	20.0	20.0	
Heat Release per Burner:						
Design Maximum:	(MMBtu/hr)		6.800	6.800	6.800	
Normal:	(MMBtu/hr)		5.913	5.913	5.913	
Minimum:	(MMBtu/hr)		1.360	1.360	1.360	
Flame Dimensions: @ ft						
Cross Section (Dia):			4.000	4.000	4.000	
Length:			16.000	16.000	16.00	
Turndown:			5:1	5:1	5:1	
Excess Air @ Design:			10	10	10	
Conditions @ Burner:						
Heater Draft Available:	(w.c.)		0.80	0.80	0.80	
Burner dP @ Design:	(w.c.)		0.80	0.80	0.80	
Combustion Air Temp:	(degF)		100	100	100	
Guarantees:						
NOx	ppm(vd)		100	100	100	
CO:	ppm(vd)		50	50	50	
Note 1 Particulate:	#MMBtu (hv)					
Note 1 UHC:	#MMBtu (hv)					

TABLE 9.4
Test Procedure Gas Specification Sheet (Continued)

JOHN ZINK COMPANY TULSA, OK		BURNER PERFORMANCE DEMONSTRATION			
(English)		BURNER SPECIFICATION (GAS)			
DSCF / MMBtu @ 3% O ₂ (d)	(hv)				
Noise:	dBA (spi) @ 3 ft.	85	85	85	
Conditions of Guarantees:					
% Oxygen Corrected to:		3	3	3	
Combustion Air Temp:	(degF)	100	100	100	
Heat Release:	(MMBtu/hr)	4.500	4.500	4.500	
Furnace Temperature:	(degF)	2100	2100	2100	
COMMENTS: General – Heat Releases are shown as Net or Lower Heating Value.					
<i>Note 1:</i> Particulate and UHC are NOT measured during Test Demonstration.					

relevant operating parameters (e.g., temperatures, pressures, and flow rates), but also the conditions of both the burner and the combustor. For example, if the insulation pattern changes inside the test furnace from test to test, then this should be recorded for future reference. If, for example, orifice plates are used to measure gas flows, then these need to be recorded for a given test in case verification is needed later. Any unusual features of the test should also be recorded, including photos where appropriate. For example, if a structure such as an internal wall is temporarily built inside the test furnace, this should be documented. Therefore, it is recommended that a comprehensive checklist be developed to ensure that all the appropriate information is recorded for a given test.

The test data should be put into some type of test report to summarize the results of the test. Enough information must be included so that the test can be replicated if necessary and that proper analysis can be done at a later time if desired. For example, CFD analysis (see Chapter 5) will only be meaningful if enough data has been collected for proper comparison between the measurements and computer predictions. The data should be presented in tabular or graphical form to make it easier for the reader to both find and compare the data. The data should also be presented in the proper units or, in some cases, multiple units (e.g., English and SI). This may include converting some of the measurements to other units. For example, raw NO_x emissions are typically measured in ppm (parts per million) at some oxygen level in the exhaust stack. These are usually converted to ppm at a specific oxygen level (e.g., 3% O₂) and often to another unit, such as lb NO_x per million Btus (lb NO/MMBtu). Noise measurements may need to be filtered by subtracting the background readings if they are significant. Both the raw and corrected data should be included in the report in case any future analysis is required. (The raw data is often included in an appendix for the interested reader.)

The test report should be written in such a way that someone who is not necessarily an expert on testing or is not intimately familiar with the test apparatus can understand the data collected and the data analysis. The report should be a permanent record of the findings from a particular test. The test report is one of the most important outputs from a burner test.

9.6 CONCLUSION

While burner testing is mostly a well-defined process, there is still a considerable amount of both art and discretion used. Part of the art of testing is to determine the appropriate operating conditions in a pilot test furnace that best represent those in the actual end-use furnace. It also includes making some subjective measurements such as flame shape and stability. It is nearly impossible to exactly

TABLE 9.5
Example Test Procedure²¹

[illegible]

GENERAL COMMENTS:		DATA TO BE RECORDED:			
1) Refer to the schematic of the equipment set-up for approximate instrument and sight point locations. 2) The firebox temperature will be within the range of 1900°F and 2100°F for Normal and Maximum Heat Release. It will be lower at reduced rates. 3) Once the O ₂ has stabilized, at the target value for a given test point, data will be recorded and adjustments for the next point will begin. 4) All data points will be run with the furnace draft as specified, controlling excess O ₂ with the blower (forced draft), or with the damper (register(s)) (natural draft). 5) The proposed time frame for the duration of the test is approximate and could be longer, or shorter, depending on equipment operation and/or weather. 6) Standard tolerances on measurements will be as follows: Air Temp. +/-20°F, Fuel Temp. +/-20°F, O ₂ +/-0.2%. Draft or dP +/-6% of specified.		Fuel Flow	X	Burner dP	X
		Fuel Press.	X	NOx	X
		Fuel Temp.	X	CO	X
		Air Temp.	X	O₂	X
		Draft	X	Noise	X
		Box Temp.	X		
Test Procedure Acceptance:					
__Approved__ Approved as Noted:	Company:	Signature:		Date:	
Test Acceptance:					
Name:	Company:	Signature:		Date:	

replicate field conditions in a test furnace; therefore, compromises are necessary. One example is in the test fuel composition. In petrochemical applications, the actual fuel may have ten or more components, although many are in very small concentrations. These fuels are typically simulated by blending a handful of components.

Probably the largest compromise in pilot-scale testing is either using a reduced burner size or a reduced number of burners. The latter is particularly an issue when burner-to-burner interactions play an important role in the actual field furnace. It is nearly impossible for burner manufacturers to have full-size test furnaces, given the cost and variety of furnaces in any given field of industrial combustion. Therefore, the skill of the test engineer is required to first make the pilot testing as close as possible to the actual end-use conditions, and then to make the appropriate corrections and adjustments so that the test results are meaningful. Fortunately, tools such as computational fluid dynamic modeling (Chapter 5) and physical modeling (Chapter 10) can be used to assess the validity of pilot-scale burner testing and extend the test results to the actual furnace conditions.

REFERENCES

1. C.E. Baukal, V.Y. Gershtein, and X. Li, *Computational Fluid Dynamics in Industrial Combustion*, CRC Press, Boca Raton, FL, 2001.
2. American Petroleum Institute, Burners for Fired Heaters in General Refinery Services, API Publication 535, First Edition, American Petroleum Institute, Washington, D.C., July 1995.
3. J.M. Beér and N.A. Chigier, *Combustion Aerodynamics*, Applied Science Publishers, London, 1972.
4. C.I. Okoh and R.A. Brown, *Combustion Experimentation Handbook*, Gas Research Institute Report GRI-88/0143, Chicago, IL, 1988.
5. D.F.G. Durão, M.V. Heitor, J.H. Whitelaw, and P.O. Witze, *Combusting Flow Diagnostics*, Kluwer Academic Publishers, Dordrecht, 1992.
6. A.M.K.P. Taylor, *Instrumentation for Flows with Combustion*, Academic Press, London, 1993.
7. R.M. Fristrom, *Flame Structure and Processes*, Oxford University Press, New York, 1995.
8. A.C. Eckbreth, *Laser Diagnostics for Combustion Temperature and Species*, Abacus Press, Cambridge, MA, 1988.
9. N. Chigier, *Combustion Measurements*, Hemisphere Publishing, New York, 1991.
10. R.M. Fristrom, Probe measurements in laminar combustion systems, in *Combustion Measurements — Modern Techniques and Instrumentation*, R. Goulard, Ed., Academic Press, New York, 1976.
11. C.T. Bowman, Probe measurements in flames, *Prog. Astr. Aero.*, 53, 1–24, 1977.
12. F.C. Gouldin, Probe measurements in multi-dimensional reacting flows, in *Testing and Measurement Techniques in Heat Transfer and Combustion*, AGARD CP-281, paper #4, 1980.
13. H.A. Becker, Physical probes, in *Instrumentation for Flows with Combustion*, A.M.K.P. Taylor, Ed., Academic Press, London, 1993, 53–112.
14. J. Newbold, M.Q. McQuay, B.W. Webb, and A.M. Huber, The experimental characterization of the combustion process in an industrial, gas-fired, flat-glass furnace, *29th Int. ISATA Conf. — Automotive Technology & Automation*, Florence, Italy, June, Automotive Assoc. Ltd., Vol. 2, pp. 967–976, 1996.
15. P.R. Solomon, P.E. Best, R.M. Carangelo, J.R. Markham, P-L Chien, R.J. Santoro, and H.G. Semerjian, FT-IR emission/transmission spectroscopy for *in situ* combustion diagnostics, *Twenty-First Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, 1986, 1763–1771.
16. A.C. Eckbreth, Recent advances in laser diagnostics for temperature and species concentrations in combustion, *Eighteenth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, 1980, 1471–1488.
17. S.S. Penner, C.P. Wang, and M.Y. Bahadori, Laser diagnostics applied to combustion systems, *Twentieth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, pp. 1149–1176, 1984.
18. R.K. Hanson, Combustion diagnostics: planar imaging techniques, *Twenty-First Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, 1986, 1677–1691.

19. N.R. Fornaciari, R.W. Schefer, P.M. Walsh, and L.E. Claytor, Application of laser-based diagnostics to industrial scale burners, *Proc. 1995 International Gas Research Conf.*, D.A. Dolenc, Ed., Government Institutes, Rockville, MD, 1996, 2398–2405.
20. M. Perrin, J. Imbach, S. Albert, J. Mariasine, and A. Quinqueneau, Application of advanced instantaneous in-flame measurements techniques in an industrial flame with preheated air, *Proc. 1995 International Gas Research Conf.*, D.A. Dolenc, Ed., Government Institutes, Rockville, MD, 1996, 2406–2415.
21. J. Lewallen, R. Hayes, P. Singh, and R.T. Waibel, Chapter 14: Burner Testing, in *The John Zink Combustion Handbook*, C.E. Baukal, Ed., CRC Press, Boca Raton, FL, 2001.
22. D.W. Spitzer, *Practical Guides for Measurement and Control*, Instrument Society of America, Research Triangle Park, NC, 1991.
23. C.E. Baukal, *Industrial Combustion Pollution and Control*, Marcel Dekker, New York, to be published in 2004.
24. EPA. 40 CFR 60 – Standards of Performance for New Stationary Sources, U.S. Environmental Protection Agency, Washington, D.C., 2001.
25. J. Chedaille and Y. Braud, *Vol. 1: Measurements in Flames*, Crane, Russak & Co., New York, 1972.
26. Y. Goldman, Gas temperature measurement in combustors by use of suction pyrometry, in *Heat Transfer in Furnaces*, C. Presser and D.G. Lilley, Eds., ASME HTD-Vol. 74, 1987, 19–22.
27. C.E. Baukal, *Heat Transfer in Industrial Combustion*, CRC Press, Boca Raton, FL, 2000.
28. B.K. Gullett, M.L. Lin, P.W. Groff, and J.M. Chen, NO_x removal with combined selective catalytic reduction and selective non catalytic reduction: pilot scale test results, *J. Air & Waste Manag. Assoc.*, 44, 1188, 1994.
29. W.M. Coleman, L.M. Dominguez, and B.M. Gordon, A gas chromatographic continuous emission monitoring system for the determination of VOCs and HAPs, *J. Air & Waste Manag. Assoc.*, 46, 30, 1996.
30. R.S. Viswanath, Characteristics of oil field emissions in the vicinity of Tulsa, Oklahoma, *J. Air & Waste Manag. Assoc.*, 44, 989, 1994.
31. J.D. Pleil, K.D. Oliver, and W.A. McClenny, Ambient air analyses using nonspecific flame ionization and electron capture detection compared to specific detection by mass spectroscopy, *J. Air & Waste Manag. Assoc.*, 38, 1006, 1988.
32. W.O. Siegl, R.W. McCabe, W. Chun, E.W. Kaiser, J. Perry, Y.I. Henig, F.H. Trinker, and R.W. Anderson, Speciated hydrocarbon emission from the combustion of single component fuels. I. Effect of fuel structure, *J. Air & Waste Manag. Assoc.*, 42, 912, 1992.
33. J.D. Pleil, T.L. Vossler, W.A. McClenny, and K.D. Oliver, Optimizing sensitivity of SIM mode of GC/MS analysis for EPA's TO-14 air toxics method, *J. Air & Waste Manag. Assoc.*, 41, 287, 1991.
34. G.F. Evans, T.A. Lumpkin, D.L. Smith, and M.C. Somerville, Measurement of VOCs from the TAMS network, *J. Air & Waste Manag. Assoc.*, 42, 1319, 1992.
35. K.T. Larjava, K.E. Tormonen, P.T. Jaakkola, and A.A. Roos, Field measurements of flue gases from combustion of miscellaneous fuels using a low resolution FTIR gas analyzer, *J. Air & Waste Manag. Assoc.*, 47, 1284, 1997.
36. K. Wülbern, On line messung von rauchgasen mit einen FTIR spektrometer, *VGB Kraftwerkstechnik*, 72, 985, 1992.
37. J.C. Demirgian and M.D. Erickson, The potential of continuous emission monitoring of hazardous waste incinerators using FTIR spectroscopy, *Waste Management*, 10, 227, 1990.
38. R.K.M. Jayanty and B.W. Gay, Jr., Measurement of toxic and related air pollutants, *J. Air & Waste Manag. Assoc.*, 40, 1631, 1990.
39. *Standard Performance for New Stationary Sources*, Environmental Protection Agency, Federal Register, Vol. 36, # 247, December 23, 1971.
40. Office of the Federal Register, 60.2 Definitions, U.S. Code of Federal Regulations Title 40 Part 60. U.S. Government Printing Office, Washington, D.C., 2001.
41. R.L. Byers, Evaluation of effluent gas particulate collection and sizing methods, *API Proc. Division of Refining*, 53, 60, 1973.
42. API, Measurement of Noise from Fired Process Heaters, Recommended Practice 531 M., American Petroleum Institute, Washington, D.C., reaffirmed August 1995.
43. J.R. Hassall, Noise measurement techniques, in *Handbook of Acoustical Measurements and Noise Control, Third Edition*, C.M. Harris, Ed., Acoustical Society of America, Woodbury, NY, 1998.

44. W.W. Lang, Measurement of Sound Power, in *Handbook of Acoustical Measurements and Noise Control, Third Edition*, C.M. Harris, Ed., Acoustical Society of America, Woodbury, NY, 1998.
45. M.J. Crocker, Measurement of sound intensity, in *Handbook of Acoustical Measurements and Noise Control, Third Edition*, C.M. Harris, Ed., Acoustical Society of America, Woodbury, NY, 1998.
46. U.S. Occupational Safety & Health Administration (OSHA), OSHA Technical Manual — Section III: Chapter 5, Noise Measurement, www.osha.gov/dts/osta/otm/otm_iii/otm_iii_5.html, 2002.
47. K. Zahringer, J-C Rolon, J-P Martin, S. Candel, O. Gicquel, and S. Arefi, Optical diagnostics for analysis of acoustic coupling in domestic gas boilers, *Proc. of 5th European Conf. on Industrial Furnaces and Boilers*, Portugal, Vol. 1, 679–688, 2000.