Combustion Safety For Steam Reformer Operation

AIGA 082/20

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Asia Industrial Gases Association

N0 2 Venture Drive, #22-28 Vision Exchange, Singapore 608526

Tel: +65 67055642 Fax: +65 68633379

Internet: http://www.asiaiga.org

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As part of a program of harmonization of industry standards, the Asia Industrial Gases Association (AIGA) has published AIGA 082, *Combustion Safety for Steam Reformer Operation*, jointly produced by members of the International Harmonization Council and originally published as CGA H-10 by Compressed Gases Association (CGA) as *Combustion Safety for Steam Reformer Operation.*

This publication is intended as an international harmonized standard for the worldwide use and application of all members of the Asia Industrial Gases Association (AIGA), Compressed Gas Association (CGA), European Industrial Gases Association (EIGA), and Japan Industrial and Medical Gases Association (JIMGA). Each association's technical content is identical, except for regional regulatory requirements and minor changes in formatting and spelling.

ASIA INDUSTRIAL GASES ASSOCIATION

No-2 Venture Drive,# 22-28 Vision Exchange, Singapore 608526

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NOTE—Technical changes from the previous edition are underlined.

1 Introduction

Large scale hydrogen production has been practiced for decades and the demand for such production has grown over that period. Developments in crude oil processing, such as the increased use of hydrogen to remove sulfur and the refinement of heavier crude oil stocks, has driven significant growth in the demand for hydrogen supply.

In response to this demand, industrial gas companies operate and maintain large scale hydrogen production facilities worldwide and have done so with an exemplary safety record for many years. However, it should be noted that large scale hydrogen production involves potential personnel and process safety hazards that must be addressed in design and operation. Such hazard potential is inherent to the processing of toxic and flammable gases via high temperature reforming as practiced in hydrogen production.

The steam reformer represents the core operating unit of most large scale hydrogen production facilities. Therefore, steam reformer furnace combustion safety is fundamental to the overall safe operation of these large scale hydrogen plants. This publication provides best practices for managing the combustion safety aspects of steam reformer operations. The associated potential safety hazards include fire, rapid uncontrolled energy release, gas release, as well as personnel exposure related to such hazards.

There are some internationally accepted standards that apply to the combustion systems of process furnaces. Such standards, including NFPA 86, *Standard for Ovens and Furnaces*, EN 746, *Industrial thermoprocessing equipment*, Parts 1-3, and API RP 556, *Instrumentation, Control, and Protective Systems for Gas Fired Heaters,* some of which are not specific to reforming furnaces, provide guidance on combustion safety systems [1, 2, 3].[1] These standards and other standards referenced in this publication shall be consulted when considering combustion safety for steam reformers.

It should be noted that there are other industries, such as ammonia and methanol production, that operate large steam reformers. Therefore, it may be instructive to consider the learning and experiences from those industries through organizations such as the American Institute of Chemical Engineering and their Ammonia Safety Symposium and the International Methanol Producers and Consumers Association (IMPCA).

Steam reformer furnace design will continue to develop along with methods to implement combustion safety in these furnaces. A wide variety of steam reformer designs, configurations, and component equipment exists today. Therefore, this publication includes some generalized statements and recommendations on matters on which there might be diversity of opinion or practice. Users of this publication should recognize that it is presented with the understanding that it can supplement, but not take the place of, sound engineering judgment, training and experience. It does not constitute, and should not be construed to be, a code or rules or regulations.

2 Scope and purpose

2.1 Scope

This publication applies to steam reformers that are operated with natural gas, refinery off-gas, naphtha, and other light hydrocarbon streams. It specifically applies to large volume hydrogen production plants, defined for this publication as a production capability of 373 000 scfh (10 000 Nm^3/hr) (9 MMSCFD or 241 000 Nm^3D) or greater.

This publication covers operation, maintenance, and certain design aspects of steam reformers relative to the potential safety hazards of the combustion process inherent to these units. Emphasis is placed on operational guidance and features that provide safeguards against such hazards such as furnace control philosophies, safety interlocks, and inspection routines. The publication is not intended to address the details of design, installation, and construction of steam reformers.

[1] References are shown by bracketed numbers and are listed in order of appearance in the reference section.

2.2 Purpose

The purpose of this publication is to inform and guide interested parties on the procedures and practices fundamental to combustion safety in the operation of steam reformers. This publication presents a baseline for safe reformer operation which, if followed, assures our customers that the hydrogen they receive from member companies has been produced according to accepted industry-wide safety guidelines.

3 Definitions

For the purpose of this publication, the following definitions apply.

3.1 Publication terminology

3.1.1 Shall
Indicates that the procedure is mandatory. It is used wherever the criterion for conformance to specific recommendations allows no deviation.

3.1.2 Should
Indicates that a procedure is recommended.

3.1.3 May
Indicates that the procedure is optional.

3.1.4 Will
Is used only to indicate the future, not a degree of requirement.

3.1.5 Can
Indicates a possibility or ability.

3.2 Technical definitions

3.2.1 Air change
Quantity of air, provided through the burners, equal to the volume of the furnace and the convection section.

3.2.2 Air to Fuel ratio
Ratio of combustion air flow rate to the fuel flow rate typically expressed as a molar ratio.

3.2.3 Alarm
Audible or visible signal indicating an abnormal or potentially critical condition.

3.2.4 Autoignition temperature (AIT)
Minimum temperature required to initiate self-sustained combustion of a solid, liquid, or gas in air.

3.2.5 Boiler
Closed vessel in which water is heated and steam is generated by heat input from combustible fuels in a self-contained or attached furnace.

3.2.6 Burner
Device for the introduction of fuel and air into a combustion chamber at the velocity, turbulence, and concentration required to maintain ignition and combustion of fuel.

3.2.7 Burner management system (BMS)
Control system dedicated to combustion safety and operator assistance in the starting and stopping of fuel preparation and combustion equipment and for preventing misoperation of and damage to fuel preparation and combustion equipment.

3.2.8 Casing
Metal plate used to enclose the fired heater.

3.2.9 Combustion air
Air used to react with the fuel in the combustion process.

3.2.10 Control element
Component of a safety instrumented system that implements the physical action necessary to achieve a safe state. Examples include valves, switch gear, motors, etc., including their auxiliary elements.

3.2.11 Convection section
Portion of the reformer, downstream of the furnace, where flue gas passes over heat exchangers and heat transfer occurs via radiation and convection.

3.2.12 Damper
Valve or plate for controlling draft or the flow of gases, including air.

3.2.13 Double block and bleed (DB&B)
Piping or instrument arrangement that combines two block (or isolation) valves in series with a vent valve in between the block valves as a means of releasing pressure between the block valves with the intent to provide positive isolation.

3.2.14 Draft
Negative pressure (vacuum) measured at any point in the furnace, typically expressed in inches of water column (mm of water column).

3.2.15 Duct
Conduit for air or flue gas flow.

3.2.16 Excess air
Air supplied for combustion in excess of theoretical air. Frequently expressed as a percentage above stoichiometric requirements (e.g., 10% excess air or 110% of stoichiometric).

3.2.17 Excess oxygen
Flue gas oxygen measurement, typically on a wet gas basis (e.g., 1.5% excess oxygen approximately corresponds to 10% excess air, depending on fuel composition).

3.2.18 Explosive mixture
Flammable or combustible mixture in a confined space.

3.2.19 Explosion vent
Vent designed to relieve explosion pressures resulting from ignition of a mixture of combustible gases and air.

3.2.20 Feed-forward control
Signal used to anticipate a change in the measured variable.

3.2.21 Flame
Body or stream of gaseous material involved in the combustion process and emitting radiant energy at specific wavelength bands determined by the combustion chemistry of the fuel. In most cases, some portion of the emitted radiant energy is visible to the human eye.

3.2.22 Flame detector
Device that senses the presence or absence of flame and provides a usable signal.

3.2.23 Flue gas
Gaseous products of combustion including the excess air.

3.2.24 Forced draft (FD) fan
Device used to pressurize and supply ambient air to the combustion chamber to support combustion.

3.2.25 Furnace
Portion of the reformer where the combustion process takes place <u>and which contains reformer tubes</u>.

3.2.26 Hazard and operability study (HAZOP)
Structured and systematic examination of a planned or existing process or operation in order to identify and evaluate problems that can represent risks to personnel or equipment, or prevent efficient operation.

3.2.27 Induced draft (ID) fan
Device used to remove the products of combustion from the reformer furnace by introducing a negative pressure differential.

3.2.28 Interlock
Device or an arrangement of devices in which the operation of one part or one mechanism of the device or arrangement controls the operation of another part of another mechanism.

3.2.29 Levels of protection analysis (LOPA)
Method to assess the number and types of protection layers (e.g., engineered protection features or systems) needed to provide an adequate safeguard against a specified hazard or risk in an industrial process.

3.2.30 Light hydrocarbons
Compounds consisting of hydrogen and carbon with low molecular weights, such as methane, ethane, propane and butane.

3.2.31 Logic system
Decision-making and translation elements that provide outputs in a particular sequence in response to external inputs and internal logic and are comprised of the following:

- hardwired systems—individual devices and interconnecting wiring;
- microprocessor-based systems;
- computer hardware, power supplies, I/O devices, and the interconnections among them; and
- operating system and logic software.

3.2.32 Low fire (minimum fire)
Minimum fire rate that results in stable combustion.

3.2.33 Monitor
To sense and indicate a condition without initiating automatic corrective action.

3.2.34 Overfiring
Combustion of fuel and air in excess of amount required for the reforming reaction that could cause damage to equipment or surrounding areas, and/or injury to personnel.

3.2.35 Permissive
Condition to meet before a piece of equipment can be operated or a step in a sequence can be completed. After the equipment is operated or sequence step is completed the permissive is ignored.

3.2.36 Pressure swing adsorption (PSA)
Multiple fixed bed gas purification process that uses materials that selectively adsorb one or more gas species from a mixture. Regeneration of the adsorbent is accomplished with a pressure reduction or swing.

3.2.37 Purge
Flow of air or an inert medium at a rate that will effectively remove any gaseous or suspended combustibles and replace them with the purging medium.

3.2.38 Radiant section
Portion of the furnace in which the heat is transferred to the reformer tubes, primarily by radiation.

3.2.39 Refinery off-gas
Gas stream removed as a by-product or purge from various crude oil processing units; typically consisting of a mixture of hydrogen, olefins, and alkanes.

3.2.40 Reformer tube (catalyst tube)
High-alloy metal tube containing reforming catalyst which is part of the furnace.

3.2.41 Safety instrumented function (SIF)
Function implemented by a safety instrumented system (SIS) that is intended to achieve or maintain a safe state for the process and/or personnel regarding a specific hazardous event.

3.2.42 Safety instrumented system (SIS)
Independent system composed of sensors, logic solvers, and final elements designed for the purpose of:

- automatically taking an industrial process to a safe state when specified conditions are met; and/or
- permitting a process to move forward in a safe manner when specified conditions allow (permissive functions).

Use of the term SIS implies IEC 61511, *Functional safety–Safety instrumented systems for the process industry sector,* has been used to design, operate, and maintain the safety system [4].

3.2.43 Safety integrity level (SIL)
Relative performance measure of a safety instrumented function (SIF) as described in industry standards as either an average probability of failure to function on demand or as a risk reduction factor.

3.2.44 Steam reformer
Processing unit where steam is reacted with hydrocarbons over a catalyst at high temperatures to produce hydrogen and carbon oxides. The reformer includes a furnace/radiant section and a convection section.

3.2.45 Tail gas
Low pressure contaminant rich rejection stream from pressure swing adsorption.

3.2.46 Wet basis
Gas stream composition including water versus dry basis where water is excluded.

4 Fundamentals of combustion safety

4.1 Combustion fundamentals

Oxygen (air), fuel, and an ignition source are required for combustion to occur. Combustion reactions involving organic compounds and oxygen take place according to stoichiometric combustion principles.

Stoichiometric oxygen requirements for combustion of a fuel can be determined from the balanced chemical reaction equations.

Based on the stoichiometric reactions below, the air requirement is calculated by including excess margin over the stoichiometry.

Ideal combustion reactions that can occur in a reformer furnace include:

Hydrocarbon gas: $C_nH_m + (n + m/4)O_2 \rightarrow nCO_2 + \left(\frac{m}{2}\right)H_2O$

Carbon monoxide: $2CO + O_2 \rightarrow 2CO_2$

Hydrogen: $2H_2 + O_2 \rightarrow 2H_2O$

Complete combustion occurs when all of the fuel is burned. Air is the source of oxygen (21% by mole or volume). Usually 8% to 10% excess air is required for complete combustion to occur and for optimum operation.

4.2 Basic combustion hazards

Basic combustion hazards that should be considered include flame instability, flame lift off, back burning, after burning, fuel accumulation, and exposure to hot gases.

4.2.1 Flame instability

Flame instability can occur when fuel pressure or fuel mixing in the burner is insufficient, fuel composition deviates too strongly from design, or if flue gas is not evenly distributed in the furnace. Flame instabilities can lead to incomplete combustion, severe furnace pulsation or flame impingement that can damage the equipment in the furnace (e.g., tubes, refractory, etc.)

4.2.2 Flame lift off

When the reformer draft or fuel pressure is too high (compared to the burner design parameters), a lift off of the flame from the burner tip(s) can occur. Depending on the operating status of the furnace it can produce the following results:

- flame is extinguished and creates the potential for uncombusted fuel to accumulate in the furnace; or
- burner is reignited if the gas is above the autoignition temperature (AIT) and can cause severe pulsation and potential damage in the furnace.

4.2.3 Back burning

Back burning can occur if the fuel pressure drops in the fuel line below the burner design parameters. There are two basic types of back burning: one where the flame backs into the burner assembly due to low velocities and damages the tip; the second where the flame backs into the fuel piping during a shutdown because a malfunction of the double block and bleed (DB&B) allows air into the system. This condition creates the potential for abnormal combustion or an unintended energy release.

4.2.4 After burning

After burning occurs due to a lack of combustion air or insufficient mixing of the fuel and air. This condition can result from incomplete combustion of the fuel near the burner. When the fuel-rich flue gas passes through the furnace, it reacts with any available oxygen (e.g., air ingress) and burns, resulting in combustion in the convection section. This condition can cause damage to the convection section equipment and refractory materials.

4.2.5 Fuel accumulation

Fuel accumulation consists of any accumulation of combustible gases that, when mixed with sufficient air, can result in an energy release when an ignition source is present. The severity of the energy release will depend on the air to fuel ratio and quantity of the mixture at the moment of ignition. This energy release can result in total destruction of the furnace.

4.2.6 Exposure to hot gases

Combustion gases are very hot, therefore proper personal protective equipment (PPE) shall be worn when there is a potential of being exposed to these gases. The reformer furnace draft control shall maintain the furnace at a slight vacuum to prevent these hot gases from being released.

5 Steam reformer

The steam reforming reactions are overall endothermic. As a result, a furnace is used to provide the necessary heat of reaction. Heat transfer is predominantly by infrared (heat) radiation. The furnace is a fired heater containing radiant tubes filled with nickel-based reforming catalyst(s). Therefore, the steam reformer is not simply a catalyst reactor; it is a complex combination of catalyst reactor and heat exchanger.

The steam reformer consists of two main sections:

- furnace (also called radiant section); and
- convection section.

Elements of the furnace include:

- steel casing;
- heat-resistant insulation;
- combustion air system, which can be either balanced draft (induced draft [ID] and forced draft [FD] fans) or induced draft (ID fan only);
- burners;
- flue gas collection system; and
- reformer tubes.

The furnace provides the heat for the steam reforming reaction by burning a fuel and air mixture. It operates at a slight negative pressure at temperatures in excess of 1832 °F (1000 °C) with radiant heat transfer. The design of a steam reformer distributes heat as optimally as possible across the steam reformer and collects the combusted gas in a way that allows an even flow of hot gas through the furnace.

Steam reformers can be put into one of three categories:

- top-fired
- side-fired; or
- bottom-fired.

5.1 Top-fired steam reformers

A typical top-fired steam reformer is shown in Figure 1, with process gas flowing downwards through multiple tubes in one or more rows, all of which are contained within a single furnace box.

The burners are located on the furnace ceiling and the flue gas is extracted at the bottom of the furnace.

Flue gas collection tunnels with openings (sometimes referred to as coffin tunnels) are frequently used to ensure an even flow of flue gas through the furnace.

The main features of a top-fired furnace include:

- co-current flow of process gas and flue gas;
- a small number of large burners (relative to a side-fired reformer) located on the top of the furnace; and
- single operating level for burner access.

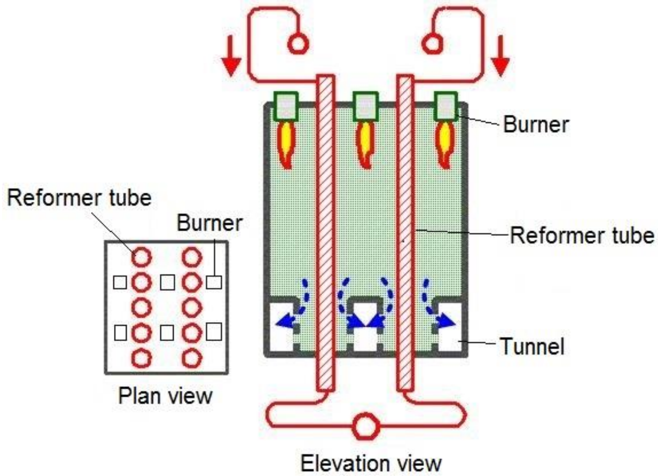

Figure 1—Top-fired furnace

5.2 Side-fired steam reformers

A typical side-fired steam reformer is shown in Figure 2, with process gas flowing downwards through multiple tubes in a single row, all of which are contained within one or more compartments known as furnace cells.

This design is based on the concept of uniform heat flux. Uniform heat flux is achieved by positioning the reformer tubes in the center of the furnace cell with heat input provided by burners located along the entire sidewall of the furnace.

Flue gas exhaust is at the top of the furnace and is directly connected with the convection section. It is common for two furnace cells to run parallel to each other with a common convection section.

The main features of a side-fired furnace include:

- cross-current flow of process gas and flue gas;
- a large number of small burners (relative to a top-fired reformer) located along both sides of the furnace; and
- multiple operating levels for burner access.

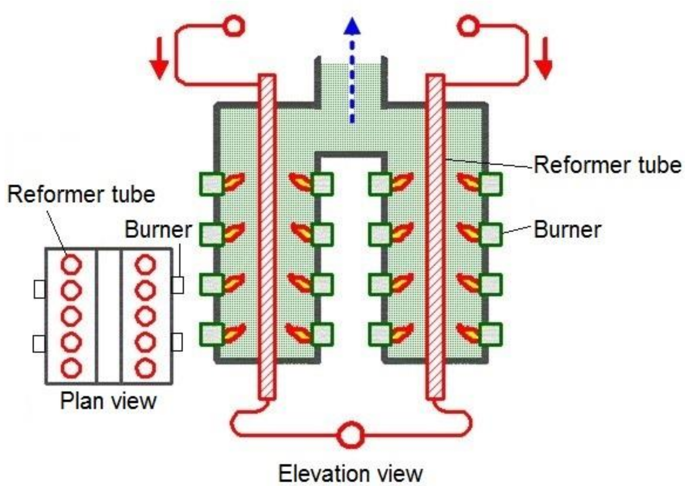

Figure 2—Side-fired furnace

5.3 Bottom-fired steam reformers

A typical bottom-fired reformer is shown in Figure 3. The burners are located at the floor level and, in essence, the firing arrangement is opposite of a top-fired unit. The flue gas is extracted from the top. Bottom-fired reformers are typically cylindrical rather than box-type.

The main features of a bottom-fired furnace include:

- co-current or counter-current flow of process gas and flue gas;
- a small number of large burners (relative to a side-fired reformer) located on the bottom of the furnace; and
- single operating level, with burners accessible from grade (easier maintenance).

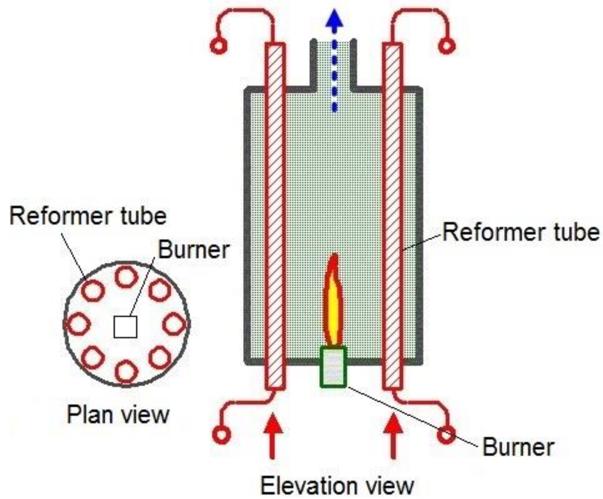

Figure 3—Bottom-fired furnace

6 Personnel safety

This section describes the hazards to personnel associated with reformer combustion and appropriate safeguards to minimize these hazards. Serious hazards to personnel include exposure to toxic releases, fire or explosion, asphyxiation, burns, and noise. For additional safety information, see AIGA 086, *Safe Startup and Shutdown Practices for Steam Reformers* [5].

Safeguards include utilizing PPE, limiting exposure, and controlling area access to assure safety of personnel.

6.1 Personal protective equipment

The following PPE shall be worn by all personnel in the steam reformer area. An example is shown in Figure 4:

- hard hat;
- safety shoes or boots;
- flame-retardant uniform;
- work appropriate gloves;
- safety glasses; and
- hearing protection.

Wearing portable personal gas monitors (e.g., carbon monoxide detection) is recommended when the risk of a gas leak is present. The necessity should be determined based upon site/task-specific risk assessment.

Figure 4—Recommended PPE for steam reformer area

The following additional PPE should be worn for reformer tube temperature measurement. An example is shown in Figure 5:

- thermal protection gloves; and
- thermal protection for face.

Figure 5—PPE for tube temperature measurement

6.2 Areas of potential personnel exposure

Signs stating the potential hazards (e.g., heat, fire, toxicity, anoxia, restricted area, etc.) should be posted visibly at the reformer structure and in other hazardous areas to alert personnel. Personnel who are exposed to these areas shall be trained in the risks and shall wear adequate PPE to mitigate potential hazards.

6.3 Specific combustion safety hazards and appropriate safeguards

6.3.1 Toxic release

The fuel gases (e.g., natural gas, tail gas, refinery fuel gas, or syngas) feeding the burners or combustion products can contain toxic molecules such as carbon monoxide; in case of leakage to the atmosphere the operator can be affected.

Procedures shall exist to address the response and corresponding mitigation of a toxic gas release.

6.3.2 Flammable gas release

During periods of startup, shutdown, or upset operations, an explosive mixture can develop either within the equipment or outside of the equipment that can lead to an energy release that can cause significant damage and personnel injury.

A fire and gas detection system shall be considered in the burner area to detect any leakage. A detection system is required by some regional regulations.

Procedures shall exist to address the response and corresponding mitigation of a fire or uncontrolled energy release.

6.3.3 Asphyxiation/Anoxia

Asphyxiation can occur in any confined area or insufficiently ventilated location; danger begins when oxygen content is less than 19.5% in the air (normal content being approximately 21% by mole or volume). For example, this hazard can exist in a top-fired steam reformer penthouse during startup when nitrogen flowing through the tubes leaks.

6.3.4 Burn exposure

6.3.4.1 Contact with hot surfaces

Some surfaces of the furnace or the burners can reach high temperatures during normal operation or in the case of deterioration of insulation (e.g., furnace wall, burner plates, furnace inspection port handles). The human body will face a burn hazard if it is in direct contact with surface temperatures higher than 140 °F (60 °C).

The operator shall wear heat-resistant gloves and flame-retardant clothes with long sleeves to manipulate these surfaces or to prevent any burns in case of accidental contact.

6.3.4.2 Exposure to heat radiation and combustion gases

The operator may have to perform a visual inspection of the furnace or tube temperature measurements through appropriate inspection ports. The operator can be exposed to hot flue gases from the inspection ports if the furnace pressure goes positive while performing these tasks. In order to reduce the hazards, personnel:

- shall be equipped with the appropriate PPE; and
- should stand to the side of the opening while slowly and carefully opening the inspection port to avoid exposure to hot combustion gases and heat radiation.

In accessible areas where hot gas releases are expected, such as explosion vent doors (installed in some reformers) or flue gas dampers (usually installed in side-fired reformers to allow air entrance in case of a reformer trip to cool down the convection section), protective devices such as deflectors should be implemented to offer additional protection for personnel.

6.3.5 Noise

The area surrounding the reformer can expose personnel to high noise levels. Personnel shall be aware of the cumulative effects of working in a high noise environment. These effects can include irreversible damage to the ear or additional fatigue that can lead to accidents.

A noise level survey should be completed and shall meet regional regulatory requirements. Hearing protection requirements shall meet regional regulations.

7 Controls and instrumentation

7.1 General

The combustion control system shall be designed to maintain stable fuel firing and safe air to fuel ratios in all operating conditions. The control variables should include furnace pressure, outlet process temperature, flue gas temperature, flue gas oxygen level, fuel pressure, fuel flow, and air flow. The combustion control system shall be functionally independent of the safety instrumented systems (SIS)/burner management system (BMS). All instrumentation and equipment shall be designed to the area electrical classification. All instrumentation and control functions shall be programmed using fail safe methodology (upon loss of signal the program logic defaults to the fail position). See Section 3 of API RP 556 and AIGA 086 [3, 5].

7.2 Control functions

7.2.1 Firing control

Effective control of firing is needed to maintain flue and process temperatures within the desired operating range and equipment design limits. The steam reformer firing control scheme is used to achieve appropriate operating temperatures by balancing the firing rate with the heat demand of the steam reforming reaction.

During normal operation the fuel gas stream generated by the downstream hydrogen purification system, typically PSA tail gas, provides the majority of the firing duty requirement in most steam methane reforming (SMR) designs. An auxiliary fuel gas is adjusted to make up the balance of the firing duty required to maintain the appropriate operating temperature.

Firing control performance and temperature stability can be improved through implementation of advanced controls features. Feed-forward controllers or model predictive controllers can adjust firing to respond to changes in variables such as process feed rate, combustion air flow and temperature, fuel flow, and fuel heating value.

7.2.2 Overfiring protection

Overfiring, particularly at startup or during rate changes, can result in overheating and potential damage to tubes. Alarms, fuel flow controller output limit or override, and/or interlocks may be used to mitigate the risk. There are multiple parameters that may be used to set overfiring protection limits, including:

- flue gas temperature rate of rise;
- reformer outlet process temperature rate of rise;
- comparison of calculated energy requirement with theoretical reforming requirements;
- temperature difference between the flue gas and reformer outlet process:
    - different values should be used during startup before feed is introduced and normal operation;
- flue gas temperature based on mechanical design limitations;

- reformer outlet process temperature; and
- minimum nitrogen/steam flow during startup.

7.2.3 Flue gas oxygen control

Control of the oxygen level in the flue gas is important to confirm complete combustion of the fuel streams. Incomplete combustion in the firebox can lead to a further ignition with air ingress into the flue gas duct or in the stack with the potential for damage to equipment and subsequent injury to personnel.

A minimum of one oxygen analyzer in the flue gas is used to measure the oxygen levels and provide the input for the oxygen control strategy. The measurement should be made at the exit of the radiant section to minimize the possible effect of air ingress on the oxygen reading. Typical set points for the excess oxygen level are 1.2% to 1.5% (wet basis), which approximately corresponds to excess air values of 8% to 10%.

Flue gas oxygen should be controlled through manipulation of combustion air flow via fan speed or fan damper position. Flue gas oxygen control can be enhanced through a lead lag arrangement to make sure there is always excess air during load changes. If the plant load is increased, then combustion air flow is first increased followed by the fuel gas flow. If the plant load is decreased, then the fuel gas flow is first decreased followed by the combustion air flow.

If the oxygen measurement falls below a critical minimum value (e.g., 1%), immediate corrective steps shall be taken such as increasing air flow and/or decreasing fuel flows.

7.2.4 Draft control

A draft is maintained in the reformer box to protect personnel from exposure to hot combustion gases and to make sure reformer design pressure limits are not exceeded. Box pressure is reported as a negative number. Draft pressure is the same value as the box pressure but is reported as a positive number. An ID fan maintains box pressure at approximately –0.6 in (–15.2 mm) water column.

Draft is typically adjusted by manipulating the ID fan speed or the ID fan damper position.

7.2.5 Fuel gas pressure

Fuel gas pressure shall be controlled within an appropriate range as defined by the burner design or a burner test to avoid low pressure flame instability or loss of flame and high pressure overfiring or flame liftoff conditions.

7.3 Instrumentation considerations

7.3.1 Combustion air flow

Air flow determination can be accomplished by various means including but not limited to a venturi, an averaging pitot, a hot wire anemometer, or a piezometer. Because it is a critical measurement, care should be taken in the selection of the device. Fouling from ambient air conditions and non-ideal straight run conditions can contribute to measurement errors.

7.3.2 Combustion air temperature

Thermowell material selection for temperature measurement of combustion air flow should be made based on convection section temperature and process environment. Location of the measurement should avoid radiant adsorption errors.

7.3.3 Flue gas oxygen

Analysis is typically completed using a zirconium oxide cell sensor installed in the flue gas stream. Redundant analyzers may be used.

7.3.4 Draft measurement

Where reformer configuration (e.g., top-fired) allows, a sample manifold with at least two taps in opposite ends of the reformer box should be used to obtain a representative sample. The manifold should be insulated and heat traced. It should be located near the burner end of a top-fired or bottom-fired reformer box and be designed with a slight (e.g., 1%) slope back to the box for drainage. The positive side tap should be muffled and located in a wind-free area.

7.3.5 Fuel gas pressure

The measurement used for the high pressure shutdown should be made by a pressure sensing device(s) located after the flow control valve. The pressure measurement used for the low pressure shutdown should be made by a low range sensing device(s) separate from the high pressure shutdown sensing device(s). In cases where the shutdown set point value is very low, the measurement may be based on differential pressure between the furnace and the fuel at the burner to account for the vacuum conditions in the reformer box.

7.3.6 Pressure swing absorption tail gas flow and heating value

Flow measurement can be difficult because of low pressure and the physical characteristics (e.g., size) of the piping. Flowmeter technology that can be recommended for this service includes an averaging pitot, venturi, orifice, and ultrasonic measurement.

The composition and heating value of the tail gas may be determined by a process gas chromatograph.

7.3.7 Process outlet temperature

Thermowell materials shall be suitable for a high temperature reducing atmosphere.

7.3.8 Auxiliary fuel flow and heating value

Unless the fuel is of known constant composition, measurements should be made to accurately determine the fuel flow and heating value. Instrumentation to perform the gas composition analysis may include a gas chromatograph or a mass spectrometer. The heating value would then be calculated from the measured composition, and the gas density would be used to correct the flow measurement. Alternatively, a calorimeter may be used in conjunction with a densitometer to determine these values.

7.3.9 Flame detector

Successful installation and operation of flame detectors requires consideration of multiple variables including fuel composition, environmental conditions, physical sensing geometry, and device output signal transmission. In large hydrogen production facilities, ultraviolet (UV) detectors are typically used because they are not sensitive to visible light or infrared (IR) radiation emitted from hot surfaces.

A clean, dry purge gas is required to keep the flame detector lens area free of debris and to provide cooling. Minimum purge is usually specified by the manufacturer but additional flow and protective thermal insulation can be required to control the temperature.

The sensor should be aimed at the base of the flame where UV radiation is highest. The line of sight should be angled slightly from the burner center line. The sight pipe should have complete flame coverage. The mount should be adjustable so corrections for flame changes associated with fuel composition and/or firing rate can be accommodated. In cases where the fuel characteristics and flame shape cause an excessive flame signal affecting flame discrimination, an orifice may be used to reduce the field of view.

The scanner should be self-checking by chopper shutter or equivalent means.

The wiring between the detector and the controller has distance, and shielding requirements that vary with the manufacturer/model of the device. If multiple devices are being installed as a set (e.g., 2 out of 3 voting) the wiring shall be appropriately segregated. Manufacturers' recommendations shall be followed.

Consideration should be given to the flame detection challenges associated with its installation on a steam reformer burner; challenges include maintaining signal strength through the varying levels of fuel flow and composition and maintaining flame detector integrity despite exposure to high temperatures.

7.4 Unattended or partially attended plants

Computer-based plant control systems allow large scale hydrogen facilities to safely operate either locally unattended for limited periods of time (e.g., nights and weekends) or with minimal staffing. See 13.5 of AIGA 056, *Safe Practices Guide for Cryogenic Air Separation Plants* [6].

In the case of locally unattended operations, process conditions shall be monitored and controlled from an attended remote facility or centralized operating center. A dedicated review shall be performed to identify the process and equipment conditions that need to be remotely monitored. Response actions to process conditions that can be completed by an operator at a locally attended facility shall be considered in the design of the control hardware and software.

The dedicated review shall also consider the emergency notification and response system.

The system shall be designed to safely shut down and secure the process and plant equipment without any manual intervention in the event of an unplanned process upset or shutdown.

8 Interlocks/Permissives

8.1 General

For the purpose of this publication, interlocks and control logic permissives are considered types of SIS that provide a safety instrumented function (SIF). Interlocks and permissives are safeguards that provide a layer of protection against the potential hazards of combustion as outlined and described in 4.2.

A combustion safety interlock typically consists of a sensing instrument, logic controller system, and control element that function together to take action to ensure the process is in a safe state or, in the case of a permissive, only allows the process to proceed under a safe set of conditions. This type of system is typically referred to as a BMS and is required to ensure safe operation of the burner and burner equipment.

8.2 Components and integrity

The combustion safety logic controller and control algorithms shall be separate from the operating controls configuration. The combustion safety logic controller may be implemented with a hardwired system, programmable logic controller, or distributed control system module.

The expected reliability of a combustion safety interlock shall be determined and documented based on methods of safety integrity level (SIL) quantification per industry standards. See IEC 61508, *Functional safety of electrical/electronic/programmable electronic safety-related system* [7].

In order to achieve the expected reliability of a combustion safety interlock, it can be necessary to use multiple instrument input signals along with voting logic. If multiple signals are used as inputs to a safety interlock, then alarms should be used to alert operators of significant deviations between the multiple signal values.

8.2.1 Double block and bleed

The key control elements in combustion safety are the safety isolation valves on the fuel systems. The fuel system shall be equipped with automatic positive isolation via DB&B. Each fuel source that enters the burners independently shall be automatically isolated by a DB&B. For example, where two fuel streams are combined, a single DB&B downstream from the mix point is adequate isolation.

The valves shall be configured with position feedback indication or proof of closure switch. The design of the safety isolation valves shall be fail-safe, where loss of power or motive force results in the valve moving to the safe position. The DB&B shall be placed close to the furnace to minimize the volume of fuel that enters the reformer after the isolation valves are closed.

The amount of time required for completion of each isolation valve closure, from time of activation signal, (referred to as valve closing time) shall be considered in the design and operation of a DB&B. The isolation valve closing times shall meet applicable standards such as EN 746 [2]. Isolation valve closures should occur quickly (within seconds) to minimize the volume of fuel that enters the reformer after the initial activation signal. The use of fast-acting valve actuators can be necessary to achieve acceptable valve closing times, especially in larger diameter (4 in [100 mm] and greater) fuel lines.

The sequence of isolation valves closing and the bleed valve opening should be configured so the bleed valve is not opened prior to isolation valve closure (and bleed is closed before opening isolation valve) to prevent excessive venting of fuel and to prevent air ingress into the piping.

8.3 Function and hazard protection

The identification, design, and implementation of combustion safety interlocks shall be completed based on a review of appropriate codes and regulations and should be supplemented with qualitative hazard analysis (e.g., HAZOP) and, as warranted, quantitative hazard analysis (e.g., LOPA).

8.3.1 Startup sequence functions

The combustion safety system shall provide the following permissives to eliminate combustion hazards during the startup process:

- Purging of the reformer furnace box with air to ensure removal of flammable gases. The minimum total purge flow volume shall be 4 to 5 air changes, or shall comply with regional regulations when more volume exchanges are required;
- The purge sequence will only proceed if combustion air fan(s) are confirmed to be running, air flow is greater than a minimum value, and all fuel valves are confirmed to be closed. The purge sequence will reset if such conditions are not met;
- Testing of the fuel isolation valves and burner isolation valves to ensure there are no leaks; the test sequence shall include a pressurization of the fuel piping systems where pressure is maintained for a period of time adequate to confirm the seal;
- Confirmation of minimum nitrogen or steam circulation flow needed to avoid excessive reformer tube temperatures after the burners are lit, via flow measurement indication through the reformer tubes prior to ignition of fuel in the furnace and continuing through the startup sequence;
- Confirmation of flame at key burners (see 8.3.3) through positive flame detection signals or visual inspection during the burner lighting sequence where flame detectors are not installed; and
- Time-based interlocks to ensure the startup sequence steps are completed without excessive periods of delay or intermission.

8.3.2 Combustion air flow/ventilation

Combustion air flow shall be established and maintained at a minimum flow adequate to support combustion during the startup sequence and throughout normal operation of the reformer.

Loss of the minimum adequate air flow should activate a combustion safety interlock to isolate all fuel sources to the reformer and flammable process feed streams.

Failure to prove ID or FD fan operation shall also activate an interlock to isolate fuel sources.

8.3.3 Flame detection

Flame detection instruments should be installed on the reformer burner system to ensure that there is flame present at the burner. The number and location of burners with flame sensors installed should be evaluated for each reformer configuration to ensure sufficient survey of the reformer. A minimum of one sensor looking at one burner in each burner row shall be installed. The flame detection system shall confirm and require establishment of flame at key burners through positive flame detection signals during the burner lighting sequence. This permissive is a critical function to ensure startup safety. Loss of flame detection signal(s) during operation when the reformer furnace is below the AIT of the fuel shall result in activation of a combustion safety interlock to isolate the fuel sources. The setpoint, including safety margin, shall be between 1382 °F and 1400 °F (750 °C and 760 °C).

Loss of flame detection shall activate an alarm when the reformer is above the AIT. Generally, a loss of flame detection signal during normal operation when the reformer is above the AIT should not result in the activation of a combustion safety interlock; however, the loss of multiple flame detection signals can initiate a combustion safety interlock.

For existing reformers, use of flame detection instruments should be evaluated; however, retrofit is not a requirement.

8.3.4 Fuel pressure

Fuel pressure shall be monitored on all fuel sources. Pressure sensing devices should be located downstream of final pressure regulating device.

The sensors <u>shall</u> activate a combustion safety interlock if low pressure limits are exceeded based on the burner design and/or performance test criteria. <u>The interlock should also be activated on a high pressure limit.</u>

<u>If a combustion safety interlock activates on the primary fuel source, the reformer should shut down. If a combustion safety interlock activates on a secondary fuel source, that fuel source should shut down.</u>

8.3.5 Reformer box pressure or draft

The pressure in the reformer furnace box (also referred to as reformer draft measurement) shall be monitored.

Pressure sensing device(s) shall be directly connected to the reformer furnace box and shall activate a combustion safety shutdown that includes stopping the fan(s) based on both high and low pressure limits.

The high pressure setpoint(s) provides a safeguard against personnel exposure to hot combustion gases and are based on the reformer box <u>structural</u> design limits.

The low pressure setpoint shall be based on reformer box <u>structural</u> design limits.

8.3.6 High temperature protection

High temperature in the steam reformer process flow outlet shall activate a combustion safety interlock. The high temperature limit should be based on the mechanical integrity and design limits of the reformer process outlet system.

High temperature in the flue gas leaving the radiant section should activate a combustion safety interlock. The high temperature limit should be based on the mechanical integrity and design limits of the reformer furnace and convection section. As an alternate to activation of a complete combustion safety interlock, high temperature in the flue gas should activate a low fire shutdown interlock, where process feed is isolated and fuel and steam flows are reduced to a minimum preset value.

8.3.7 Manual shutdown

A manual shutdown function that activates a combustion safety interlock shall be provided. Activation of the manual shutdown shall be a manual action via a button located in the control room or on the distributed control system interface and at the reformer burner area or structure.

8.3.8 Process conditions that activate combustion safety interlocks

8.3.8.1 Low process feed flow

Low process feed (steam and hydrocarbon) flow through the reformer tubes shall initiate a combustion safety interlock. The low flow setpoint shall be based on the minimum operating point for the reformer.

8.3.8.2 Steam drum level low

Low level in the steam drum shall initiate a combustion safety interlock. The low level setpoint shall be based on steam drum and boiler water circulation system design.

8.3.8.3 Additional process considerations

Several other process condition deviations in the steam reformer operation can activate a full combustion safety interlock or a low fire process shutdown interlock. Parameter deviations that should be evaluated for such safeguards include high process feed pressure, low process feed pressure, high steam drum level, and low steam-to-hydrocarbon feed ratio.

8.4 Testing considerations

Multi-year plant runs can cause conflicts with desired critical safety system validation intervals. The preventive maintenance program should have a policy to address this issue. When a functional test including the final control element cannot be performed without shutting the plant down, a functional test without the final element should be performed. Interlocks should be bypassed and appropriate controllers should be placed in manual mode. Supervisory control should be inactivated as necessary.

9 Operating considerations

9.1 General

The proper safety attitude and program shall be promoted in the plant with attention to the operations and equipment associated with combustion. Such a program shall include operating procedures, operator training, management of change, incident investigation/reporting, regulatory compliance, safe work permit procedures, contractor safety, and hazards analysis.

9.2 Regulation of operations

The operation of large hydrogen plants and their associated steam reformer combustion systems are often regulated by local, regional, or national governing authorities. Regulations that cover the operation of facilities that handle significant quantities of hazardous chemicals, including flammable substances that have the potential for a significant industrial accident, can apply to large hydrogen plants.

In the United States, Occupational Safety and Health Administration's (OSHA) Process Safety Management (PSM) in Title 29 of the *Code of Federal Regulations,* Part 1910.119, regulates facilities handling hazardous chemicals, including flammables such as hydrogen [8]. In Europe, the Seveso III Directive 2012/18/EU requires member states to establish regulations for the prevention measures against major industrial accidents [9].

10 Maintenance and inspections

10.1 General

A preventive maintenance, testing, and inspection program of furnace equipment shall be practiced to keep it in a safe and reliable working condition. The program shall be documented. Regular inspections during plant operation and regularly scheduled shutdowns shall be conducted to identify any damage and/or deterioration. An inspection and/or testing schedule should be prepared for each equipment item. Intervals shall be determined using local/national codes, vendor recommendations, site environment, and equipment condition.

Intervals may be adjusted based on the following criteria:

- specific safety issues associated with a failure of the equipment; and
- operating and maintenance history of the equipment (experience, runtime, wear rate data, and trending from predictive maintenance measurements).

Only qualified personnel shall service or inspect plant equipment.

Components should be replaced in-kind unless a substitute is approved under an appropriate management of change program.

For more information on maintenance and inspections of syngas outlet systems, see AIGA 095, *Mechanical Integrity of Syngas Outlet Systems* [10].

10.2 On-line furnace inspections

On-line furnace inspections shall be completed to assess the burners, reformer tubes, and refractory materials.

Before the furnace inspection, verify with the control room or check on the control system that the steam reformer is running under stable conditions and check that there will be no voluntary change in the process during the inspection. During the inspection, maintain contact with the control room operator or control system, to be warned in case of alarms, and especially in case of an increase of the furnace pressure. The inspection shall be carried out only when the furnace pressure is kept negative and stable.

10.2.1 Burners

The burners should be operated to provide uniform heat distribution inside the furnace with flames that are appropriate in shape under all operating conditions. Flame shape is important but varies considerably with reformer box and burner design. All burners should remain in service under normal operating conditions. Inspectors should be aware of the appropriate flame shape and color for the burner that is in use.

The burners should be visually inspected on a regular basis, typically daily, to determine if the flames are impinging (touching) on the furnace tubes and to assess the flame color, stability (see 4.2), and shape. Flame impingement is one of the major causes of damage to a reformer furnace tube. If impingement is noticed, the burner should be adjusted or turned off without delay.

10.2.2 Reformer tubes

The tubes shall be visually inspected at the same time as the burner inspections. The tube inspection should include looking for hot areas along the length of the tube as manifested by discoloration patterns such as mottling, banding, striping, and localized spotting. The inspection should also include evaluating the tube to tube color uniformity, noting any tubes that are of a significantly different color. Color is an indication of temperature and the inspector should be familiar with the appropriate colors for the reformer being inspected.

In addition, the inspection should note the mechanical condition of the tubes such as bending or leaking. A tube leak can be identified by sound or by observing an unusually bright spot (possibly with visible flame).

Tube wall temperatures should be measured on a regular basis. Tube temperatures may be measured using an infrared pyrometer or other suitable measurement device. Tube temperatures should be logged or recorded along with the corresponding operating plant data.

Tubes expand longitudinally with increasing temperature. The suspension system takes this into account and the inspector should verify that all tubes have uniformly reached their hot position.

10.2.3 Furnace refractory

A visual inspection of the condition of the furnace refractory should be completed at the same time as the burner and tube inspections to ensure there are no gaps, cracks, missing sections, or other non-uniformities in the refractory finish.

An external inspection of the reformer should also be completed on a regular basis. Thermal imaging (thermography) may be used to complete this inspection. The detection of a hot spot on the external surface of the reformer indicates refractory damage and/or can indicate the combustion of leaking syngas.

10.3 Off-line furnace inspections

During regularly scheduled maintenance shutdowns, visual inspections (see 10.3.1) and reformer tube inspections (see 10.3.2) should be completed.

10.3.1 Visual inspections

The following components should be visually inspected for damage, deterioration, excessive wear, and defects:

- furnace internal wall insulation and reformer tube condition;
- convective section crossover;
- burner tiles;
- flue gas tunnels;
- exterior surface;
- reformer tube seals;
- reformer tube hangers;
- cold settings of hangers or counterweights; and
- representative number of burner tips.

10.3.2 Inspection of reformer tubes

The long-term aging mechanism for reformer tubes includes internal pressure stresses and thermal stresses across the wall itself. Typical creep damage then occurs between the inner and outer walls and can progress to through wall cracking.

The commercially available inspection methods to detect creep damage include dimensional measurements, eddy current, and ultra-sonic testing. The dimensional measurement of the reformer tubes should confirm an acceptable degree of circumferential expansion of the tubes.

Each inspection technique has advantages and weaknesses. An inspection and life assessment program should be developed. The program should determine which method or methods are most suitable.

11 References

Unless otherwise specified, the latest edition shall apply.

[1] NFPA 86, *Standard for Ovens and Furnaces*, National Fire Protection Association. www.nfpa.org

[2] EN 746, *Industrial thermoprocessing equipment*, Parts 1-3, British Standards Institute. www.bsigroup.com

[3] API RP 556, *Instrumentation, Control, and Protective Systems for Gas Fired Heaters*, American Petroleum Institute. www.api.org

[4] IEC 61511, Function Safety – Safety Instrumented System for the Process Industry Sector, International Electrotechnical Commission. www.iec.ch

[5] AIGA 086, *Safe Startup and Shutdown Practices for Steam Reformers,* Asia Industrial Gases Association, www.asiaiga.org

[6] AIGA 056, *Safe Practices Guide for Cryogenic Air Separation Plants*, Asia Industrial Gases Association, www.asiaiga.org

[7] IEC 61508, *Functional safety of electrical/electronic/programmable electronic safety-related systems*, International Electrotechnical Commission. www.iec.ch

[8] *Code of Federal Regulations*, Title 29 (Labor), U.S. Government Printing Office. www.gpo.gov

[9] Seveso III Directive 2012/18/EU, European Commission, Environment DG. ec.europa.eu

[10] AIGA 095, *Mechanical Integrity of Syngas Outlet Systems,* Asia Industrial Gases Association, www.asiaiga.org