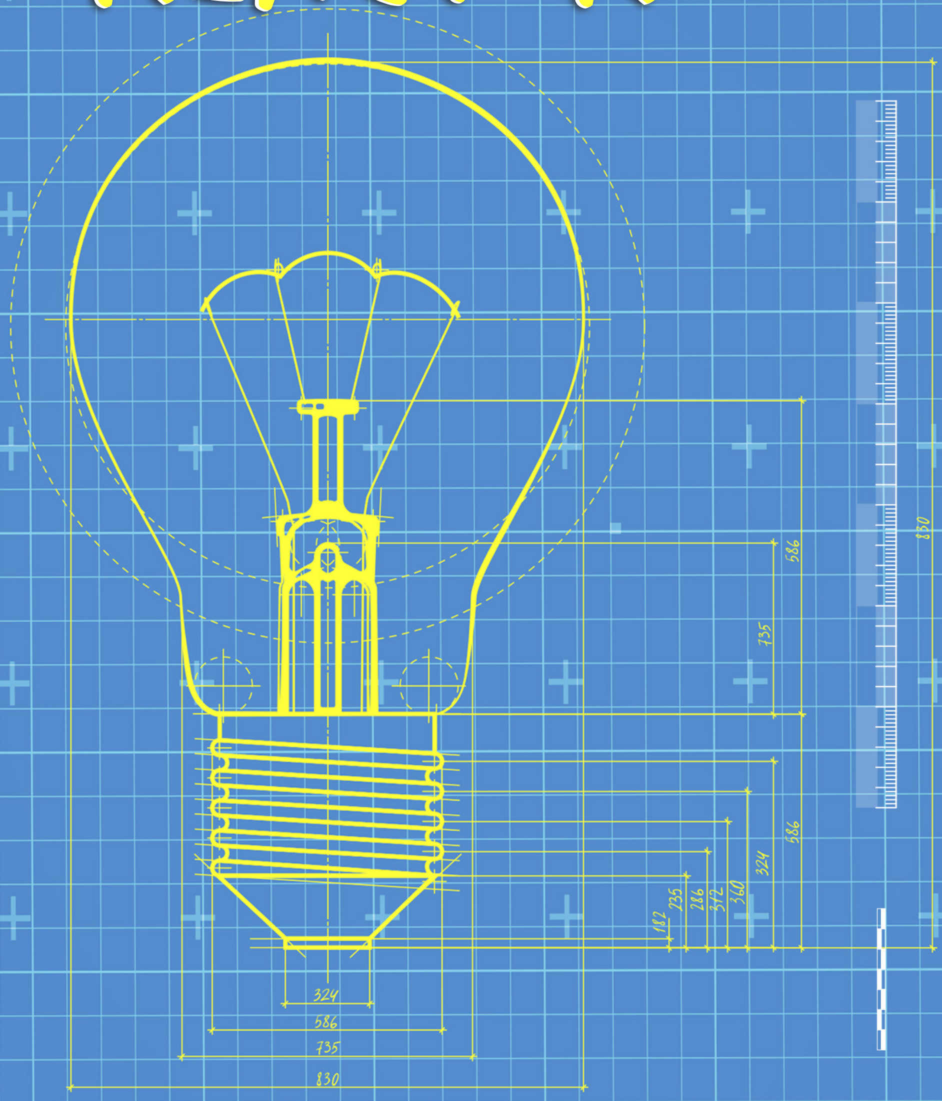
DESIGNING YOUR SRU THERMAL REACTOR



Sreeram Krishnan, Zeeco Inc., outlines the fundamental design principles of SRU thermal reactor packages.

Sulfur is the eleventh most abundant element in the human body and the tenth most abundant element in the universe (Hobart M. King, 2025). Much of the world's elemental sulfur, however, is recovered from hydrogen sulfide (H_2S) by-products that are produced within crude oil refineries or natural gas processing plants. These facilities utilise a conversion method known as the Claus process to recover elemental sulfur from sulfur-bearing off-gases. The elemental sulfur recovered from the Claus process can then be distributed for use in numerous applications, such as fertilizer or chemical production.

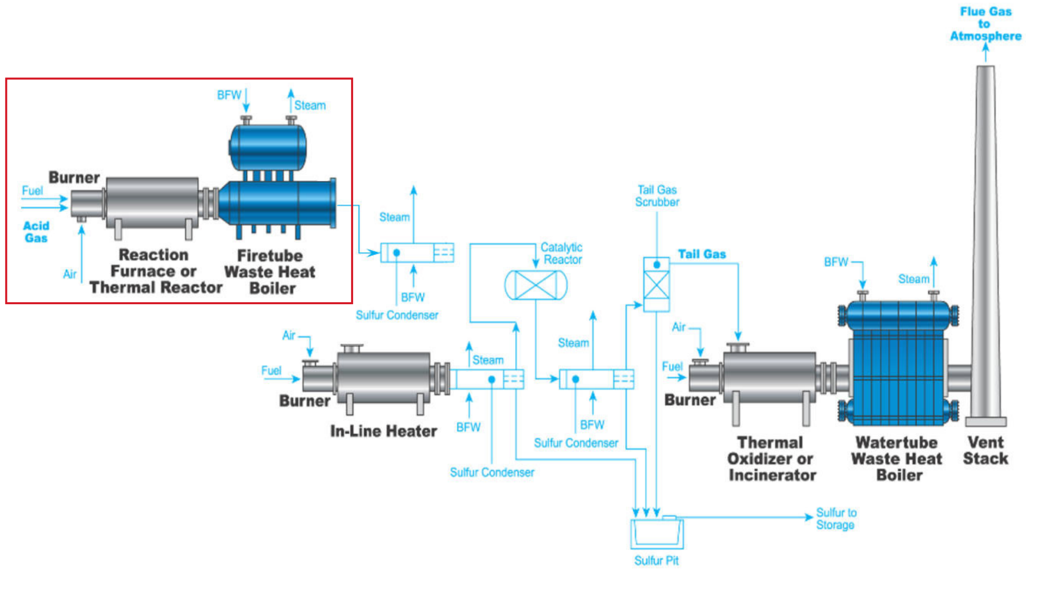


Figure 1. Typical Claus sulfur recovery unit (SRU).

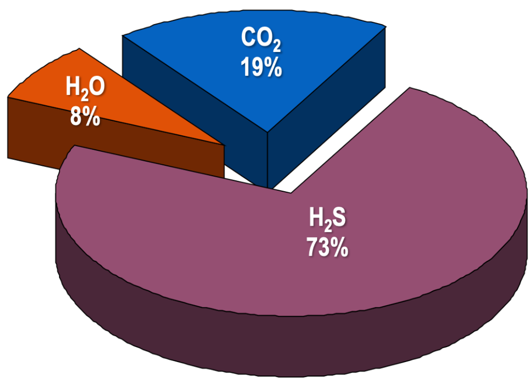


Figure 2. Typical acid gas composition.

Background information

The Claus process is carried out through a sulfur recovery unit (SRU) that is comprised of a wide range of process vessels and equipment packages that convert H_2S gas into elemental sulfur through an oxygen-deficient combustion process, before eventually being condensed into a liquid state and stored within a sulfur pit for final distribution. A Claus SRU typically utilises several different types of combustion equipment, such as thermal reactors, in-line heaters, and tail gas incinerators, as shown in Figure 1.

Reducing gas generators (RGGs) can also be found within a Claus SRU, even though they are not reflected within Figure 1. RGGs are commonly utilised within more complex recovery and treatment systems such as the Shell Claus off-gas treating (SCOT) process, which is typically implemented within facilities that demand higher levels of sulfur recovery (≥ 99.9%) and lower levels of produced SO_2 emissions (≤ 150 mg/Nm^3).

This article, however, will focus on the fundamental design principles associated with a typical Claus SRU thermal reactor package (the elements outlined in red within Figure 1), and how these design principles can be employed to ensure that all equipment is operated in the most safe and efficient manner possible.

General process overview

Two of the most common H_2S rich waste gases processed within a Claus SRU are acid gas and sour water stripper (SWS) gas. Figures 2 and 3 reflect typical compositions of these waste streams.

It should be noted that the gas compositions indicated in Figures 2 and 3 can vary based on individual applications. The purpose of these figures is to highlight the elevated concentrations of H_2S and NH_3 that are commonly present within each waste gas.

The primary reactions that convert H_2S into elemental sulfur within a Claus SRU thermal reactor package can be described by the following chemical reactions:

- Reaction one: a sufficient quantity of air is introduced to the system to combust ⅓ of the H_2S within the incoming acid gas into SO_2 and H_2O while simultaneously destroying all contaminants that may be present within the stream, i.e. NH_3, BTEX, etc.

$$H_2S + \frac{3}{2} O_2 \longrightarrow SO_2 + H_2O$$

- Reaction two: the remaining ⅔ of H_2S reacts with the SO_2 produced in reaction one to yield elemental sulfur vapour (S_2).

$$2H_2S + SO_2 \rightleftarrows \frac{3}{2} S_2 + 2H_2O$$

The elemental sulfur produced by the thermal reactor is then quenched in the waste heat boiler before passing through a condenser, where it is liquified and collected in the covered sulfur pit prior to distribution. The remaining flue gasses from the thermal reactor, which still contain significant amounts of recoverable elemental sulfur, then pass through a series of downstream in-line heaters, catalytic reactors, and condensers, where additional sulfur is recovered.

Although a Claus SRU has the ability to remove the majority of the sulfur within the processed waste gas streams, it is still necessary to further combust and destroy a by-product waste stream commonly referred to as tail gas. Tail gas streams contain residual amounts of sulfur-bound compounds, as well as carbon monoxide and hydrogen, all of which must be fully oxidised prior to discharge. This process is carried out by a tail gas incinerator, which fully combusts and destroys the waste by-products to acceptable emissions levels before they are released to the atmosphere.

Critical design considerations

The following critical design elements must be evaluated and implemented within a thermal reactor package in order to optimise the overall efficiency and performance of the entire Claus SRU.

Mixing dynamics

Intense mixing devices must be considered in the design of the thermal reactor package in order to ensure the overall performance of the Claus SRU. Because of the necessity to operate under sub-stoichiometric (oxygen-deprived) conditions, excessive quantities of air cannot be used to compensate for mixing inefficiencies. Reactions one and two described earlier must occur at a carefully balanced stoichiometry in order to yield an optimal ratio of H_2S and SO_2 to maximise the yield of elemental sulfur. Poor mixing may result in stratification where H_2S and SO_2 may be out of balance in different zones, preventing the ideal conversion to elemental sulfur.

For these reasons, static mixing devices, such as choke rings and/or checker walls, are commonly implemented within the thermal reactor furnace. Additional mixing devices, such as acid gas and combustion air spin-stabilised vane assemblies, are also commonly considered within SRU thermal reactor burners to further ensure that proper mixing and turbulence is achieved. It is recommended to perform additional CFD analyses to evaluate the velocity profiles within a thermal reactor package in order to further validate mixing dynamics, as shown in Figure 4.

Soot formation

Soot formation is a potential negative outcome of poor mixing dynamics within the thermal reactor package. Improper mixing can result in the formation of pockets or zones within the thermal reactor containing hydrocarbons that are exposed to insufficient quantities of O_2. As a result, these hydrocarbons are unable to fully oxidise into CO_2 or partially oxidise into CO, which can increase the likelihood of soot formation. Soot deposits within the downstream SRU catalytic reactors could also reduce the overall efficiency of the entire Claus SRU, thereby reducing the overall potential to recover sulfur. Excessive soot deposits can also result in a visible discolouration of the condensed liquid sulfur product, making it less desirable for distribution or sale.

In order to prevent these outcomes, reputable SRU design firms will perform a CFD analysis of acetylene (C_2H_2) concentrations across the internal profile of the SRU thermal reactor package. Past experimental data has indicated that C_2H_2 mole fractions greater than 10^{-8} are required to produce observable soot formation within the unit.

Oxygen stratification

Unreacted O_2 at the outlet of the SRU thermal reactor or the in-line heater packages is undesirable because of its potential to react with H_2S or condensed sulfur further downstream in the Claus SRU, resulting in higher SO_2 concentrations and reduced sulfur recovery efficiency. Unreacted oxygen can also prompt sulfur fires within the system, posing additional risks to personnel and equipment safety. For these reasons, it is recommended to perform additional CFD analyses to simulate O_2 concentrations throughout the internal profile of an SRU thermal reactor package.

Uniform temperature distribution

It is important to evaluate temperature distribution profiles within the SRU thermal reactor furnace in order to optimise the overall performance of the Claus SRU. Reactions one and two must occur at an appropriate temperature and residence time suitable to complete each reaction. Temperature impacts the equilibrium products of each reaction, thereby affecting the overall recovery of elemental sulfur across the system.

Temperature stratification occurring within specific pockets or zones within the thermal reactor, especially near the burner face, can result in improper or insufficient mixing, reducing the potential yield of elemental sulfur. Flue gas temperatures at any given location within the thermal reactor

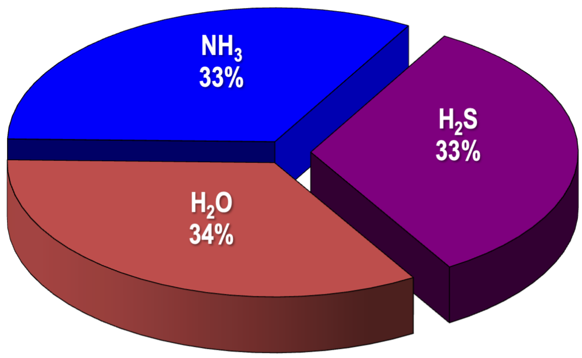


Figure 3. Typical sour water stripper (SWS) gas composition.

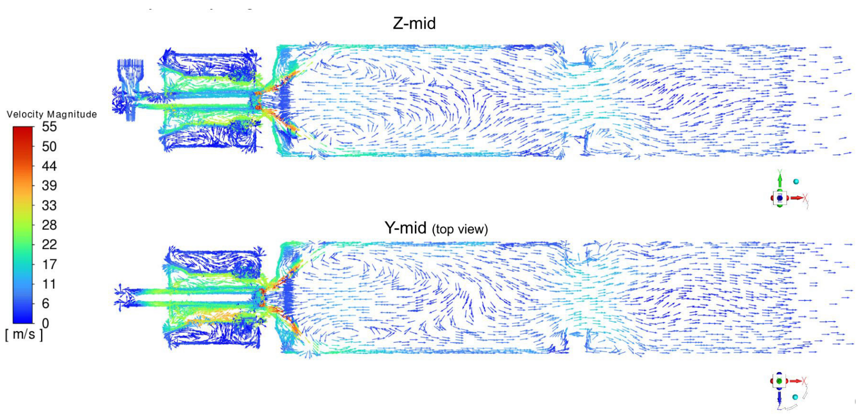


Figure 4. CFD model of the velocity profiles within an SRU thermal reactor.

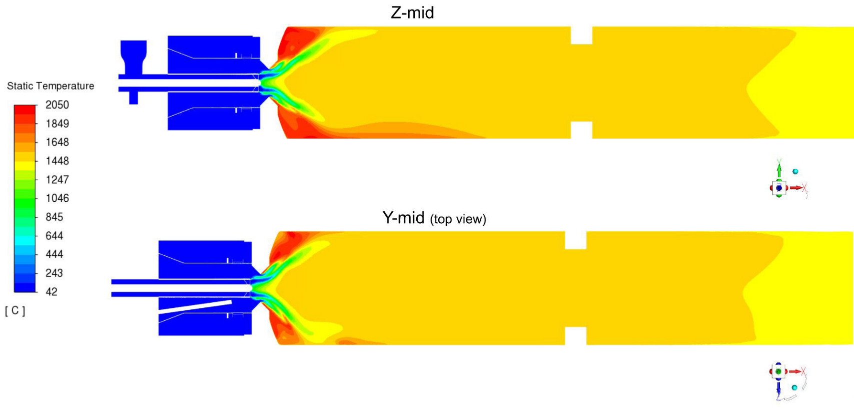


Figure 5. CFD model of temperature contours within an SRU thermal reactor.

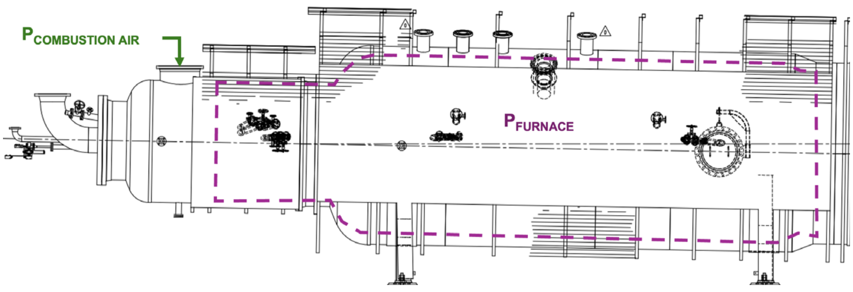


Figure 6. Critical pressure measurements within an SRU thermal reactor burner and furnace.

furnace are governed by the equilibrium temperature of the local reactant stoichiometry. The liberation of exothermic reaction energy is also limited by oxygen availability. Zones with higher oxygen concentrations will be prone to higher temperatures with the potential to damage internal refractory and/or burner components. Uniform peak flame temperature management within the system is largely based on the mixing devices within the thermal reactor burner. Burner aerodynamics and inert gas injection are used to mitigate peak temperatures especially in systems that may be operated with oxygen-enriched air streams. CFD models can be used to verify uniform temperature distribution across the profile of the thermal reactor burner and furnace, as further reflected in Figure 5.

Contaminant destruction removal efficiency (DRE)

Undesirable contaminants such as NH_3, BTEX, and other residual hydrocarbons must be destroyed within the thermal reactor to avoid damage downstream in the Claus SRU. NH_3 at the outlet of the thermal reactor can potentially react with SO_2, resulting in the formation of ammonium sulfate salts. These salts could then precipitate, plugging or fouling the downstream catalytic reactors and creating consequences similar to those previously discussed for soot formation. For these reasons, contaminants must be destroyed within a reducing atmosphere with limited oxygen availability.

Superior mixing devices and thermal reactor operating temperatures greater than 1250°C (2370°F) are recommended to further ensure that these contaminants are sufficiently destroyed at the outlet of the thermal reactor package.

Co-firing natural gas or splitting the process gas injection into different zones of the furnace can also be done to increase the furnace temperature where NH_3 must be destroyed.

Burner turndown capability

The burner pressure drop within the thermal reactor provides the mixing energy necessary to mix the gases properly. Insufficient mixing can result in performance limitations, as discussed. The streams contributing the most mass into the system are the combustion air and process gas streams. Together these streams must provide enough mixing energy for successful operation at any given operating condition within the variances in flow and composition typical for that Claus SRU.

Burn-back prevention

Burn-back is another common concern associated with low operating rates within the thermal reactor package. Maintaining a suitable velocity through the burner throat prevents damage to the burner's internal components by limiting exposure to any incidental radiation from the downstream thermal reactor furnace.

The aerodynamics of a spin-stabilised burner naturally produce a central recirculation zone, similar to the eye of a tornado or typhoon. This recirculation zone will pull furnace gas back to the face of the burner, which can damage internal components. Maintaining a minimum flow through injectors also helps to prevent damage regardless of the velocity through the burner throat.

In some cases, the operating conditions within the thermal reactor package may result in little to no flow through the fuel gas tips or acid gas injectors. During these events, steam may be used as an alternative method of maintaining a minimum velocity through the injectors in lieu of process or fuel gas. Differential pressure transmitters on the SRU thermal reactor furnace ($P_{Furnace}$) and combustion air inlet nozzle on the burner ($P_{Combustion\ Air}$) can also be used to monitor pressure drop across the burner as an additional preventative measure for burn-back, as indicated in Figure 6.

Conclusions

SRU thermal reactor packages must both maximise sulfur recovery and minimise SO_x emissions produced by the Claus SRU at any given refinery or natural gas processing plant. All packages within a Claus SRU must be carefully designed and operated to function as stipulated by the process licensor. Given the critical design principles and features that must specifically be considered for an SRU thermal reactor package, it is important to consult with a trusted and proven SRU supplier for any specific questions related to the detailed design, manufacturing, or operation of SRU packages.