A GENERATIONAL SHIFT

Chris Ferguson and Kurt Kraus, Callidus Technologies, USA, overview a fourth generation flare which has been designed to take full advantage of the water gas shift reaction.

Flare combustion technology has evolved over time and each evolution has been driven by the fundamental need to dispose of flare waste streams with efficient smokeless combustion. For purposes of understanding flare combustion evolution, each breakthrough in flare combustion represents a 'generational' change in technology. This article provides an overview and outlines three previous generations of flare combustion technology and introduces a new stage in steam flare technology. The patent-pending Callidus nViro-XSR™ 4G is a fourth-generation, low-pressure, elevated flare which further extends the art of combustion technology to minimise emissions.

Past generations

The original first generation elevated low-pressure flare technology is a simple pipe flare. While still broadly used today, these 1G flares tend to smoke easily even with the lightest of hydrocarbons, methane.

The second generation of elevated flares added external steam such as an upper steam ring. The steam ring encircles the exit rim of the flare exit with nozzles that induct air from the surrounding atmosphere, driving combustion air and steam into the flare's effluent stream. The injected air and steam serve to enhance combustion, thereby extending the smokeless capacity of the flare.

The smokeless capacity of a flare is defined as the maximum mass flow rate of the flare where the flame is not smoking (Ringlemann Scale 0 or R0). With these 2G flares it was found that saturated hydrocarbons such as methane, ethane and propane could be flared to some smokeless rates. However, at higher flare loads, larger flare tip diameters and with unsaturated hydrocarbons such as ethylene and propylene, these 2G flares have very low smokeless ratings.

The third generation of flares used steam to entrain and mix more air into the effluent stream. These 3G flares are characterised by steam jets around the periphery of the flare injecting steam and inducting air into a tube with a bell or venturi shaped tube that then subsequently injects the steam/air mixture into the effluent stream. These 3G flares may have up to three modes of steam injection with an 'upper steam' ring like a 2G flare, external

air-injecting into a venturi steam 'internal steam,' and where some portion of the steam is injected into the effluent some distance upstream of the flare effluent exit nozzle 'centre steam.'

A new generation

While both 2G and 3G flares rely on using the motive force of the steam to mix air into the flare effluent stream, 4G flare technology changes the paradigm of how steam energy and chemistry is used in the combustion process. 4G flares use the steam's kinetic energy directly on the effluent stream. It is well known that 100% smokeless capacity is demonstrated in pressure staged multipoint ground flare burners. For stage multipoint ground flares, kinetic energy of the pressurised flare gas provides mixing energy to achieve 100% smokeless combustion. 4G steam flares use steam to add kinetic energy to the effluent stream.

Callidus 4G technology has been designed specifically to fully leverage the effects of the water gas shift reaction (WGSR). The key advancement is that the steam is thoroughly mixed with the effluent immediately prior to and upon exiting the flare tip. This is where combustion is initiated and stabilised, delivering the steam exactly where it is needed to take fullest effect of WGSR.

What is the WGSR?

First it is essential to understand what WGSR is, how it works and how it can be used to deliver better flare performance. WGSR has been studied, theorised, experimented with, simulated, and employed on a wide range of organic chemical processes, beyond just the realm of combustion. At least as far back as the 1950s, steam has been recognised as having positive influential effects on diffusion flames and early editions of API 521 make mention of WGSR.[1,2]

To start with, WGSR occurs after carbon monoxide (CO) is formed by partially combusting the hydrocarbons with the reforming reaction (R1):

$$CnH_2n+2 + nH2O \rightarrow nCO + (2n+1)\ H_2 \qquad (R1)[3]$$
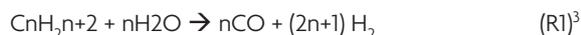
This enables WGSR[3], which is a moderately exothermic reversible reaction expressed by:

$$CO + H_2O \longleftrightarrow CO_2 + H2\ \Delta H^0_{298} = -41.09\ kJ/mol \qquad (R2)[4]$$

These reactions (R1) and (R2) are intermediate reactions of the overarching hydrocarbon combustion reaction:

$$C_nH_{2n+2} + (1\frac{1}{2}n+1/2)O_2 \rightarrow nCO_2 + (n+1)\ H_2O \qquad (R3)[3]$$

The reforming products are finally combusted:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \qquad (R4)[3]$$
$$CO + \frac{1}{2}O_2 \rightarrow CO_2 \qquad (R5)[3]$$

But the interesting mechanisms happen with the partial products of the WGSR inside the double arrows '$\longleftrightarrow$' of (R2). It is here where the highly reactive H+ and OH-

free radicals are joining the already present and highly reactive CO. Depending on what other intermediate products of combustion form and interact with these highly reactive free radicals, a variety of unstable intermediate products can briefly exist as intermediate products or permanently reside in the final products of combustion. The complex nature of these intermediate products and their internal reactions and interactions is the subject of recent and ongoing studies by various laboratories.

There has been a lot of study of the effect of these intermediate reactants and their associated, unstable intermediate or final products, but the work by Melius and colleagues at Sadia National Labs describes these radicals causing "large lowerings of the activation energies for the reaction when additional water molecules are included in the reaction mechanism" and goes on to describe water acting "as a solvating agent and as a catalyst."[5] Thus, water drives more complete reaction of the hydrocarbons to carbon dioxide and water by reducing activation energies and acting as a solvate and catalyst, thereby reducing the likelihood of residual unburned hydrocarbons and soot (carbon) as the reactions proceed to completion, (R3), (R4), and (R5).

More recently, Wu and a team from Washington University in St. Louis, US, found that "the main factor contributing to this phenomena (WGSR) is the abundance of the H radical on the fuel side of the flame; this leads to a fast forward reaction for the first step and a fast reverse reaction for the second step, and the two balance each other, yielding apparent equilibrium."[6] This provides another clue to where and how flare burner design might be optimised to leverage WGSR. Wu et al. go on to say: "The abundance of the H radical on the flue side of the flame [...] leads to a fast forward reaction" over a much broader range of temperatures and concentrations than when water is mixed on the air side. Interestingly, the range of low activation energy is broader for unsaturated hydrocarbons (ethylene) than for saturates (methane and propane) where "the hydrocarbon flames exhibit two zones of WGSR equilibrium that are separated by the location of stoichiometry. The zone on the fuel side of stoichiometry shows a profile with a clear broad region of (R2) are controlled by the external supply of radicals from the radical pool, instead of being self-balanced by their thermodynamic nature." Meanwhile, "the zone on the oxidizer side exhibits a very narrow region of equilibrium or none at all."[6]

To summarise, the WGSR works within the hydrocarbon combustion process by reducing activation energies, solvating, and catalysing, thereby accelerating the disassociation of carbon-carbon and carbon-hydrogen bonds. Hydrocarbons, particularly unsaturated hydrocarbons, are burned more easily, fully and rapidly with intimately present and thoroughly mixed water. Further, it is much more effective to mix water with the fuel at elevated temperatures than it is to mix steam with air before entering the hydrocarbon stream.

Applying to the flare design

The Callidus nViro-XSR 4G flare tip injects steam into the effluent stream immediately before exiting the flare tip.
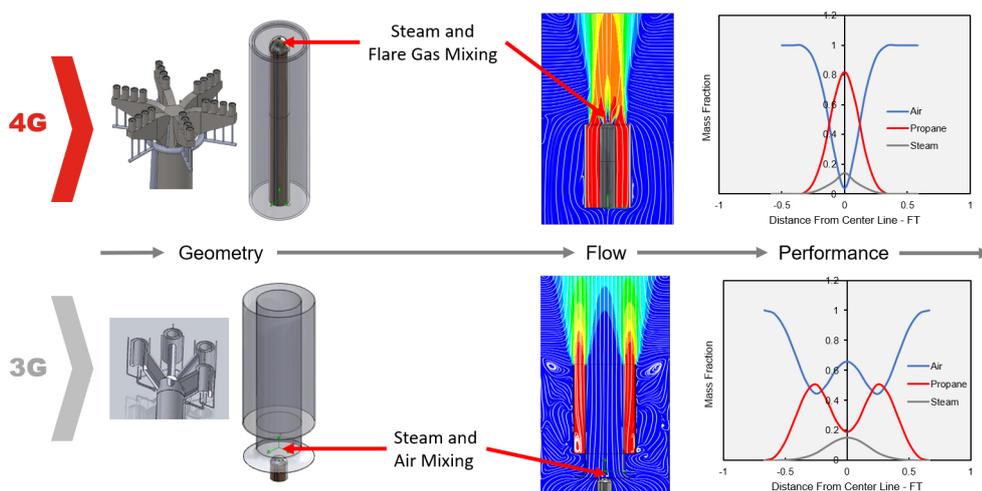
Figure 1. Comparison of flare effluent/air mixing.

flares do, may reduce or even completely negate the combustion enhancing qualities of steam injection.

The 4G technology has been designed to rapidly mix steam and air exactly where and when needed to take full advantage of these theoretical insights into WGSR mechanisms. The result is a 100% smokeless steam flare, smokeless across and beyond the flare's full capacity range.

This injection point allows rapid premixing of steam with the fuel as the mixture is entering the flame zone and simultaneously increases the kinetic energy of the effluent stream. In this arrangement, the relative high temperature of the mixture is immediately increased in the flame, accelerating the initiating reactions: (R1) and (R2).

Through this process, the momentum of the steam jet scavenges gasses from the flare tip, thereby reducing back pressure in the tip and increasing the flare's capacity before being pressure limited. This scavenging effect improves with increased steam rates, thereby mitigating and regulating flame burn back into the flare tip.

Results

Full scale test results of the nViro-XSR with 100% propylene are consistently below 0.2 lbm-steam/lbm-effluent for R0 performance. Full scale test results with 100% propane yields results at or below 0.1 lbm-steam/lbm-effluent for R0 performance. Most importantly, these values remain consistent for steam loads ranging from standby or utility flare loads (exit velocities ‹10 ft/sec.) to higher rates over 400 ft/sec. Though rates over 500 ft/sec. have not been fully explored, it appears that the steam flow rate can remain constant or be reduced to maintain R0 performance. Therefore, steam consumption on a mass basis may continue to be reduced as exit velocities approach supersonic. The new technology delivers 100% smokeless performance across the entire operating range.

Conclusion

While it has been long observed that steam can enhance the combustion process, it is only more recently that the research community has been able to simulate and better understand just how steam may work and interact within flames. The work of Melius et al. indicates the solvating and catalysing effects of steam while Wu et al. shows that mixing first and well with fuel rather than oxidant can be more effective. Further, premixing steam with air before mixing with the effluent gas, as all 3G and earlier steam

Areas for further study

It is speculated that this performance (i.e. reducing steam consumption with increasing effluent rates) may continue until the exit velocity reaches sonic, at or over 1000 ft/sec. for lighter hydrocarbons. However, application of WGSR theory may indicate that steam consumption values may remain reasonable, even at extreme emergency rates exceeding supersonic. Further full-scale testing of nViro-XSR style flares is needed to verify the theoretical validity of smokeless performance in the supersonic realm.

Initial observations of high wind testing find that optimising flare design for WGSR also improves smokeless performance in high winds. It is well known that both high-pressure (no steam assistance) and low-pressure steam-assist flares tend to smoke more readily when subjected to high wind. Wind-driven air can cool and quench the flame, prematurely halting combustion, resulting in incompletely burned product, forming soot and smoke. With 3G flare designs, air that is driven into the effluent by steam cools the steam before entering the combustion process, thus delaying the WGSR. There is ample air surrounding the flare and further air driven into the effluent reduces the flame temperature, making wind-driven smoking more likely. Conversely, the WGSR optimised design, with greatly reduced activation energies and catalysing effects, means the lowered temperatures of wind-driven quench are mitigated. **HE**

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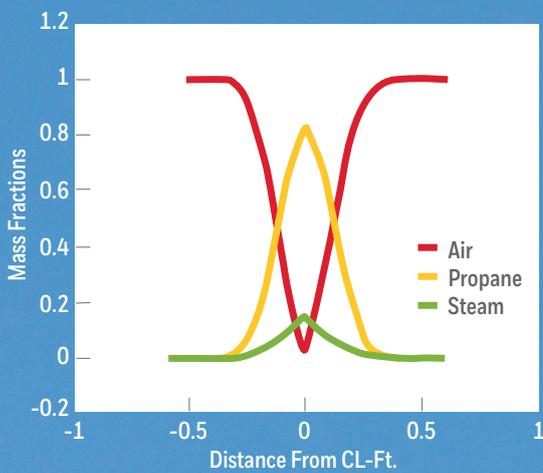
Going Beyond
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Callidus 4G Flare Technology is a game changer for the flare combustion industry. 4G technology uses less steam to add more energy to the flare gas, resulting in better mixing and less smoke. 4G technology uses water gas shift to further reduce the formation of smoke and enables NOx reduction. The combined effects of 4G physics and chemistry can deliver up to 175% greater smokeless rate using up to 64% less steam, and a less than one year payback on OPEX.

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