Driving down costs in hydrogen production

An optimised hydrogen plant design achieves the right balance of minimising both Capex and Opex costs, while meeting the specific objectives of the end user

Luigi Bressan and Chris Davis *Foster Wheeler*

The global demand for refinery hydrogen has increased significantly over the past decade due to changes in available crude feedstocks and tighter environmental regulations, which have forced the refining industry to reduce sulphur, olefins and aromatics content in transportation fuels. This, coupled with the continued growth in diesel demand, means that refiners are investing heavily in both hydrotreating and hydrocracking facilities, and are constantly looking for access to low-cost, reliable sources of high-purity hydrogen.

Foster Wheeler pioneered steam methane reforming (SMR) technology and has delivered more than 100 hydrogen and synthesis gas plants around the world, with a total installed capacity of more than 3.5 million Nm^3/h of hydrogen. The company's patented and proprietary Terrace Wall reformer furnace was developed in conjunction with SMR technology in the early 1960s. Updates and improvements to plant efficiency, lower maintenance costs, simplified operations and enhanced plant safety have been documented in previously published articles.

These hydrogen-producing SMR plants process a wide range of feedstocks from natural gas to naphtha and range in size from 5000 to 200 000 Nm^3/h. The range of hydrogen solutions provided include:

- Optimised plant design and operating parameters tailored to the operator's requirements, integrating overall plant and reformer furnace design to reduce total lifecycle costs
- Full understanding of constructability issues and impact on total installed cost, with the ability to incorporate a high degree of modularisation of the Terrace Wall reformer, reducing construction costs
- One-stop shop, providing consistency through all design phases, ensuring single-point accountability for process and operational guarantees
- Safety in design that incorporates the latest state-of-the-art design principles as well as end user feedback, to enable safe and reliable plant operations.

Steam reformer-based technology

SMR continues to be the leading technology for hydrogen production and, although it is a mature technology, incremental economic improvements are being continuously developed, which improve overall plant efficiency, reduce the cost of hydrogen production and minimise the impact on the environment by reducing CO_2 emissions.

The hydrogen production plant consists of five main sections:

- **Treatment section** Feedstock is hydrotreated and the resulting H_2S is captured in a zinc oxide bed. Different schemes are available, with the most commonly used being a lead-lag reactor arrangement. Reaction temperatures are obtained by thermal exchange in the reformer's heater convection section
- **Pre-reforming section** A pre-reforming section is generally installed to eliminate the long-chain hydrocarbons in heavier feedstocks before they enter the reforming section. When natural gas is used as a feedstock, the pre-reforming section helps to reduce the reforming duty, thereby lowering the initial investment cost of the reformer
- **Reforming section** This is the heart of the plant

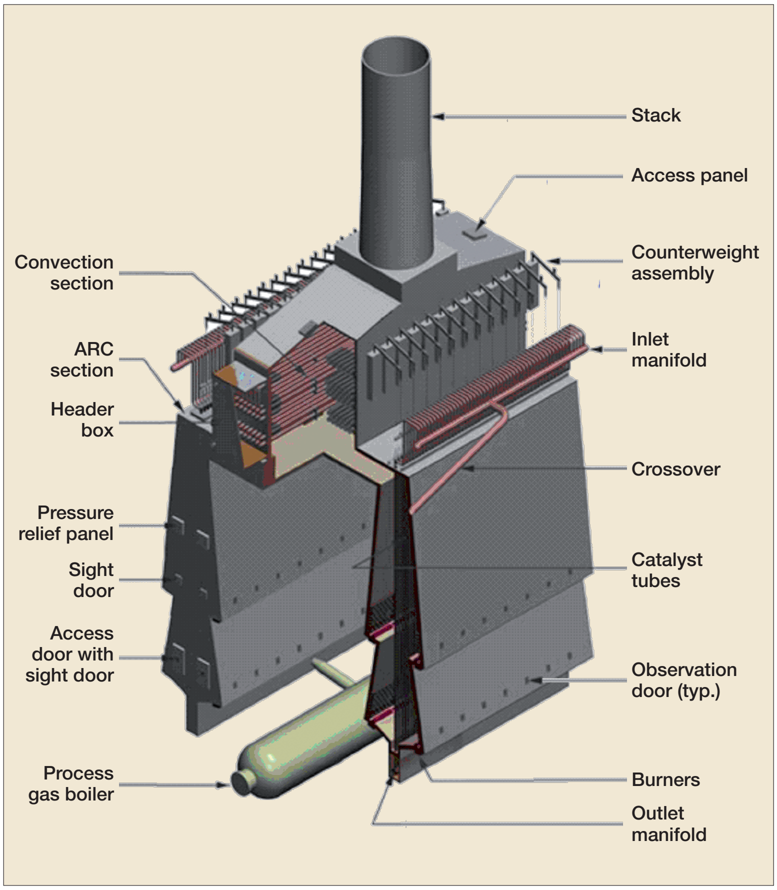

Figure 1 Steam reformer description

and will be discussed in detail in the next section. The Terrace Wall technology allows for steam reformer outlet temperatures of up to 930°C

• **Syngas cooling and shift reaction section** For the shift reaction, four options are available: high-temperature shift (HTS), HTS and low-temperature shift (HTS + LTS), medium- temperature shift (MTS) and isothermal shift (ITS). The syngas cooling section is normally optimised using pinch technology

• **Pressure swing adsorption (PSA) section** Final hydrogen purification is typically achieved using PSA, as this technology is both effective and well known. Process parameters need to be carefully defined to optimise both overall cost and operating expenses.

The centrepiece of Foster Wheeler's hydrogen plant design is the Terrace Wall reformer. This design incorporates unique features that provide controlled heat transfer to the reformer catalyst tubes, which translates into longer tube life, longer catalyst life and better stability at turndown conditions.

General description

The Terrace Wall reformer, shown in Figure 1, features a radiant section consisting of a firebox, which contains a single row of catalyst tubes with burners on either side located at two terrace levels. Hot flue gases flow naturally upwards into the convection section very much like a conventional fired heater. The convection section, located on the top of the heater in between the radiant sections, has several coil sections, which recover much of the remaining heat from the flue gas for various process and steam duties. A close-coupled process gas boiler (PGB) with an internal bypass and associated steam generation system complete the reformer design.

Advantages

The advantages of the Terrace Wall reformer include the following:

• The sloped firing walls and terraces of the reformer are its trademark feature. Each terrace is capable of being independently fired to provide the particular heat flux desired in a given zone. Controlled delivery of heat to the reformer catalyst tubes is essential to control the reaction progressing along the tubes. The sloped walls are uniformly heated along the length of the furnace as a result of the special burner design, which provides for a continuous re-radiating plane with no marked discontinuity. The sloping walls also provide a uniform vertical flux profile, since the distance from the tube to the radiating wall decreases as the flue gas cools. The burners are selected to spread the flames both horizontally and vertically along the firing wall for a uniform planar heat flux pattern. Low-heating value, low-pressure PSA off-gas is stabilised against the brick firing wall, preventing the flame impingement or instability that is common in top-fired designs with free-standing burners

• The burners are located at two levels in the radiant section, firing upwards adjacent to the brick firing walls. This configuration significantly reduces power requirements for the induced draft/forced draft (ID/FD) fans compared with competing technologies, which need to operate against the natural buoyancy of the flue gases, as well as to overcome the larger burner pressure drop required to shape the flames. Power consumption can be reduced by at least 40-50% compared with competing technologies

• The burner flames adhere to the sloped firing walls, providing unmatched flame stability and virtually eliminating any possibility of flame impingement and catalyst tube failures compared with other technologies, which require constant observation and expensive instrumentation to confirm flames are not leaning into the catalyst tubes

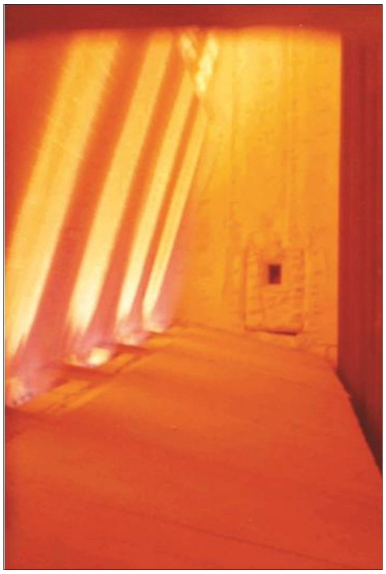

Figure 2 View inside firebox

• By varying the upper terrace height, the reformer design can be tuned to the end user's specific requirements, while still maintaining maximum radiant fuel efficiency

• The simple up-fired design of the heater allows for the instantaneous shift to natural draft operation without losing both hydrogen and steam production in the event of fan failure. This improves the overall reliability of the plant by avoiding costly shutdowns, reduces material stresses from unplanned thermal cycling and also keeps hot flue gases from being trapped in the top of the radiant firebox (Figure 2), which could leak and cause injury to operating personnel

• The process gas boiler is located between the two radiant cells, close to the outlet manifolds. This results in a highly compact design, which both significantly reduces plot requirements and minimises the length of the costly internally lined transfer line

• Specialised mechanical systems minimise the stress applied to individual components, eliminating tube bowing. The counterweight support systems are dependable, reliable and require less maintenance than the spring hanger designs common in similar technologies

• The single-row tube layout provides excellent visibility throughout the heater and allows for visual inspections of every burner and catalyst tube from top to bottom. This eliminates the need for expensive flame and tube monitoring equipment

• As a safety point, the burners are side-mounted and easily accessible from outboard platforms at each terrace, meaning that operators do not have to work in the reformer "penthouse" to perform burner maintenance

• Turndown to 30% of design is possible, as individual burners can be adjusted or an entire terrace shut off without the need to change other operating parameters

• The reformer is ideally suited to a high degree of shop assembly, requiring only a handful of field welds on site. The entire radiant section from the inlet manifold to the outlet manifold, including all the tubes, refractory and burners, are shop assembled into overland truckable modules, thereby reducing freight and logistics costs

• The reformer is very compact, with the convection section and stack mounted above the radiant section. This configuration has a much smaller footprint than the top-fired design, making it an excellent choice for installation in existing plants or in any location where plot space availability is a concern.

Extended tube and catalyst life

The Terrace Wall design allows the operator to match the vertical heat flux to the process heat demand within the catalyst tubes, which ultimately prolongs the life of both the catalyst and the tubes. This principle is illustrated in Figures 3 and 4. Figure 3 shows the expected process and tube metal temperature profiles along the tubes for both the top-fired and Terrace Wall reformer designs. Figure 4 illustrates the corresponding heat flux profiles for each reformer down the tube, clearly showing the intense heat flux at the top third of the tube for the top-fired design, where carbon deposition onto the catalyst is most

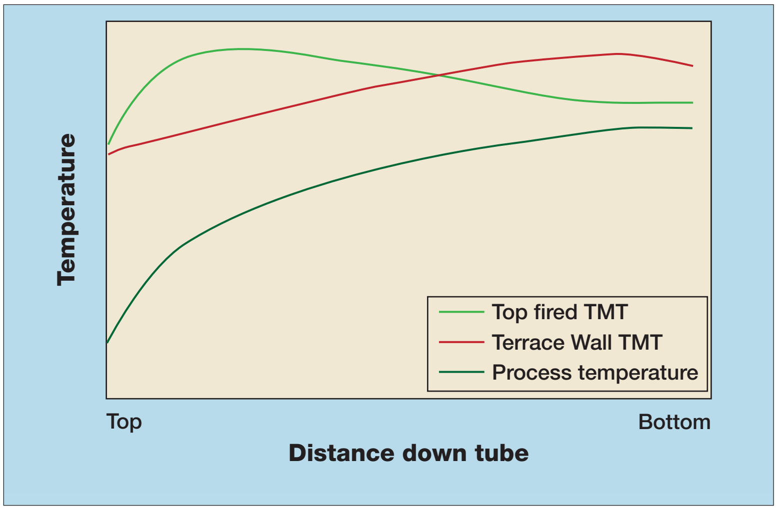

Figure 3 Temperature vs distance down tube

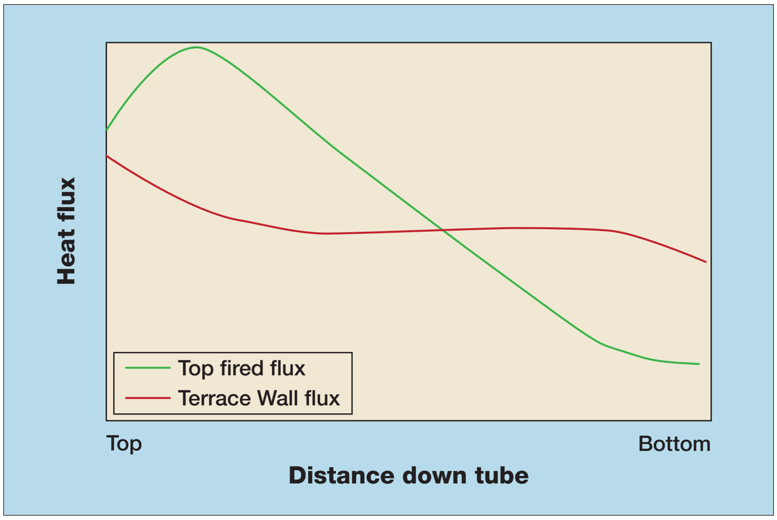

Figure 4 Heat flux vs distance down tube

likely to occur. These carbon deposits create localised hot spots, or bands, which can be up to 50°C hotter than a nearby, unaffected section of the tube. A temperature excursion this severe will typically result in a decrease of between 33% and 75% of the design tube life expectancy.

Furthermore, for top-fired and Terrace Wall reformer designs, the point of peak internal pressure within the catalyst tubes occurs at the top of each tube. In a top-fired design, the point of peak metal temperature also occurs near the top of the tube, whereas in the Terrace Wall design the point of peak metal temperature is closer to the outlet of the tube. The net result is that, for a given point in the tube, the overall operating conditions in a Terrace Wall design are less severe than in a top-fired design. Lower operating severity means lower tube stresses, which in turn mean longer tube life.

Hydrogen plant optimisation: the design steps

An optimised plant design achieves the right balance of minimising both Capex and Opex costs, while meeting the specific objectives of the end user. To achieve this balance, significant time and attention are dedicated to developing an in-depth understanding of each facility's specific needs. The following design criteria are evaluated and agreed:

- Hydrogen product quality, characteristics and delivery pressure
- Feed quality, characteristics and cost
- Fuel quality, characteristics and cost
- Utilities characteristics, costs and availability
- Site constraints
- Layout limitations
- Specific codes to be observed.

Once the design is agreed, it is necessary to define the plant configuration and main parameters. The following elements are considered:

- Selection of purification steps based on the feedstock characteristics; an accurate selection extends the catalyst life, increasing the time between catalyst overhauls
- Integration of the pre-reformer in the plant design to eliminate long-chain hydrocarbons and reduce the steam reformer size, lowering the necessary reaction duty
- Adopt the most adequate reformer outlet temperature
- Selection of the most adequate steam-to-carbon ratio and the relevant shift reactors scheme
- Determine the pressure drop profile of the plant.

Optimising the hydrogen plant design will always be very dependent on specific client criteria and must consider a combination of operating and capital costs (Opex and Capex). The optimal plant configuration will always be assessed through cost/benefit analysis to minimise the cost of hydrogen over a defined operating period, while meeting the design parameters provided. When evaluating the efficiency of a hydrogen plant design, it is necessary to refer to the net energy input required to produce a given amount of hydrogen. The lower the number, the less energy is required to produce the hydrogen. This is described by the following equation:

[Feed (as GCal/h) + fuel (as GCal/h) – steam (as GCal/h)]/1000 Nm^3/h of H_2 produced

In this case, "steam" refers to the net export energy rate of steam from the plant. For newly designed plants operating on a natural gas feedstock, this number is typically less than 3.0 Gcal per 1000 Nm^3 of hydrogen (based on LHV). However, the lowest net energy solution may not provide the lowest cost solution. Depending on the relative pricing of feedstock, fuel and steam, the reformer design can be adjusted, such that a fit-for-purpose solution minimises the lifecycle cost of hydrogen production. This is achieved by minimising the following equation:

Feedstock x $cost_{feedstock}$ + fuel x $cost_{fuel}$ – steam x $value_{steam}$ = Opex (hourly Opex if flows are on an hourly basis).

Power and cooling water consumption can also be considered.

When the plant configuration is selected, it is necessary to undergo systematic optimisation steps, such as:

- Detailed simulation with suitable software
- Perform an analysis based on pinch technology
- Review the design alternatives based on the net present value (NPV) concept
- Optimise the plant pressure drop profile, accurately selecting the equipment (exchangers and reactors)
- Evaluate HSE aspects and establish the safeguarding philosophy
- Define the control system for the overall plant and verify it with dynamic simulation tools when necessary to confirm instrument design parameters
- Establish turndown cases from both a plant and fired heater performance perspective
- Ensure any potential developments and improvements from catalyst suppliers have been factored in
- Evaluate carefully the PSA performance, soliciting PSA vendors for the latest enhancements.

Technical and economic parameters	
Technical parameters	
Plant size	100 000 Nm^3/h
Feed/fuel type	Natural gas
Plant configuration	Pre-reformer, MTS, A/P @ 520ºC, S/C = 2.2
Economical parameters	
Plant cost	$114 MM
IRR (full equity)	10
Plant life	15 years
Feed/fuel cost	04/08/12 $/MMBtu
Steam credit	0.9 feed/fuel cost
Other parameters	Taxes = 20% Inflation = 2%

Table 1

Hydrogen production cost

Based on a 15-year NPV calculation, the operating cost for a hydrogen plant sized for 100 000 Nm^3/h with a natural gas price of 4.0 $/MMBtu is approximately three times higher than the installed capital cost. Therefore, when evaluating various reforming technologies for the manufacture of hydrogen, it is extremely important that any analysis includes an assessment of the total overall lifecycle cost of production as to note that natural gas cost has the largest impact on plant economics. This is further compounded knowing that the expected operating life of the hydrogen plant will typically be greater than 30 years, making it even more critical that the design is optimised to the site-specific process parameters, that it runs efficiently, has extremely high reliability, and incurs minimal maintenance and repair costs.

To illustrate this point further, the example in Table 1 considers three different feed/fuel price scenarios ($4/8/12/MMBtu), including the technical and economic parameters.

As can be seen from Figure 5, the operating

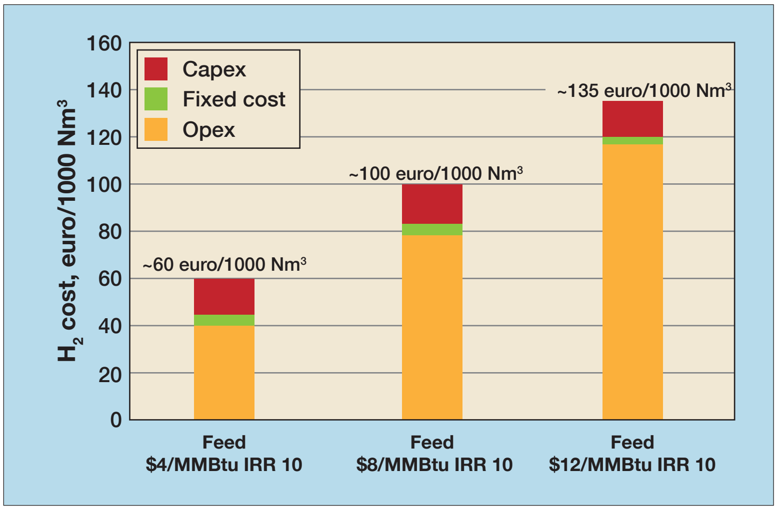

Figure 5 Operating costs (Opex) as a percentage of overall hydrogen production costs

costs (Opex) become a larger percentage of the overall hydrogen production costs, increasing from approximately 67% for the $4/MMBtu case to up to 85% for the $12/MMBtu case.

Conclusions

There are several competing technologies available for the manufacture of hydrogen via steam reforming. These technologies are mature and the comparison between them usually comes down to the differences in the primary reformer design and operation. Therefore, careful analysis is required to understand these differences and how they impact the cost of hydrogen production over the entire operating life of the plant. This analysis needs to consider all cost factors, including initial capital outlay, ongoing operating expenses, as well as any foreseen maintenance and repair costs.

Terrace Wall is a mark of Foster Wheeler.

Luigi Bressan is Director of Process and Technology at Foster Wheeler, Italy. A graduate in chemical engineering, he has been with Foster Wheeler since 1976. His experience covers process design of refinery and chemical units, utilities and off-site systems and power stations. In addition, he has been involved in the optimisation and design of combined cycle and integrated gasification combined cycle power plants from the very beginning of their appearance on the market. He is a member of several national and international committees and author of many papers.

Chris Davis is the Business Development Manager at Foster Wheeler's fired heater division in Hampton, New Jersey. He is responsible for leading the sales effort for fired heaters in support of Foster Wheeler's coking and reforming technologies along with other fired heater equipment. Prior to joining Foster Wheeler, he worked for 10 years in the industrial gases business developing long-term hydrogen supply schemes for refining customers and 10 years in oil refining for BP Oil in process engineering, capital projects and operations roles. He holds a bachelor's degree in chemical engineering from the Royal Melbourne Institute of Technology (RMIT) in Australia.

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