Large-Scale Hydrogen Plants – Design and Engineering Experience

*By M. MICHEL**

2 x 100,000 Nm³/h hydrogen manufacturing unit at the SINCOR upgrader, Venezuela

Abstract

Due to the stringent requirements of low sulfur fuel and heavier crude oil feedstock more hydrogen will be consumed in the refineries. In particular if large scale capacities are the response to an increased hydrogen demand, certain design and engineering experience are required. These will be described in this article with the Hydrogen Manufacturing Unit for the SINCOR upgrader as an example. Selected process design requirements will be listed and described in accordance to the flowsheet. Additionally, a selection of innovative design features, like process condensate reuse, safe reformer start up and CO_2 sequestration will be highlighted.

Introduction

A general trend over the past several years has been the dramatic increase of the hydrogen demand in refineries. Since the crude oil feedstock has become heavier and more sour and more stringent environmental regulations have been put into place, refineries fell short of hydrogen. This trend has led to numerous installations of hydrogen production capacities and revamps of existing hydrogen plants all over the world. Moreover, the production capacity of individual hydrogen plants has increased to a range where process design and plant arrangement generate new challenges and opportunities.

In the following the design and engineering experience with large capacity production units will be shown with the hydrogen manufacturing unit of the SINCOR upgrader complex as an example.

Furthermore an approach will be made to individual options and opportunities for innovative considerations in the process design with respect to important issues like low emissions and increased safety awareness in the petrochemical and refinery industry.

The Sincor Upgrader Project

The upgrader complex in Jose, Venezuela named Sincrudos de Oriente (SINCOR), which produces 180,000 b/d of high quality low-sulphur syncrude (API 32°) for export, demands a total hydrogen supply of 200,000 Nm³/h. The unit consists of two steam reforming based production trains, each with a capacity of 100,000 Nm³/h of high purity hydrogen. The Hydrogen Manufacturing Unit (HMU) for this upgrader was delivered by Uhde on a LSTK basis with the Pressure Swing Adorption (PSA) units subcontracted to UOP.

The feedstock for the total upgrader complex which is owned by TotalFinaElf/France (47%), Statoil/Norway (15%) and state owned oil company PDVSA (38%) is a high sulphur extra heavy crude of 8.5° API gravity. This crude is produced from the Orinoco Belt near Zuata within the state of Anzoategui. To reduce the viscosity of the crude it is blended with a diluent (a naphtha cut that comes from the upgrader) before it is transported via a 200 km pipeline to several upgrader units within the Jose industrial complex near Barcelona at the Caribbean coast. Here the high sulphur extra heavy crude is upgraded to synthetic crude of high quality while the diluent is separated and returned to Zuata via a parallel second pipeline.

The process steps involved at the upgrader are desalting, atmospheric and vacuum distillation, delayed coking, hydrotreating and hydrocracking. A simplified upgrading scheme is shown in Figure 1.

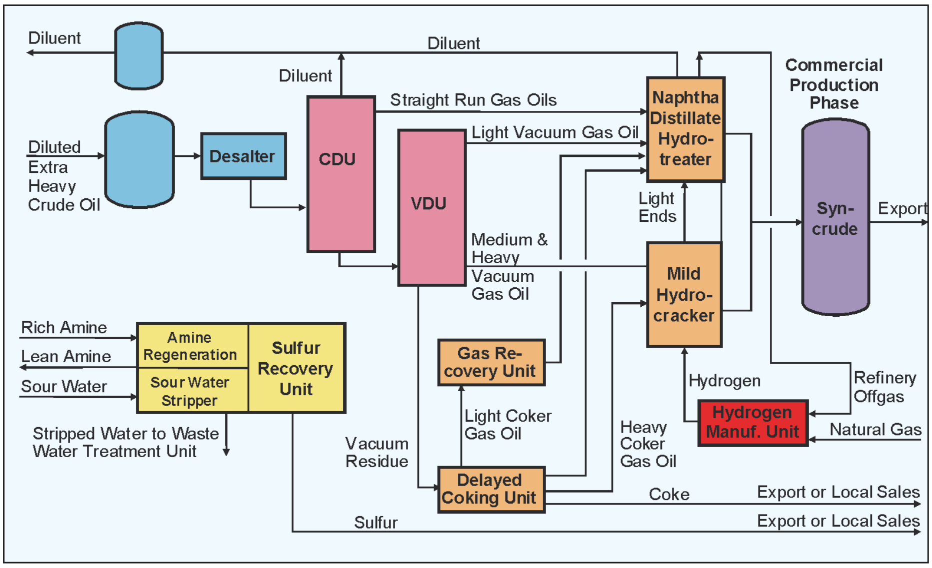

Fig. 1 Simplified scheme of the SINCOR upgrader

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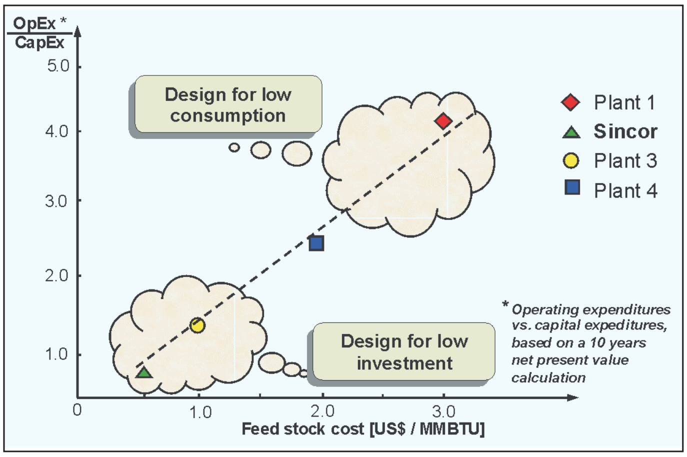

Fig. 3 Ratio of operating expenditures OpEx and capital expenditures CapEx

Process Design Criteria

In this case the configuration of the hydrogen manufacturing unit HMU was driven by reliability issues regarding the hydrogen supply to the upgrader. This requirement consequently led to a two-train concept for the HMU. Two independent trains (Fig. 2) ensure that – even in the unlikely event of a plant trip – the hydrogen supply to the upgrader will not be lost completely and ensures that the upgrader can be kept in operation.

Further plant features which contribute to the reliability of the HMU are:

- reformer fans and BFW pumps are equipped with dual drives (steam turbine with E-motor, connected via overriding clutch) in order to provide two independent drives
- two out of three voting systems for all vital shutdown/emergency trip configurations
- highly reliable PSA technology with 14-adsorber system for increased number of operating modes, plus installation of a redundant valve header
- critical plant equipment (reformer tubes, outlet manifold system, process gas cooler) designed according to proprietary know-how and proven technology to deliver the highest possible reliability.

A fundamental design criteria that shall always be applied is the choice and trade-off between consideration of operating expenditures (OpEx) and capital expenditures (CapEx). Figure 3 highlights the ratio between OpEx and CapEx.

The OpEx/CapEx ratio is plotted over the feedstock cost in US$/MMBTU. For a given plant design one can calculate the ratio between the OpEx and the CapEx, where the OpEx are based on a net present value calculation for 10 years. According to Uhde experience, typical hydrogen plant designs will be arranged in a more or less linear manner along the indicated dotted line.

There is always a trade-off between the cost factors OpEx and CapEx, e.g. in order to achieve very low, competitive consumption figures which lead to low OpEx one has to install equipment for optimal heat recovery which leads to increased CapEx.

To give a practical example: the operator of plant 1 will spend during 10 years of operation 4 times as much on operating cost as he will spend on the initial investment. The reason for this high ratio is the high gas price at the specific location of plant 1. Obviously, this scenario calls for a design for low consumption figures.

Much the opposite is true for the SINCOR HMU design: the gas price is extremely low, and therefore the most important cost factor for the client is the initial investment.

In case the plant owner considers additional costs such as those related to carbon dioxide emission treatment then these trade-offs become even more significant.

As demonstrated by the four example plants displayed in the above figure, all being actual hydrogen project examples, solutions can be provided to the client for the whole range of possible design cases.

Flow Scheme

The basic process steps for the two independent parallel HMU trains are the following:

- feed gas compression
- feed gas desulphurization
- steam reforming
- high temperature CO conversion
- process gas cooling and condensate recovery
- hydrogen purification (PSA).

These process steps are also displayed in the simplified flow scheme in Figure 4.

Innovative Design Features

Each process step requires a study at the design stage and there are options and opportunities for innovative features at every process step.

Reformer design

Shown in Figure 5 is a sectional representation of a typical Uhde reformer box. The reforming tubes are arranged in rows with rows of burners in between. The reformer is of a top fired design, that results in a co-current flow of process gas and flue gas. Once the flue gas reaches the bottom of the reformer box it enters the flue gas tunnels and is conveyed to the waste heat recovery in the convection bank. The reformer tubes are connected to the downstream process gas cooling via the brick lined cold outlet manifold, a proprietary and highly reliable feature of the Uhde reformer design. In particular for the large capacity the top fired design is the most suitable reformer type because of its reasonable tube/burner arrangement.

Safe reformer start-up philosophy

Increased safety awareness of steam reformer operators can be responded by an improved safe reformer start-up philosophy. The principle of this philosophy is to avoid the formation of an explosive mixture of combustible gases and air in the reformer radiant box. The avoidance of explosive mixture formation in the reformer can be achieved in different ways. One improved scheme which has been applied in recent Uhde designs is based on installing a special start-up valve in the fuel gas piping in conjunction with the respective shut-down logic (Fig. 6).

This safe start-up scheme consists of the following four steps:

I. The internal volume of the reformer box and convection bank is purged with fresh air. With all fuel gas piping still securely

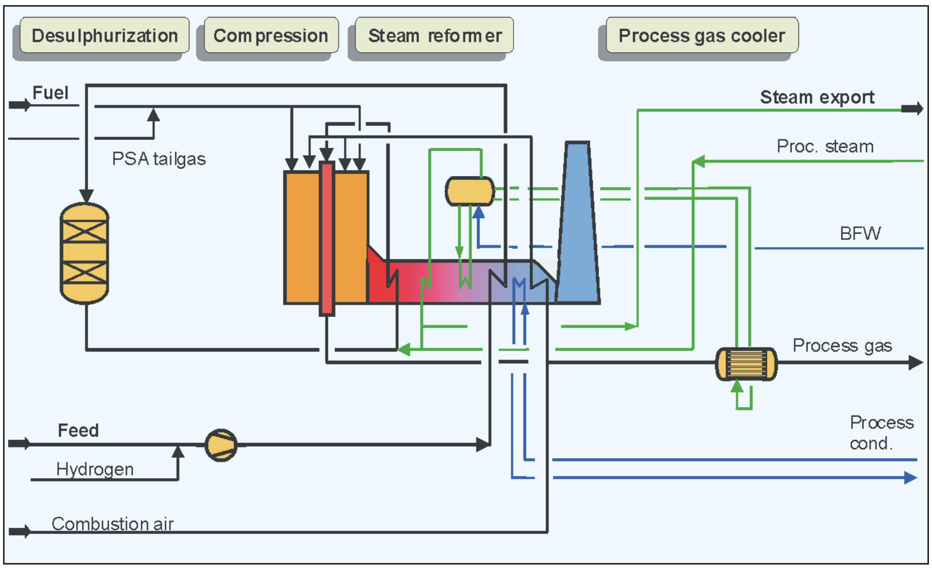

Fig. 4 Flow scheme hydrogen plant (Front End)

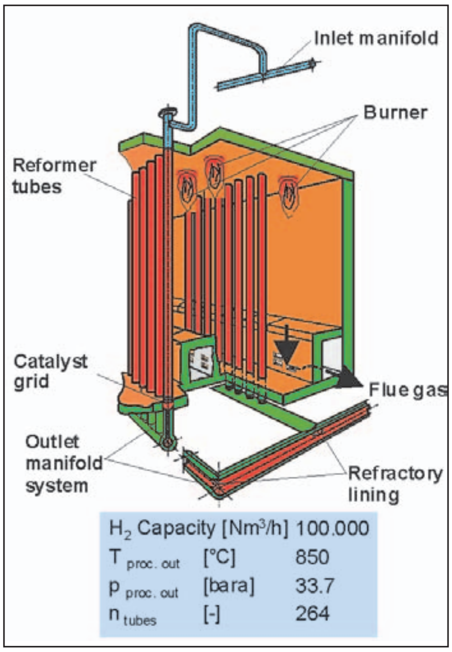

Fig. 5 **Uhde steam reformer design**

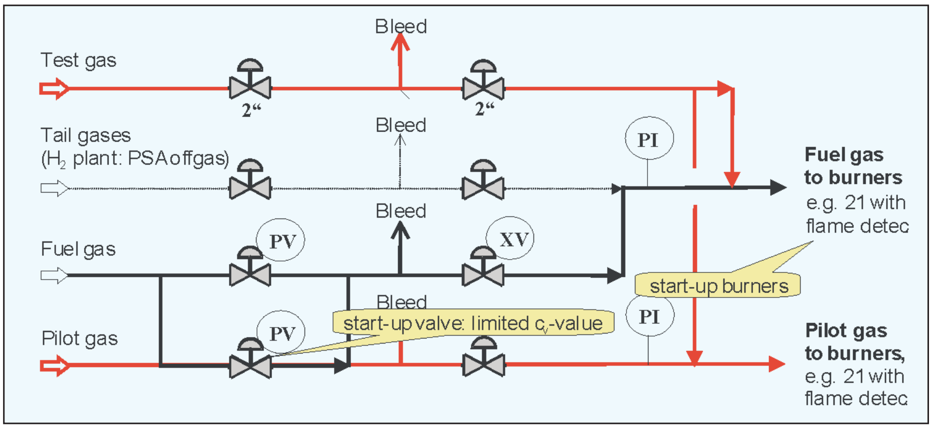

Fig. 6 **Safe reformer start-up philosophy**

closed, the combustion air fan and the flue gas fan are started and operated at partial load for a certain time period. After this period the complete internal volume has been exchanged several times with fresh air and any combustibles have been purged out via the stack.

II. Before the burners can be ignited, a tightness test of the fuel gas piping has to be completed. For tightness testing a test gas is used (natural gas or nitrogen) to pressurize the fuel gas piping between the fuel gas control station and the individual burners and check for any pressure decrease over a defined time period. This test ensures that the entire system is tight and that no combustible gas can enter the reformer box in an uncontrolled manner when opening the fuel gas pressure control valve to start the first burner, e.g. via a manual burner ball valve accidentally left open.

III. When the tightness test has been successfully completed a permission signal will be received to open the start-up valve in the fuel gas bypass around the main valve. The operator can now commence with igniting the first burners, the so called start-up burners (or on request pilot burner), that are equipped with a flame scanner. The start-up valve is designed with a limited flow coefficient. This design ensures on the one hand that enough fuel gas can be supplied to the furnace in order to ignite the start-up burners and the flame scanners deliver a positive signal to the shut-down system; on the other hand the flow will always be safely below a flow that would lead to the formation of an explosive mixture in the reformer box considering the constant flow of combustion air. With the physical design of this valve the system is therefore inherently safe against explosions under all conditions.

IV. Only once all start-up burners are ignited and there is positive flame detection, the main fuel gas valve receives permission to be opened and further main burners can be ignited. Should any flame detectors, e.g. the hydrogen manufacturing unit of the SINCOR upgrader is equipped with a 18 out of 21 voting, fail to deliver a positive signal the furnace will be tripped because of the risk of forming an explosive mixture.

By implementing the above steps of purging, tightness testing, ignition of start-up burners and finally the ignition of the main burners, the operator is supported in the start-up of the reformer firing in the most safe and monitored manner.

Process condensate recycle

One special technology that makes the hydrogen process design more attractive with respect to lower volatile emission requirements is the Uhde direct process condensate recycle (Fig. 7). The process condensate that is formed when the process gas is cooled down to the inlet temperature of the PSA unit (approx. 35°C) is collected and pumped to the process condensate preheater coil in the convection bank. Here waste heat from the reformer flue gas is used to preheat and partially evaporate the condensate with further complete evaporation in the process condensate evaporator downstream the HT shift reactor. The saturated steam from the evaporator is then directly used as process steam for the feed/steam mixing upstream the reformer. The complete re-use of process condensate as process steam avoids a dedicated treatment of process condensate which contains traces of organic compounds, thus avoiding any related emissions. This innovative feature for direct process condensate recycle is in successful commercial operation now for more than 10 years.

Advanced PSA process design

Based on operability, capital cost and reliability of hydrogen supply for the downstream processing units, two 14-adsorber systems, with additional enhanced reliability features, were selected as the optimum choice for the HMU in the SINCOR upgrader (Fig. 8). Also evaluated was the option of having a single PSA unit purifying the feed from the two steam reformers. This option was considered to be technically viable and offered cost advantages, but two separate PSA units were finally selected to be in line with the overall plant concept.

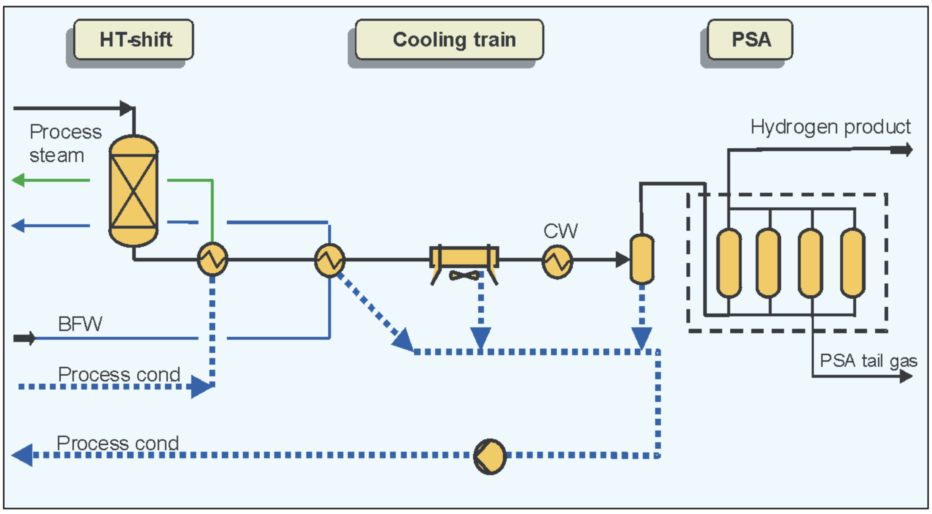

Fig. 7 **Back End flow scheme with process condensate recycle**

Fig. 8 **Site view PSA – 14-Adsorber Polybed Units of UOP at the SINCOR upgrader**

Some of the advantages of the 14-adsorber PSA cycle selected are:

– Four adsorbers on one adsorption step – This gives a very smooth flow of feed and product with minimal disturbances when switching from one adsorber to the next, giving a reliable constant hydrogen supply.
– Three pressure equalisations – This gives the optimum hydrogen recovery taking into account the cost of the PSA unit and the cost of feedstock.
– For the first half of the cycle, five vessels provide tail gas to the mixing drum, and for the remainder of the cycle six vessels provide tail gas to the mixing drum – This gives an essentially constant and very well mixed gas composition and flow at the inlet of the mixing drum. This is very important for optimal firing of the reformer furnace, helping again with the reliability of the hydrogen supply.

CO_2 emission reduction measurements in HMUs

Due to different international directives several countries have already committed themselves to reduce CO_2 emissions. To achieve the set goal of CO_2 emission reduction companies are looking for CO_2 reducing technologies for their new investments. CO_2 removal in HMUs based on steam reforming can be achieved by an innovative design.

In a standard hydrogen plant CO_2 emissions are generated by the combustion of carbon containing fuel such as natural gas and PSA offgas including the CO_2 produced in the process. Conventionally the CO_2 emissions in the flue gas can be reduced by recovering CO_2 from the process syngas prior to entering the PSA unit. In this process concept the bulk CO_2 formed in the steam reforming and in the high temperature CO shift process is consequently removed by a common amine washing unit installed upstream the PSA. The CO_2, a product of adequate quality, can be used for sequestration purposes. In this way the CO_2 emissions via flue gas are reduced significantly by almost 70% compared to a hydrogen manufacturing unit without CO_2 recovery. Additionally the capacity of the PSA unit can be decreased accordingly. Due to an increased lower heating value (LHV) of the PSA offgas the firing is more efficient leading to less combustion air flow resulting in a flue gas flow that is reduced by approx. 30% compared to a hydrogen manufacturing unit without CO_2 recovery.

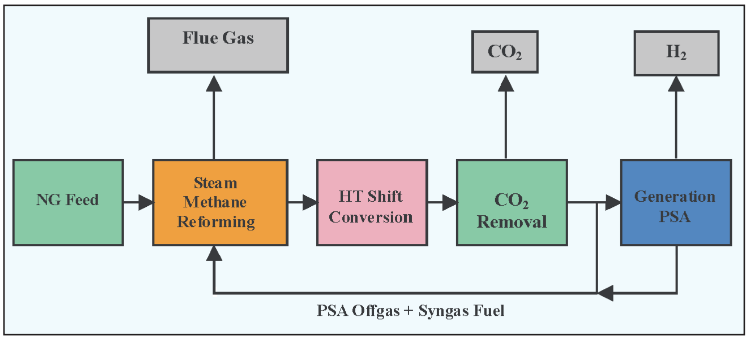

Fig. 9 **Low CO_2 emission concept for a hydrogen manufacturing unit**

Alternatively, fuel gas can be replaced by recycled CO_2-reduced syngas. Figure 9 shows this new development of the steam reforming based hydrogen technology towards maximum reduction of CO_2 emissions. It is obvious that the potential of further reducing the CO_2 emissions is to replace the carbon rich fuel by using hydrogen rich fuel. To meet this target, only approved components are applied. The size of the steam reformer is increased by approx. 25% to meet the requirement that the entire make up fuel gas is produced within the steam reformer itself. Downstream the CO_2 recovery unit a nearly CO_2-free fuel gas is then extracted from the process gas and recycled together with PSA offgas, which is also nearly CO_2-free, to the burners of the steam reformer. By doing so, a CO_2 emission reduction of up to 82%, compared to a hydrogen manufacturing unit without CO_2 recovery can be achieved.

In comparison to the conventional HMU design the cost effectiveness of each individual option, can be summarized as follows: The conventional CO_2 removal process is an economical way to achieve a significant CO_2 reduction. Installation costs are lower than for the alternative CO_2 removal process concept. However, for the alternative concept the amount of CO_2 reduction in the flue gas will be increased by more than 37%. Depending on the overall costs for CO_2 removal with regard to restrictions as given in diverse emission directives, the higher investment cost of the alternative process may pay out by generating additional income from emission trading. For the low emission concept the enlarged front-end will increase the initial expenditures. Even though slightly more feed is consumed, this concept may be of interest as it reduces a maximum of CO_2 in the flue gas under technically and economically feasible conditions.

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