

NEW KBR PROCESS FOR COAL TO AMMONIA

Authors:

Kamal Gursahani - KBR

Siva Ariyapadi - KBR

Meghji Shah - KBR

Richard Strait - KBR

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New KBR Process for Coal to Ammonia

The KBR Transport Reactor Integrated Gasifier, also known as TRIG™, is an advanced coal gasification technology that provides clean, particulate-free syngas. The TRIG is a compact, high pressure, circulating fluidized bed reactor, with no internals or moving parts. Its operation and mechanical design are derived from KBR's fluidized catalytic cracking (FCC) technology, which has over 60 years of successful commercial operating experience. In this paper, we describe the new KBR coal to ammonia process, in which the TRIG is integrated into the process flow sheet of a KBR ammonia plant, supplying hydrogen for a typical 1500 MTPD ammonia synthesis loop. The paper further discusses overall process integration and optimization elements that build on the unique attributes of the TRIG to produce an efficient and robust coal based ammonia plant design.

Kamal Gursahani, Siva Ariyapadi, Meghji Shah and Richard Strait
KBR

Introduction

The recent high prices of oil and natural gas are leading to an increased interest in technologies such as coal gasification, which convert lower value hydrocarbon feedstocks into higher value end products. In the past, before oil and natural gas were widely available as energy sources, coal was used to make coal gas which was piped to customers in towns and cities for lighting, heating and cooking needs. Even today, South Africa still uses coal gasification as a technology to meet much of its petrochemical needs. Likewise, in China, much of the ammonia production is based on synthesis gas obtained via coal gasification.

Ammonia, the most widely used intermediate for making fertilizers, is usually manufactured by the catalytic steam reforming of natural gas. Natural gas has one of the highest proportions of hydrogen among all fossil fuel feedstocks. Hence, from an efficiency standpoint, natural gas is an ideally suited feedstock for the manufacture of ammonia. However, with increasing natural gas

prices, coal gasification can be an economically viable alternative route.

This paper presents a new KBR process technology for converting coal to ammonia.

Coal Gasification

Coal, like other fossil fuels, is basically a mixture of compounds of carbon and hydrogen, but also containing appreciable amounts of oxygen, nitrogen, sulfur, and mineral matter. Coal gasification breaks down coal into its constituents by subjecting it to high pressure and temperature, in the presence of steam, and a limited amount of oxygen. By limiting the amount of oxygen, the feed coal does not burn and produce combustion products, but instead breaks down into more valuable syngas, containing mainly carbon monoxide and hydrogen. For the manufacture of ammonia, coal needs to be converted into as much hydrogen as possible. The syngas from coal gasification can undergo a catalytic water-gas shift reaction with the addition of more steam, to convert the carbon monoxide to carbon dioxide and produce additional hydrogen for ammonia synthesis.

The actual chemistry of coal gasification is quite complex. It is based on partial oxidation reactions of coal. These reactions are essentially non-catalytic and occur at a high temperature, typically inside a refractory lined vessel. The following is a simplistic representation of the basic reactions taking place during coal gasification:

Exothermic:

- Partial Combustion of Carbon

$$\text{C} + 0.5\text{O}_2 \leftrightarrow \text{CO}$$

$$\Delta H_{298}^0 = -110.5 \text{ kJ/mol}$$
- Complete Combustion of Carbon

$$\text{C} + \text{O}_2 \leftrightarrow \text{CO}_2$$

$$\Delta H_{298}^0 = -393.5 \text{ kJ/mol}$$
- Water Gas Shift Reaction

$$\text{CO} + \text{H}_2\text{O} \leftrightarrow \text{CO}_2 + \text{H}_2$$

$$\Delta H_{298}^0 = -283.0 \text{ kJ/mol}$$
- Methanation

$$\text{C} + 2\text{H}_2 \leftrightarrow \text{CH}_4$$

$$\Delta H_{298}^0 = -74.5 \text{ kJ/mol}$$

$$\text{CO} + 3\text{H}_2 \leftrightarrow \text{CH}_4 + \text{H}_2\text{O}$$

$$\Delta H_{298}^0 = -205.8 \text{ kJ/mol}$$

Endothermic:

- Boudard Reaction

$$\text{C} + \text{CO}_2 \leftrightarrow 2\text{CO}$$

$$\Delta H_{298}^0 = +172.5 \text{ kJ/mol}$$
- Steam Reforming Reaction

$$\text{C} + \text{H}_2\text{O} \leftrightarrow \text{CO} + \text{H}_2$$

$$\Delta H_{298}^0 = +131.3 \text{ kJ/mol}$$
- Liberation of Bound Hydrogen

$$2\text{H} \leftrightarrow \text{H}_2$$

$$\Delta H_{298}^0 = +431.0 \text{ kJ/mol}$$

Carbon and hydrogen are molecularly bonded in the coal. There are several other side reactions that take place, resulting in the formation of numerous by-products from coal gasification. Most of the sulfur in the coal gets converted to hydrogen sulfide and carbonyl sulfide, while the nitrogen gets converted to ammonia and hydrogen cyanide. The extent of combustion of the coal depends on the amount of oxygen fed to the gasifier. As coal gasifiers are normally operated in an

adiabatic mode, the heat liberated by the exothermic reactions must balance the heat consumed by the endothermic reactions, plus the heat required to bring the feed streams to reaction temperature. Reaction temperature is usually moderated by the addition of water or steam to the gasifier.

KBR Transport Gasifier

The KBR Transport Reactor Integrated Gasifier, also known as TRIGTM, is an advanced circulating fluidized bed reactor. It has no internals or moving parts. It is designed to operate in both air-blown and oxygen-blown modes. The mechanical design and operation of the TRIG are based on KBR's fluidized catalytic cracking (FCC) technology, which has more than 60 years of successful commercial operating experience. The TRIG operates at considerably higher solids circulation rates, gas velocities, and riser densities, as compared to conventional circulating fluidized beds. These result in higher throughput, higher carbon conversion, better mixing, and increased heat and mass transfer rates.



Figure 1: Picture of the Demonstration TRIG Unit at Wilsonville, Alabama, USA

An engineering scale, 50 MTPD demonstration unit of the TRIG (see Figure 1), has been in operation since the mid-1990's, at the Power Systems Development Facility (PSDF) in Wilsonville, Alabama, USA [1]. It has run successfully on a wide range of coals, including bituminous, sub-bituminous, and various lignites. A unique advantage of the TRIG is its ability to operate in both air-blown and oxygen-blown modes. While the air-blown mode is ideally suited for IGCC power generation applications, the oxygen-blown mode provides syngas for a variety of chemicals and fuels applications. Engineering is currently underway for a 600 MWe KBR TRIG-based IGCC power plant to be built for Mississippi Power in Mississippi, USA. The project is based on the gasification of lignite and will employ two KBR TRIG gasifiers operating in an air-blown mode.

Coal gasifiers are classified as either slagging or non-slagging types. Coal contains inorganic ash components. In slagging type gasifiers, high temperatures are employed for gasification. At these high temperatures, ash fuses forming a molten slag which must be removed from the gasifier. The slag coats the inner walls of the gasifier and flows downward into a separate chamber where it is quenched and solidified using recycled water. The slag must be periodically removed and disposed off as non-leachable solid waste stream. In contrast, the TRIG operates at moderate temperatures and is a non-slagging gasifier. This makes the TRIG well suited to low rank coals *i.e.* coals with high ash and moisture contents. The moderate temperatures employed in the TRIG, reduces the specific oxygen consumption, resulting in reduced cost and auxiliary power consumption associated with the air separation unit (ASU). Moreover, for low rank coals, the moderate temperatures in the TRIG are sufficient to provide high carbon conversions, while ensuring that tar formation does not occur. In addition, the dry ash handling system eliminates the technical difficulties associated with slag handling and removal. Thus, the TRIG offers several advantages when

compared to other commercially available gasifiers.

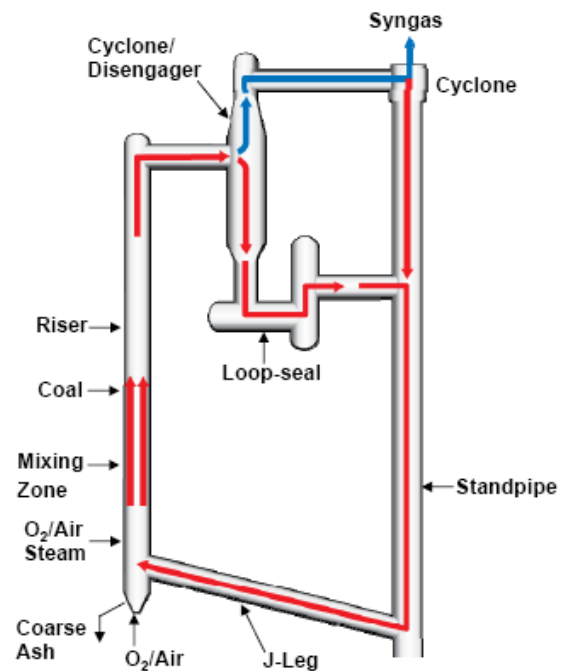


Figure 2: Sketch of the KBR Transport Gasifier (TRIG)

As shown in Figure 2, the TRIG gasifier consists of a mixing zone, riser, disengager cyclones, loop-seal, standpipe and a J-leg. Steam and oxygen (or air) are routed separately and mixed together in the mixing zone, along with the solids returning from the standpipe. In the mixing zone, the unconverted carbon (char) in the returning solids from the J-leg is combusted to generate heat for the gasification reactions. Coal is fed above the mixing zone to avoid premature combustion with the oxygen in the mixing zone. Coal gasification reactions take place primarily in the riser above the coal feed injection point. The produced syngas and solids, move up the riser together, and enter the disengager (cyclone) via a crossover or bend. The disengager removes majority of the particles in the mixture by gravity and/or centrifugal forces. The gas and remaining solids then move to a second stage cyclone, which removes most of

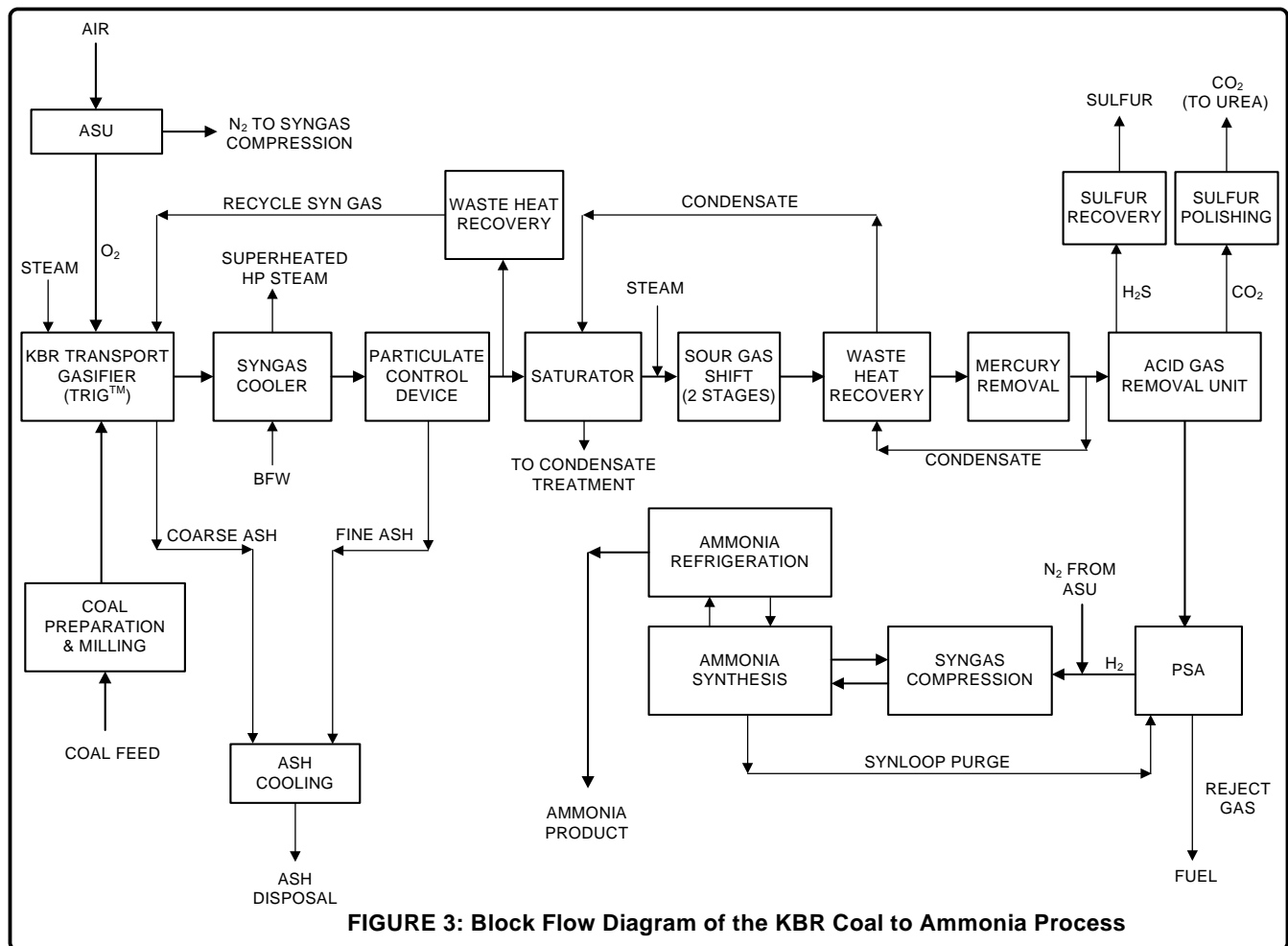
the particles not collected by the disengager. The syngas leaves the unit at the top of the second stage cyclone and goes to waste heat recovery. The solids collected by the cyclones are recycled back to the gasifier mixing zone through the loop seal, standpipe and J-leg arrangement. A blow-down of coarse ash is provided to prevent the accumulation of solids in the gasifier.

Process Description of New KBR Coal to Ammonia Process

In the new KBR coal to ammonia process, the proprietary TRIG technology is integrated with a conventional KBR ammonia synthesis loop. Figure 3 shows a block flow diagram of the KBR coal to ammonia process.

In this case, oxygen, instead of air, is used as the oxidant in the TRIG. This reduces the volume of the process gas to be handled by the downstream processing units.

For this paper, the capacity of the ammonia plant is assumed to be 1500 MTPD (1650 STPD). This capacity makes the back-end of the ammonia plant (*viz.* the ammonia synthesis, ammonia recovery, ammonia refrigeration sections), identical to another 1500 MTPD natural gas based ammonia plant designed by KBR a few years ago. This plant has operated successfully at Hainan Island, China since 2003. The 1500 MTPD ammonia plant capacity is also a good fit with the same size TRIG as that being used in the Mississippi Power IGCC plant project.



The TRIG unit is compatible with a wide range of coal feedstocks, particularly low rank coals. For this paper, it is assumed that the TRIG unit is fed with Powder River Basin (PRB) coal, which is the single largest mined coal in USA. PRB coal is classified as a sub-bituminous coal. It is a low rank coal and has a relatively low heating value and sulfur content as compared to other bituminous or anthracite coals. The lower heating value (LHV) of PRB coal (as received) is about 19,000 kJ/kg (8170 Btu/lb). Table 1 gives the typical composition of PRB coal (as received).

Table 1: Typical Composition of PRB Coal (as received)

Component	Wt%
C	51.74
O	11.52
H	3.41
N	0.71
S	0.26
Cl	0.01
F	0.01
Moisture	27.21
Ash	5.13

The main process steps in the new KBR coal to ammonia process are as follows:

Syngas Generation

- Coal Preparation & Ash Handling
- Air Separation
- Coal Gasification
- Waste Heat Recovery
- Particulate Control
- Syngas Saturation
- Sour Gas Shift

Syngas Purification

- Mercury Removal
- Acid Gas Removal
- PSA

Ammonia Synthesis

- Syngas Compression
- Ammonia Synthesis

- Ammonia Refrigeration
- Ammonia Recovery

Utility Section

- Steam System
- Cooling Water System

Each of the steps above is described in detail below.

Coal Preparation & Ash Handling

Coal is first crushed to the required size and fed to the coal dryers. Because the TRIG can accept larger size coal particles than other gasifiers, crushing energy required is less. Dried, pulverized coal is transferred to the gasifier coal storage bin. Coal is then fed to the pressurized TRIG unit through a system of lock hoppers and conveyed using recycled syngas as a carrier fluid. The coal feed is introduced slightly above the gasifier mixing zone, and it fluidizes as it enters the gasifier. For a TRIG unit fed with PRB coal, the coal feed rate to the plant on a moisture and ash free (MAF) basis is about 1.45 tons of coal per ton of ammonia produced.

Air Separation

The KBR coal to ammonia process uses oxygen as the oxidant in the TRIG. Oxygen is provided by a cryogenic air separation unit (ASU) supplied by a suitable process licensor. To maintain a reasonable size and energy consumption of the ASU, oxygen purity of about 98 mol% is selected. This oxygen purity represents a reasonable trade-off between the size and cost of the ASU, and the size and cost of downstream processing equipment and plant capacity. The main impurities in the oxygen stream are argon and nitrogen. Oxygen is supplied to the gasifier at about 4100 kPaa (600 psia) and ambient temperature. The ASU also supplies pure gaseous nitrogen (>99.999 mol%), at about 2400 kPaa (350 psia) and ambient temperature to the synthesis loop for ammonia synthesis. Because of the low specific oxygen consumption of the TRIG, the size and power requirements of the

ASU are relatively less compared to other gasifiers. For a 1500 MTPD ammonia plant, the oxygen requirement from the ASU is about 1800 MTPD or about 0.82 tons of oxygen per ton of coal on a moisture and ash free basis. The nitrogen requirement is about 1300 MTPD. The power consumption of the ASU is in the range of 35-40 MW (46,900-53,620 hp).

Coal Gasification

Partially dried, pulverized coal, oxygen and steam are fed to the TRIG gasifier near the mixing zone where they contact the circulating solids. Coal gasification reactions take place in the resulting fluidized bed operating in the high velocity, ‘transport regime’. The flow of oxygen is carefully controlled to limit carbon combustion within the gasifier. Steam is added to the gasifier, both as a reactant and as a moderator to control the reaction temperature at about 980 °C (1800 F). The syngas produced along with the remaining ungasified solids move up the riser to the disengager. The larger solid particles in the syngas are removed in the primary disengager. Syngas along with the remaining smaller solid particles enter a second stage cyclone separator, where most of the remaining particles are removed and returned to the standpipe. Here, they are mixed with the larger, previously removed particles, and circulated back to the gasifier mixing zone. A small continuous blowdown of coarse ash is provided from the bottom of the standpipe to prevent the accumulation of solids in the gasifier.

Syngas free of most solid particles leaves the gasifier from the top of the second stage cyclone separator to the primary syngas cooler at about 980 °C (1800 F) and 3585 kPaa (520 psia). A small portion of the cooled syngas from downstream of the PCD is recycled back to the gasifier, for coal conveying and as fluidizing gas within the gasifier. The composition of the syngas leaving the gasifier depends on the type of coal used. For a PRB coal with oxygen as the oxidant, the typical composi-

tion of the syngas leaving the TRIG is shown in Table 2.

Table 2: Typical Composition of Syngas Produced by TRIG using PRB Coal and Oxygen

Component	Mol% (dry basis)
CO	45.0-50.0
H ₂	30.0-35.0
CO ₂	13.0-18.0
CH ₄	1.0-5.0
NH ₃	0.1-1.0
N ₂	0.1-0.5
Ar	0.1-0.5
H ₂ S	500-1000 ppmv
HCN	50-300 ppmv
COS	10-100 ppmv
HF	10-50 ppmv
HCl	10-50 ppmv

Waste Heat Recovery

Syngas exits the TRIG at a temperature of about 980 °C (1800 F). This temperature is in line with secondary reformer outlet temperatures in conventional ammonia plants. The gas is passed through a specially designed high pressure (HP) steam waste heat boiler and HP steam superheater. Thus, the high grade process heat is recovered as superheated HP steam. Final HP steam superheating is done in a superheat coil located in the offsite package boiler. The split of duties between HP steam generation and HP steam superheating can be optimized depending on the overall plant steam system. The syngas is cooled to about 370 °C (700 F) at the exit of the HP steam superheater.

Particulate Control

After waste heat recovery, syngas flows through a KBR proprietary particulate control device (PCD) that removes any particulate matter remaining in the syngas as fine ash. Removing fine particulate matter is an important part of any gasifier system as fine particles in the syngas can foul or corrode

downstream equipment, reducing performance or even leading to equipment failure.

Figure 4 shows a sketch of the proprietary PCD. The PCD employs rigid, barrier type, filter elements to remove essentially all of the fine particulates in the syngas stream. Recycled syngas is used to pulse clean the filters as they accumulate particles from the unfiltered syngas. Downstream of each filter element, a safeguard (fail safe) device is installed to protect the downstream equipment from particulate-related damage in the event of a filter element failure. The particulate stream (fine ash) is depressurized to atmospheric pressure and removed via a proprietary continuous fine ash removal system, after heat recovery.

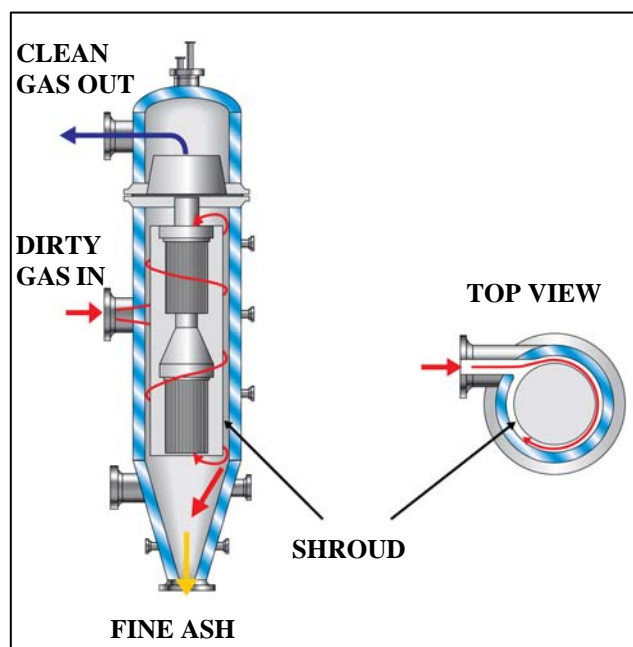


Figure 4: Sketch of the proprietary Particulate Control Device (PCD)

The PCD is a critical component of the TRIG gasifier development as it ensures that the syngas produced is particulate-free, thus eliminating the dirty water or grey water systems that are a feature of most other commercially available gasification processes. The elimination of grey water systems also implies unique heat integration and

water recovery possibilities. KBR has developed proprietary technologies around the core TRIG unit to maximize heat and condensate recovery. These novel features are incorporated in the present coal to ammonia process scheme.

Syngas Saturator

Using PRB coal, syngas produced by the TRIG contains 45-50 dry mol% carbon monoxide. The production of hydrogen needs to be maximized for making ammonia. To accomplish this, carbon monoxide is reacted with steam catalytically in a water gas shift reactor, where most of the carbon monoxide is converted to carbon dioxide and hydrogen. A catalyst that is resistant to sulfur components present in the syngas is used, typically called a sour gas shift catalyst. The raw gas from the TRIG does not contain sufficient steam to support the conversion needed for the sour gas shift catalyst. Therefore, the syngas saturator takes recycled process condensate and heat available in the syngas, and medium to low grade heat available elsewhere in the process, for generating the required steam. A small amount of fresh demineralized water (DMW) is supplied to the saturator to maintain the water balance. A small blowdown is provided from the bottom of the saturator to remove accumulated dissolved impurities. This blowdown is sent to the process condensate stripper.

Sour Gas Shift

The overhead gas from the saturator is mixed with a small amount of live medium pressure (MP) process steam to get the desired steam to gas ratio for the downstream sour gas shift reactors. The process gas goes through a two-stage sour gas shift process. The steam to gas molar ratio inlet to the sour gas shift system is about 1.0 to 1.3. Over the sour gas shift catalyst, more than 95% of the carbon monoxide in the syngas is converted to produce carbon dioxide and an equivalent amount of hydrogen via the water gas shift reaction. Moreover, carbonyl sulfide in the syngas is almost

completely hydrolyzed to hydrogen sulfide. As the water gas shift reaction is exothermic, cooling of the shift effluent is provided. The sour gas shift effluent provides heat for pre-heating feed to the sour gas shift reactors, the upstream syngas saturator reboilers, condensate and fresh water pre-heating to the syngas saturator, acid gas removal unit reboilers, and boiler feed water (BFW) pre-heating. The shift effluent is finally cooled against cooling water. Process condensate is knocked out from the cooled syngas, heated, flashed, and recycled back to the syngas saturator. The flashed gases from the process condensate contain significant amounts of ammonia, carbon dioxide and hydrogen sulfide. These are returned to the gasifier for destruction. The final carbon monoxide concentration leaving the sour gas shift system is about 2.0-4.0 dry mol%.

Mercury Removal

Syngas free of condensate, is passed through a mercury removal guard bed. It consists of an activated carbon bed that adsorbs any mercury present in the syngas. The carbon bed is replaced periodically and the carbon with adsorbed mercury sent for disposal. The mercury free syngas is then sent to the acid gas removal unit.

Acid Gas Removal

For PRB coal, the sour gas shift effluent contains about 35-45 dry mol% of carbon dioxide, and about 500-1000 ppmv of hydrogen sulfide. Carbon dioxide is produced in the gasifier and in the sour gas shift reactors. Hydrogen sulfide is produced from the sulfur present in the coal in the gasifier and from carbonyl sulfide hydrolysis in the sour gas shift reactors. The bulk of these acid gases are removed in the acid gas removal unit, supplied by a suitable process licensor. In this unit, a solvent selectively removes carbon dioxide and hydrogen sulfide from the syngas. The feed gas first flows through a hydrogen sulfide absorber followed by a carbon dioxide absorber. Lean solvent enters the top of the carbon dioxide

absorber and then flows to the hydrogen sulfide absorber, counter-currently. Solvent is flashed through successive flash drums to recover the absorbed carbon dioxide. After final sulfur polishing, the recovered carbon dioxide can be sent to a urea plant. Hydrogen sulfide is recovered from the overhead of the solvent stripper. Elemental sulfur can be recovered from this hydrogen sulfide stream by a suitable catalytic sulfur removal process.

Thus, the acid gas removal unit removes most of the hydrogen sulfide and carbon dioxide present in the entering syngas. Refrigeration load for the acid gas removal unit is provided by the ammonia refrigeration compressor. The carbon dioxide level in the syngas leaving the acid gas removal unit is about 2.0-5.0 dry mol%, while the hydrogen sulfide is removed to ppb levels.

PSA

Syngas leaving the acid gas removal unit undergoes final purification by pressure swing adsorption (PSA). Syngas from the acid gas removal unit is sent to a PSA unit which recovers hydrogen, >99.5+ mol% purity (balance nitrogen, methane, and argon), from the syngas for ammonia synthesis. The hydrogen recovery in the PSA unit is about 85-90%. The remaining components in the syngas, along with the unrecovered hydrogen, concentrate in the tail gas leaving the PSA unit and are sent to the fuel header.

A PSA purification system has been selected in preference over a conventional nitrogen wash system, as it has been shown to have lower capital and operating costs. A similar system has been successfully demonstrated in the Coffeyville Resources Nitrogen Fertilizers ammonia plant in Kansas, USA. [2]

Syngas Compression

The hydrogen from the PSA unit is mixed with high purity nitrogen from the ASU in a 3:1 molar

ratio. The mixed synthesis gas is then compressed to a pressure of about 15500 kPaa (2250 psia) in the syngas compressor. The syngas compressor is a two case centrifugal compressor with an inter-stage cooler. Recycle gas from synthesis loop primary separator mixes with the make-up syngas before the last wheel in the syngas compressor. The mixed gas then goes to the ammonia converter.

Ammonia Synthesis

As shown in Figure 5, the feed to the ammonia converter is pre-heated in a feed-effluent exchanger. The ammonia synthesis converter is a KBR horizontal converter with three equilibrium beds and inter-stage cooling. The third equilibrium stage is divided into two beds in series, so the converter contains a total of four beds. Each bed is filled with 1.5-3.0 mm promoted iron catalyst.

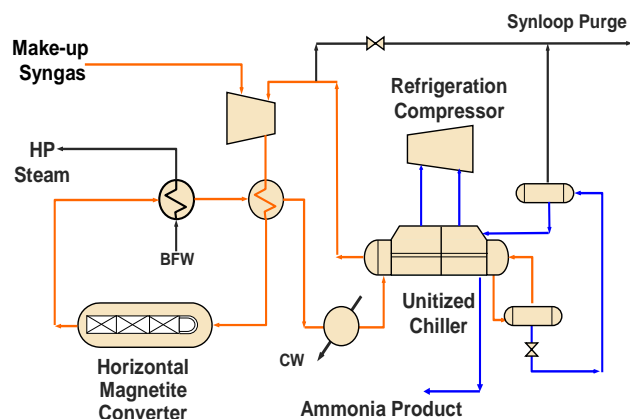


Figure 5: Sketch of a KBR Conventional Ammonia Synthesis Loop

Figure 6 shows a sketch of a typical 3-bed horizontal magnetite converter. In the converter, hydrogen and nitrogen react over the iron catalyst to form ammonia. Converter effluent is cooled by generating HP steam, pre-heating boiler feed water, pre-heating feed to the converter, and against cooling water before refrigeration. A small purge flow is provided from the synthesis loop to pre-

vent build up of inert components *viz.* methane and argon, in the synthesis loop.

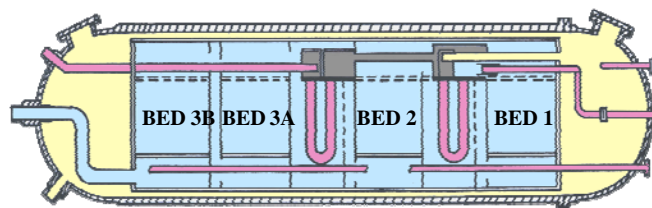


Figure 6: Sketch of Typical KBR 3-Bed Horizontal Converter

Ammonia Refrigeration

Ammonia converter effluent is chilled and ammonia condensed out in a proprietary KBR ammonia unitized chiller. This specially designed exchanger provides cooling of the converter effluent through interchange of heat with synthesis gas returning from the primary separator, and boiling ammonia refrigerant at two different temperature levels. By its unitized design, this exchanger replaces separate exchangers and flash drums. Mechanically, it consists of concentric tubes running through boiling ammonia compartments. The ammonia vapors from the refrigerant compartments are routed to the ammonia refrigeration compressor which is a two stage centrifugal compressor. The ammonia vapors from the refrigerant drums are compressed and condensed in a water-cooled ammonia condenser. The condensed ammonia then goes to an ammonia accumulator. Warm ammonia product is drawn from the bottom of the accumulator and sent to the urea plant via the warm ammonia product pump. The accumulator also supplies ammonia refrigerant for the refrigeration system. The ammonia refrigeration system is also designed to produce all cold ammonia product to be sent to a storage tank.

Ammonia Recovery

The high pressure purge gas from the synthesis loop is used as a driving stream for an ejector which pulls up inerts from the ammonia accumu-

lator and the flash vapor from the ammonia let-down drum. The ejector discharge is fed to an ammonia scrubber where the ammonia in the purge streams is recovered as an aqueous ammonia solution. The solution is then distilled to recover pure ammonia which is combined with the ammonia going to the ammonia refrigeration condenser. The overhead vapors from the ammonia scrubber are recycled back to the PSA unit to recover the hydrogen present in the purge gases.

Steam System

The ammonia plant uses three steam levels – HP steam at 12170 kPaa (1765 psia), MP steam at 4650 kPaa (675 psia) and LP steam at 415 kPaa (60 psia). The ammonia plant generates superheated HP steam. HP steam generation is accomplished by recovering heat in the gasifier effluent and from the synthesis loop converter effluent. The flow sheet is flexible in terms of driver selection for major rotating equipment, depending on project particulars. In this case, steam turbines supplied with superheated HP steam are used to drive the syngas compressor, the ammonia refrigeration compressor, and the compressors in the ASU. Deficits of HP steam during normal operation, and during start-up and shutdown are met by imported HP steam from a coal fired offsite package boiler. MP steam extracted from the steam turbines is used as process steam in the gasifier and inlet to the sour gas shift reactors. MP steam can also be exported to the urea plant for driving the carbon dioxide compressor. LP steam is used for de-aeration of BFW and to drive the ejectors for the steam surface condensers.

Cooling Water System

The ammonia plant is supplied with cooling water from an offsite cooling tower. Cooling water return is sent back to the cooling tower. Depending on site location and availability of fresh water, sea water or air can also be used as cooling media instead of cooling water.

Advantages of the KBR Coal to Ammonia Process

The KBR coal to ammonia process offers several advantages which are summarized below:

1. Flexibility of Feedstock
 - The TRIG is compatible with a wide range of coals. It is especially suited to low rank coals which are abundant and cheaper than other coals.
 - The TRIG can handle coal feeds with a wide particle size distribution. Excessive fines in the feed do not pose problems.
2. Increased Gasifier Reliability
 - Operation at moderate temperatures with no internals or moving parts, improves the reliability of the gasifier.
3. Lower Capital Cost
 - Highly compact design operating at moderate temperatures saves plot space and lowers capital cost.
 - Low specific oxygen consumption reduces the size and cost of the ASU.
 - Non-slagging type of gasifier eliminates additional equipment associated with slag handling and removal.
 - The proprietary unitized chiller offers a compact design and eliminates separate exchangers and flash drums, reducing capital cost and saving plot space.
 - The PSA unit used for syngas purification has a lower capital cost as compared to conventional nitrogen wash units.
4. Increased Energy Efficiency
 - The moderate temperatures employed in the TRIG, combined with its dry feed injection system, reduces the specific oxygen consumption while maintaining high carbon conversions. This reduces the size and energy consumption of the ASU.

- The TRIG offers very high carbon conversions for low rank coals, typically greater than 97%.
 - The syngas leaving the TRIG is not water-quenched, and hence leaves at a fairly high temperature of about 980 °C (1800 F). This allows for high-grade process heat recovery into the steam system. As a result, a large amount of superheated HP steam is generated from the gasifier effluent. This makes the process more energy efficient.
 - The syngas saturator in the flow sheet uses relatively low-grade process heat available elsewhere in the process for generating a large amount of steam from the recycled process condensate. This improves the energy efficiency.
 - All large rotating equipment in the ammonia plant are steam driven. Thus the large amount of steam generated by the process can be used efficiently. The ammonia plant can also export steam to a neighboring urea plant.
5. High Quality Syngas
- The syngas produced by the process is particulate-free.
 - The syngas leaving the TRIG has a low concentration of methane. Low methane content is desirable for hydrogen production for ammonia synthesis.
 - The syngas from the TRIG is free of any oils and tars. This makes gas clean-up relatively simple.
 - The make-up syngas inlet to the ammonia synthesis loop is pure and very low in inerts. This makes ammonia synthesis very efficient.
6. Environmentally Friendly
- The proprietary Particulate Control Device (PCD) eliminates water scrubbing systems required to remove particulates in the syngas. This reduces

pollution caused by dirty water systems.

- The unique condensate handling scheme in the flow sheet recycles most of the water in the system, requiring a very small make-up of fresh demineralized water, and a very small blowdown of dirty condensate from the system.

Economic Considerations

Depending on the overall plant configuration selected, a specific energy consumption as low as 38.5-40.6 GJ/MT (9.2-9.7 Gcal/MT) of ammonia produced, is achievable by the KBR coal to ammonia process. While this specific energy consumption is about 40-47% more than the most efficient natural gas based KBR Purifier® ammonia plants, the TRIG can process cheaper, low rank coals, which are frequently found for less than \$1/MMBtu. Thus, the KBR coal to ammonia process is low in operating costs (OPEX). Also, because of its simple design and moderate operating conditions, the TRIG gasifier has a high on-stream factor which reduces maintenance costs.

The capital cost (CAPEX) of a conventional coal to ammonia plant is about double that of a natural gas to ammonia plant [3]. However, a TRIG based coal to ammonia plant will cost less than a conventional coal based ammonia plant because of a simpler design, fewer pieces of equipment, and less severe operating conditions.

Given the TRIG's suitability to process cheaper, low rank coals, the KBR coal to ammonia process appears to have bridged the gaps of higher capital cost and higher specific energy consumptions associated with coal based ammonia plants. The process is an economically viable route for the manufacture of ammonia in places that do not have a source of low cost natural gas but have abundant low rank coals.

Conclusions

The new KBR coal to ammonia process is based on the KBR TRIG gasification technology, integrated with proven KBR ammonia synthesis technology. The process is well suited to a wide range of coal feedstocks, particularly the low rank coals, which are cheap and abundant. The process offers a robust and energy efficient design, with several advantages when compared to traditional coal to ammonia processes. It is an economically attractive option for manufacturing ammonia, especially in countries with large coal reserves and limited or high cost natural gas deposits, such as USA, China, and India.

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